SBE19 Graz

SUSTAINABLE BUILT ENVIRONMENT D-A-CH CONFERENCE 2019
TRANSITION TOWARDS A NET ZERO CARBON BUILT ENVIRONMENT
11 – 14 September 2019, Graz University of Technology
Rechbauerstraße 12, 8010 Graz, Austria

CONFERENCE PROCEEDINGS

IN CO-OPERATION WITH

University of Natural Resources and Applied Life Sciences, Vienna

Transition Towards a Net Zero Carbon Built Environment

Editors

Alexander Passer – *Graz University of Technology*
Thomas Lützkendorf – *Karlsruhe Institute of Technology*
Guillaume Habert – *ETH Zurich*
Helga Kromp-Kolb – *University of Natural Resources and Life Sciences, Vienna*
Michael Monsberger – *Graz University of Technology*

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Graz University of Technology
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ETH Zurich
Guillaume Habert, Anita Naneva, Francesco Pittau

Karlsruhe Institute of Technology
Thomas Lützkendorf

Layout

Graz University of Technology
Nora Hoti

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WELCOME TO SBE19 GRAZ

Dear ladies and gentlemen,
Dear colleagues,

we would like to welcome you to the Sustainable Built Environment D-A-CH Conference 2019 (SBE19 Graz) - Transition Towards a Net Zero Carbon Built Environment. Together with other events in the SBE-series, the goal is to prepare for the World Conference in 2020 in Gothenburg (WSBE2020 - Beyond 2020).

The aim of SBE19 Graz is to enable an exchange between scientists, practitioners, politicians and the interested public on matters regarding innovative construction products, sustainable buildings, modern design methods and tools, sustainable urban neighborhoods and future-proof urban development. This includes new business models and instruments on green financing as well as national and regional strategies to implement sustainable development principles in the construction and real estate sector. For the first time, this regional conference has been jointly organized by institutions from Germany, Austria and Switzerland following the "D-A-CH" format.

The 145 international scientific committee members put a lot of effort into the double-blind peer review process of the scientific contributions and selected the best contributions for presentations, which are available as open source, indexed publications. 188 scientific presentations from more than 30 countries highlight the wide scope and complexity of international research activities that address sustainability issues for the built environment. The program is structured accordingly including the following topics organized in six parallel sessions: Buildings, Building Design, Processes, Products, Education & Economy and National Issues.

The matter of climate change has been stated clearly by the IPCC: Every degree of warming counts, every year of delay counts and every decision counts. It is now being increasingly discussed how the demands for climate protection can be translated into concrete design requirements, e.g. in terms of environmental budgets or environmental target values. Swift action is required and the advice of our colleagues in climate and environmental research is becoming ever more urgent. What is needed are general sustainability guidelines as well as practical solutions such as planning and assessment methods, innovative construction products and building solutions.

The role of the construction and real estate industry in developing answers to the current problems is crucial. The construction, maintenance and adaptation of the built environment is a basic prerequisite for social and economic development. On the one hand, these activities require significant amounts of energy and initiate material flows and green house gas emissions that impact the global and local environment not only during construction, but for a long time thereafter – typical lock-in factors. On the other hand buildings, cities and infrastructure are not only affected by climate change but are also expected to protect people from the undesirable effects of climate change. Therefore, the sector has multiple tasks, the most pressing one being to exploit the savings potential of the sector with appropriate support through setting suitable framework conditions and policies. Greenhouse gas emissions must be reduced to 50% by 2030 and industrialized nations must achieve net zero emissions by 2050. That is an enormous challenge, but the stakes are high and the building and related industry sector must and will contribute to the effort.

From a complex analysis perspective, topics other than mitigation should not be neglected - examples are health protection, comfort, durability, adaptability, resilience, decommissioning and recyclability (circular economy) or affordability. Frequently, this not only results in synergies but also in trade-offs, sometimes conflicting goals, which only become recognizable and solvable in an integrated, systemic approach. Methodological approaches such as technology assessment or comprehensive sustainability assessment therefore remain indispensable.

The SBE19 Graz addresses questions with additional complementary formats to the regular scientific presentations. Aspects of climate change (SDG 13) and the role of sustainable cities and municipalities (SDG 11) will be discussed in roundtable events at the pre-conference. In the special fora specific topics will be discussed in a workshop character, for example regarding LEVEL(s), CRP special requirement 7, the further development of EPDs, sustainability performance of construction products (steel, concrete, wood and plastics). Last but not least, a focus will be put on how universities and research institutes can contribute to sustainable development with their own responsibility and their own building stock – where your valuable contribution would be highly appreciated.
The days of exchange and discussion at this conference at Graz University of Technology are also an important signal: inspiring cooperation and scientific exchange across all borders is not only possible but necessary - limiting global change within planetary boundaries.
Our organizing team made a special effort to make this event itself a more sustainable one following Green Events Austria suggestions.
SBE19 Graz provides a special setting to refresh existing contacts and create new partnerships and friendships. We hope that your stay in Styria, the green heart of Austria, will stir active discussion and we are looking forward to hear your thoughts and views to progress the Transition Towards a Net Zero Carbon Built Environment.

With kind regards,
SBE19 Graz Chairs

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SBE19 Graz

SUSTAINABLE BUILT ENVIRONMENT
D-A-CH CONFERENCE 2019

11 - 14 September 2019
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▶ www.sbe19.tugraz.at

TU Graz
KIT Karlsruhe Institute of Technology
ETH zürich
BOKU University of Natural Resources and Applied Life Sciences, Vienna

PROGRAM OVERVIEW

Transition Towards a Net Zero Carbon Built Environment

Wednesday 11 September

Pre-Conference

Time	Aula
09.30	Welcome Coffee
10.30	**SDGs & Universities**
13.00	Lunch & Registration
14.00	**SDG 13 Roundtable**
15.30	Coffee Break
16.00	**SDG 11 Roundtable**
17.45	
18.30	**Welcome Evening** **Mayor's Reception** Town Hall

Thursday 12 September

Conference

Time	Aula	HS I	HS VI	HS XII	HS V	ATEG-152	AT01-036	AT01-104	AT01-098
08.00	**Registration** | Conference Office								
09.00	**Opening Ceremony** | Aula								
09.30	**Keynotes** Aula								
11.00	Coffee Break								
11.30	SF Level(s)	1 Buildings	1 Building Design	SF Die 3 Schwestern Aspern Bauplatz D22	1 Processes	1 Products	1 Education & Economy	SF CONDEREF	
13.00	Lunch								
14.15	SF BWR7	2 Buildings	2 Building Design	1 Cities	2 Processes	2 Products	2 Education & Economy	SF ecoinvent	SF vinylplus
15.45	Coffee Break								
16.15		3 Buildings	3 Building Design	2 Cities	3 Processes	3 Products	3 Education & Economy	SF EPD	
17.45									
18.00	**Guided City Tour** From the conference venue to the Schlossberg								
19.30	**Conference Dinner** | Schlossberg Restaurant								

Friday 13 September

Conference

Time	Aula	HS I	HS VI	HS XII	HS V	ATEG-152	AT01-104	AT01-098	
08.00	**Registration** | Conference Office								
09.00	**ADOPTION OF THE "GRAZ 2019 DECLARATION"** I Aula								
09.20									
09.30	1 National Issues	4 Buildings	4 Building Design	3 Cities	4 Processes	4 Products	SF Beton	SF Plastics	
11.00	Coffee Break								
11.30	2 National Issues	5 Buildings	5 Building Design	4 Cities	5 Processes	5 Products			SF green.LAB Waagner-Biro-Straße
13.00	Lunch						13.30		
14.15	3 National Issues	6 Buildings	6 Building Design	5 Cities	6 Processes		SF Holz-system-bau	SF Smart City Graz	
15.45	**Closing Event** including ***Best Paper Award*** | Aula								
17.15	**Farewell Coffee**								

Saturday 14 September

Side Event

Time	
09.30	**Technical Tour**
12.00	
15.00	
15.30	

Thursday
12 September

Conference

Time	Aula	HS I	HS VI	HS XII	HS V	ATEG-152	AT01-036	AT01-104	AT01-098
08.00	**Registration** | Conference Office								
09.00	**Opening Ceremony** | Aula								
09.30	**Keynotes** Aula								
11.00	Coffee Break								
11.30	**SF** Level(s)	**1** Buildings	**1** Building Design	**SF** Die 3 Schwestern Aspern Bauplatz D22	**1** Processes	**1** Products	**1** Education & Economy	**SF** CONDEREF	
13.00	Lunch								
14.15	**SF** BWR7	**2** Buildings	**2** Building Design	**1** Cities	**2** Processes	**2** Products	**2** Education & Economy	**SF** ecoinvent	**SF** vinylplus
15.45	Coffee Break								
16.15		**3** Buildings	**3** Building Design	**2** Cities	**3** Processes	**3** Products	**3** Education & Economy	**SF** EPD	
17.45									
18.00	**Guided City Tour** From the conference venue to the Schlossberg								
19.30	**Conference Dinner** | Schlossberg Restaurant								

SF Special Fora

SF SF in German language

Conference Sessions

Special Sessions

Friday
13 September

Conference

	Aula	HS I	HS VI	HS XII	HS V	ATEG-152	AT01-104	AT01-098	
08.00	**Registration** | Conference Office								
09.00	**ADOPTION OF THE "GRAZ 2019 DECLARATION"** | Aula								
09.20									
09.30	**1** National Issues	**4** Buildings	**4** Building Design	**3** Cities	**4** Processes	**4** Products	**SF** Beton	**SF** Plastics	
11.00	Coffee Break								
11.30	**2** National Issues	**5** Buildings	**5** Building Design	**4** Cities	**5** Processes	**5** Products			**SF** green.LAB Waagner-Biro-Straße
13.00	Lunch						13.30		
14.15	**3** National Issues	**6** Buildings	**6** Building Design	**5** Cities	**6** Processes		**SF** Holz-system-bau	**SF** Smart City Graz	
15.45	**Closing Event** including ***Best Paper Award*** | Aula								
17.15	**Farewell Coffee**								

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TU Graz KIT Karlsruhe Institute of Technology ETH zürich BOKU University of Natural Resources and Applied Life Sciences, Vienna

FOREWORDS

Transition Towards a Net Zero Carbon Built Environment

Dear SBE19 Graz participants,


credit: lunghammer

sustainability is one of our most eminent topics. It is a necessity for our dealings with nature and scarce or even infinite resources. A responsibility of pressing urgency for all mankind, it is an obligation we owe to future generations. One of the most important contributions we can make for this so very urgent task is to achieve sustainable construction.

The development of sustainable solutions is not an effort limited to single scientific disciplines as we strive for sustainability. Interdisciplinary approaches are key to effectiveness and success through a broad front and are on high demand. TU Graz fosters multiple concepts and focusses on interlinking them. Our Field of Expertise Sustainable Systems – one out of five internationally outstanding research areas – involves researchers from all our seven faculties and half of our around 100 institutes. Its research topics range from future-oriented urban planning, innovative building technologies and energy systems to the use of renewable energy sources, intelligent energy networks and green mobility.

The topic is well represented in our graduate and continuing education. Furthermore, our students organize sustainability events on a regular basis. Our internationally successful student teams work on projects ranging from lightweight concrete to energy-efficient vehicles.

The initiative UniNEtZ unites Austrian universities and relevant official institutions in contributing to the goals defined and pursued by the United Nations Sustainable Development Agenda. Under the leadership of the TU Graz Sustainability Advisory Board, our university and the University of Graz co-ordinate our universities contributions make to the UN sustainable development goal (SDG) 11 of ensuring sustainable cities and communities. Furthermore, contributions are made to work on quality education (SDG 4), clean water and sanitation (SDG 6), affordable and clean energy (SDG 7), industry, innovation and infrastructure (SDG 9), responsible production and consumption (12) and climate action (13).

This conference will bring valuable contributions and yield practical results for the diverse facets and the assignments of sustainable construction. Experience an inspiring visit to Graz University of Technology while participating in fruitful discussions and gaining new insights.

Yours,

Univ.-Prof. Dipl.-Ing. Dr.techn. Dr.h.c.mult. **Harald Kainz**
Rector of Graz University of Technology, Austria

Dear participants of the SBE19 Graz,

as the President of Karlsruhe Institute of Technology, KIT – The Research University in the Helmholtz Association – it is my great pleasure to send you greetings from the executive board as well as the employees and students.


credit: andrea fabry

In an era of intense struggle to achieve the internationally recognized sustainable development goals, it is particularly important to put scientific knowledge at the service of society and to strengthen international cooperation. This also applies to the subject areas of design, construction, renovation and use of buildings, sustainable urban development and sustainable energy supply. After participating in the preparation of the SB13 in Munich and the SBE16 in Hamburg, KIT is now involved in the implementation of the SBE19 in Graz – for the first time as partners with institutions from Austria and Switzerland in a transnational format. KIT staff have directly participated in the Advisory Board and the immediate organization, as well as making scientific contributions to the conference.

At KIT, around 9.300 employees are working together on a broad disciplinary basis in natural sciences, engineering, economics, humanities and social sciences. KIT offers research-oriented studies to prepare its 25.000 students for responsible tasks in society, economy and science. Our aim is to make significant contributions to global challenges in the fields of energy, mobility and information.

Innovations at KIT bridge the gap between knowledge and application for the benefit of society, economic prosperity and the preservation of our natural resources. According to this mission, knowledge for society and the environment is developed and taught at the research university. Due to its broad profile, KIT's divisions and institutes are able to almost completely map the value added chains of the construction, real estate and energy industries. This approach allows us to develop products, technologies, assessment methods and business models that contribute to sustainable development. Thus, KIT has successfully dealt with these key issues: (1) development and testing of sustainability assessment systems for buildings and neighborhoods; (2) analysis of building-related energy and material flows in regions; (3) development of indicators for assessing energy supply systems.

The organization of scientific disciplines of KIT is purposely structured in five divisions: I: Biology, Chemistry and Process Engineering, II: Informatics, Economics and Society, III: Mechanical and Electrical Engineering and V: Physics and Mathematics, deal with research issues with direct relevance to the topics of construction and energy industry. Division IV provides a center for all topics of the natural and built environment. The creation of three overarching strategic fields: „Energy“, „Mobility“ and „Information“, ensures that targeted research contributions can be expected in the coming years to address current megatrends.

Foundations, principles and solutions for the implementation of sustainable development are an integral part of the education of students and young scientists. An extra-curricular course of studies called „Sustainable Development“ organized by the Centre for Cultural and General Studies (ZAK) is just one example. In 2018, UNESCO designated KIT as a “learning location for sustainable development”. The “Future Campus” department coordinates and promotes sustainable development at our own campus.

I am convinced that the SBE19 in Graz will not only be a showcase of past results and achievements, but also the starting point for an even more intensive cooperation in all relevant fields of research. I wish all participants every success in this regard. Finally, I would like to thank the institutions in Austria and Switzerland for their cooperative spirit and in particular TU Graz for their initiative in connection with the host's role.

Professor Dr.-Ing. **Holger Hanselka**
President of Karlsruhe Institute of Technology, Germany

Dear SBE19 Graz participants,

a continuous increase in the population over the last centuries along with the industrialization and its increasing demand for fossil energy led to a record high CO2 concentration in the atmosphere and further ecological and social challenges. The 17 SDGs (Sustainable Development Goals) proposed by the United Nations give a vision for 2030 and are based on the planetary boundary concept with the goal to avoid further damage to our planet. One of the SGDs, the SDG 11, focusses on **“Making cities and human settlements inclusive, safe, resilient and sustainable”** and directly links to the topic of this conference, a sustainable built environment. Issues like land consumption and its related consequences, the use of construction materials, energy efficiency and production are as well addressed as social implications on how we as human beings want or should live together.

BOKU University of Natural Resources and Life Sciences, Vienna is the University of Sustainability. We do research and offer study programs since 1872 based on the integration of technical, ecological and socio-economic fields. This interdisciplinary approach perfectly addresses the research and educational needs of the sustainable development goals. Not surprisingly that BOKU takes a leading role in the Austrian UniNEtZ-Project, which promotes the implementation of the SDG in Austria.

With this background we are proud to contribute to this conference. We expect new findings and we do hope that you have a successful stay in Graz.

Yours sincerely,

Univ. Prof. Dipl.-Ing.Dr. DDr.h.c. **Hubert Hasenauer**
Rector of University of Natural Resources and Applied Life Sciences, Austria

Dear SBE19 Graz participants,

credit: ETH Zurich

the construction industry accounts for over 40% of all raw materials extraction, as well as 40% of total energy supplied and 16% of annual water consumption worldwide. During the last century, overall global material consumption multiplied approximately tenfold, while consumption of construction minerals multiplied by a factor of 42, showing a positive feedback-loop between socio-technical system evolution and its construction material requirement. Following business-as-usual practices will drive building and infrastructure activities along a dramatic and unsustainable path. But these future challenges can also be turned into opportunities.

Selected building technologies can reduce or even store carbon emissions during construction and in the longer term. They can also be used as depositories of materials to be mined at a later stage. Building renovation can also be a catalyst to re-activate social and economic networks in a neighbourhood. To harness these opportunities, the Swiss Federal Institute of Technology (ETH Zurich) is engaged in research and innovation towards a post carbon environment.

ETH Zurich also wants to play a key role in training a new generation of scientists, engineers and architects. We want them to have the fundamental knowledge to tackle these challenges but also, and most importantly, to exercise critical thinking in order that they can engage in society by developing and designing the appropriate answer to the real needs of future generations.

The conference on the Sustainable Built Environment, SBE 19 in Graz, is part of a major international series of conferences supported by the International Council for Research and Innovation in Building and Construction (CIB), the International Initiative for a Sustainable Built Environment (iiSBE), the Sustainable Building and Climate Initiative (SBCI) of the UN Environment, the International Federation of Consulting Engineers (FIDIC) and the Global Alliance for Buildings and Construction (GABC). The series, now on a three-year cycle, is recognised as the world's preeminent conference series in this important field.

I am delighted to learn about the common initiative from Austrian, German and Swiss universities to co-organise this conference. It is hosted at the Graz University of Technology in collaboration with the University of Natural Resources and Life Sciences in Vienna, Karlsruhe Institute of Technology and ETH Zurich.

I wish you all success for the conference and hope that under this common roof you, as researchers and industry partners, will have exciting and fruitful discussions that will trigger the necessary dynamics for transformation towards a net zero emission built environment.

Yours sincerely,

Prof. Dr. Dr.h.c.mult. **Sarah M. Springman** CBE FREng
Rector of Swiss Federal Institute of Technology Zurich, Switzerland

Dear SBE19 Graz participants,


credit: paul gruber

with the Austrian Climate and Energy Strategy, #mission2030, we heralded the end of the fossil fuel age in our country. We want to reduce greenhouse gas emissions by 36 percent compared to 2005 and aim to produce 100 % of Austria's power consumption from renewables by the year 2030. Presently, we are working to prepare the law on the development of energy from renewable sources; we advance electromobility, ensure new funding options by means of the Green Initiative, and promote the Bioeconomy Strategy.

High-quality refurbishment and renovation of existing buildings and energy-efficient new construction are effective strategies in the fight against climate change. With the help of Austria's Heat Strategy the goals for the building and thermal sector laid down in #mission2030 are to be achieved by 2030. Promoting energy efficiency and renewable energy in buildings also creates important impulses for Austria's economy and offers substantial opportunities on international markets.

In addition to the thermal rehabilitation campaign, the subsidies offered within the framework of domestic environmental subsidisation and the Climate and Energy Fund, my climate protection initiative "klimaaktiv" is setting trailblazing impulses with the building standard, the complex evaluation system in the field of climate protection and energy efficiency.

The fight against climate change is anything but easy, but it also represents a great opportunity. Bearing this in mind, I wish the "Sustainable Built Environment Conference 2019" every success. It is a pleasure for us to offer support to this important event.

Kind regards,

Maria Patek
Federal Minister for Sustainability and Tourism, Austria

Dear SBE19 Graz participants,


credit: johannes zinner

cities and buildings of the future have to provide a major contribution to the national and European climate and energy targets. Therefore, energy driven and sustainable city planning, digitalization in the construction sector as well as renewable energy and building technologies are key to support stakeholders, especially under the requirements of building quality and affordability.

Research can significantly contribute to generate innovative solutions for the future by questioning known patterns. If they succeed, they will be put into practice, and the creation of suitable framework conditions are essential to enable a broad and successful implementation.

As an example, the Austrian Federal Ministry of Transport, Innovation and Technology (BMVIT) is committed to the implementation of plus energy districts as a mission of “City of Tomorrow”. It will do so by funding research and development on urban technologies, technological systems and services, and taking the growing importance of digitalization into account.

The focus lies on innovative technologies and systems for energy generation, distribution, transformation and storage as well as the optimization of the energy consumption in buildings and urban neighbourhoods, in addition to energy efficiency and new building technologies for new constructions and renovations.

For many years, Austria is internationally recognized as a pioneer in the field of building and urban technologies. This role is to be further strengthened by the current initiatives, an objective that can only be achieved with the involvement and cooperation of research, industry, public administration and commercial enterprises.

With this in mind I wish those attending the Sustainable Building Conference 2019 stimulant and exciting discussions!

Yours sincerely,

Andreas Reichhardt
Federal Minister of Transport, Innovation and Technology, Austria

„Architecture is a manifestation of freedom"


credit: lebensressort

Scientific evidence for a global warming and change of the climate system is unequivocal. Climate change impacts thousands of citizens' lives around the globe every day in countless ways. One way in which we are impacted is in our weather patterns: we face periods of enormous heat and extreme thunderstorms followed by particularly frosty winters. As we gradually move from a state of normality to a state of extremes, the call on our nation's leaders has become louder and louder. The call? One for sustainability.

Although it is a fact that climate change does not know any borders, Styria wants to procede as a role model. We know that climate change and its effects do not have touchpoints with just one or two thematic areas. Therefore, the Styrian government has decided not to pass just one single law, but to consider these problems in all of its political activities, ranging from tasks such as spatial planning, funding guidelines and general legislation. For Styria, sustainability is not merely one project or something that gets passed in a couple of laws by Parliament. Rather, sustainability is one lens through which all decisions will pass through.

A major area in which sustainability plays a special role is housing and its funding guidelines. Therefore, we pay particular attention to which building materials are used for construction. Another important criteria for obtaining public funding is the issue of energy efficiency when it comes to constructing or renovating houses. Land Steiermark's course of actions clearly favours buildings that protect the climate by using materials that help the buildings achieve energy efficiency, in accordance with European Union directives.

The issues related to climate change and global warming cannot be solved by a single country, yet it is our duty to make our modest contribution to preserve our liveable environment.

Yours faithfully,

Johann Seitinger

State Councilor for Agriculture and Forestry, Water and Waste Management, Housing and Sustainability, Styria, Austria

Dear SBE19 Graz participants,


credit: freisinger

the topic of sustainability affects a variety of areas in our lives; be it the production and consumption of goods, the volume of traffic or our built environment, which seals large areas of land.
All this presents future generations with ever-increasing challenges. However, it is up to us to keep this negative legacy to a minimum.

The economic efficiency, when it comes to using resources as economically as possible, the developments in economic terms as well as the social aspects of responsibility for the future and global distributive justice should guide our actions.

In the Climate and Energy Strategy Steiermark 2030, an important chapter for sustainable construction methods was opened with a focus on „buildings and settlement structures“ from a holistic perspective. It ranges from energy-optimized settlement structures as an element of energy planning to energy-efficient building technologies and climate-friendly and therefore sustainable building envelopes.

In addition, the Climate and Energy Strategy Steiermark 2030 also addresses the aspects of ecology (such as open spaces and urban climate, water and soil, resource cycles and emissions). For example, the sustainability criteria in the waste and resource industry, the energy supply and distribution and the reduction of the personal carbon footprint of each and everyone of us are essential issues.

Now it is important to suit the action to the word and take concrete measures. The fight against climate change does no longer tolerate a delay.

With this in mind, I wish all involved parties a successful participation. May you be the initiator and driving force for processes for a livable future for our children and grandchildren.

Yours faithfully,

Anton Lang
State Councilor for Finance, Transport, Environmental and Renewable Energies / Climate Protection, Sport and Animal Welfare, Styria, Austria

Ladies and Gentlemen,


credit: marija kanizaj

as the Mayor of Graz, I am particularly pleased that the „Sustainable Built Environment D-A-CH Conference 2019“ is taking place in Graz once again. Graz is growing: about 60,000 more inhabitants since 2003. That also means, we are forecasting another 40,000 new citizens by 2035. In view of this development, urban sustainability strategies, especially in the residential sector, are not „nice to have“, but indispensable.

Since this internationally renowned conference enables encounters between young researchers and established scientists, not only the content but especially the format can be described as particularly sustainable.

I hereby thank all those who have contributed to the preparation and implementation of the conference, as well as all speakers and wish you all informative and enjoyable days in Graz!

Yours faithfully,

Mag. **Siegfried Nagl**
Mayor of the City of Graz, Austria

Dear SBE19 participants,

credit: stadt graz/ fischer

it is a great pleasure for me to welcome you to Graz as the capital of the province of Styria and with nearly 300,000 inhabitants the second largest city of Austria. Graz is very proud to host four universities and two universities of applied sciences with about 50,000 students. This is one main reason to support such important scientific events like SBE19.

Another reason is that knowledge exchange and capacity building – with such a holistic approach – are essential for the public sector to keep pace with rapid technological development and changing societal and environmental framework conditions. The SBE19 Graz conference where internationally renowned experts will present important aspects of sustainable building and construction in numerous talks and lectures is a perfect possibility for practitioners, scientists and administration to learn from each other.

As a strong growing city, Graz is continuously looking for sustainable urban development solutions to preserve and even expand its high quality of life under growing framework conditions.

In this regard the City of Graz has already achieved national and international recognition for its innovative efforts to implement such sustainable solutions under its local umbrella strategy for a Smart City. This can only be achieved through a strong PPP-cooperation with numerous experienced scientific partners such as the University of Technology in Graz, the Provincial Government of Styria and with many other innovative institutions and companies.

Curbing climate change today is one of the biggest challenges facing politics, the economy and society. Sustainable building and renovation concepts are essential instruments of climate protection and important steps towards local energy autonomy. More than one third of our energy consumption results from the private, public and service sector. Hence comprehensive thermal retrofitting of building stock, greater energy efficiency in new buildings and a significant increase in the share of renewable energy can - in addition to more efficient energy use in the transport and producing sector - slow down climate change for the long term. Other important topics for urban areas, which will be addressed during the SBE19-conference, are inter alia cities as temporal carbon and energy storage or circular economy concepts for the built environment.

I wish the Sustainable Built Environment Conference 2019 every success and all participants lots of inspiring discussions, insights and findings for future practical implementation.

Kind regards,

Bertram Werle

Director for urban planning, development and construction
City of Graz, Austria

Dear Participants of the “Sustainable Built Environment D-A-CH Conference 2019”,
Dear Ladies and Gentlemen,

in an increasingly interconnected society, companies worldwide face severe challenges. Consequently, Wienerberger is continuously working to improve and further develop its products as well as system solutions for all fields of application, including the recycling and re-use of our products. The foremost goal of our entrepreneurial activities is to achieve a sustainable growth of the company in accordance with ecological, social and economic principles. To achieve this goal, we have defined a clear strategy focused on organic growth, operational excellence, investments and portfolio optimization. We do our utmost to supply future oriented sustainable building material solutions in the building sector. By providing long-lasting and resource-conserving building materials and energy efficient building and infrastructure concepts we confirm that we are taking our role as a responsible member of society very seriously. All stages of the value chain of the Wienerberger Group are covered by a voluntary commitment to sustainability.

At the SBE19, internationally renowned experts will emphasize all aspects of sustainable construction. We especially welcome the fact that many young people and students in the field of sustainable building solutions will participate in the conference. Wienerberger makes every effort to contribute to the promotion of sustainable buildings which is demonstrated by the certification of the residential construction project “D22” in the Seestadt Aspern (Vienna, Austria). The building achieved 769 of 1000 points in the ÖGNB building certification and was awarded “klimaaktiv GOLD”. Fascinating is the fact that the team opted for Wienerberger Porotherm 50 W.i bricks for the building envelope. For the first time in a long while a subsidized residential building was constructed with monolithic, loadbearing clay blocks without additional external thermal insulation. In our opinion, the project can be seen as a real lighthouse project due to its contribution to the energy efficiency of buildings and to climate protection.

Having this in mind, I wish all attendees of the SBE19 stimulating discussions and very promising results!

Yours,

Heimo Scheuch, Chief Executive Officer
Wienerberger AG, Austria

Dear SBE19 Graz participants,

credit: FV Steine-Keramik/Lukas Lorenz

in recent years new construction methods have been developed (e.g. building component activation) in order to reduce the energy consumption of the building sector. Massive research has been carried out on material components in order to minimise the use of raw materials, optimise designs and at the same time improve quality - and thus longevity. The development has also progressed in terms of circular economy. In the mineral sector, for example, almost all construction waste is recycled. A lot of things have been automated and thus undoubtedly optimized. The goal of reducing energy consumption and emissions during the use and dismantling phases of buildings as well as during the production of the building materials was also achieved.

In this context, conferences such as the SBE19 Graz contribute to discussing forward-looking methods, technologies and processes on the levels of building products, buildings, neighbourhoods and existing buildings. They contribute to pointing out solutions in the sense of resource conservation and environ- mental protection, taking into account social and economic questions.

For this reason the Austrian Association of Building Materials and Ceramic Industries makes special efforts to support various national and European research projects, e.g. in cooperation with Graz University of Technology, and thus makes a contribution to sustainable construction research.

With kind regards,

Dipl.Ing. Dr. **Andreas Pfeiler**
CEO Austrian Association of Building Materials and Ceramic Industries

Dear SBE19 Graz participants,


credit: klimafonds/ ringhofer

the significant reduction of greenhouse gas emissions by 80 to 95 percent by 2050 compared to the reference year 1990 is the primary objective of the Paris Agreement. The building sector, responsible for around a third of the local energy consumption, must therefore be completely free of CO_2 emissions in the medium to long term.

It is important to exploit the great potential in the building sector. Energy savings and the use of energy-efficient technologies help to reduce greenhouse gas emissions. From building materials and the supply with space heating, cooling and hot water to the lighting of buildings and technical equipment, there are numerous starting points for forward-looking technologies and solutions. However not only the individual-building-level shows a great untapped potential, but also the interplay in the urban network.

The Climate and Energy Fund focuses on both areas and has for years been promoting model-rehabilitations, research and technology development in the area of sustainable building. With 84 model-renovations already implemented, we show that our vision of designing the building sector free of emissions is already feasible: The energy requirement of 65 of the 84 flagship projects is 100 percent covered by renewable energies. Ten buildings are even classified as plus-energy houses. These objects act as independent power plants and generate more energy than they consume.
Entire cities are taking actions towards greater efficiency and climate compatibility too, which is an important step towards energy independence. More than 50 Smart Cities throughout Austria are already striking this path.

Austria has a pioneering role in the field of sustainable building in Europe, not least because of our funding programs. As part of this funding programs, we initiate numerous R & D activities in this field of research, focusing on the topics of building insulation, multifunctional façade systems, solar thermal and solar cooling, decentralized power supply with photovoltaics, storage technologies, highly efficient lighting technologies, demand-side management, smart home solutions as well as waste and water saving technologies. Numerous technologies and products have already been brought to industrial production and are marketed internationally.

Yours sincerely,

Theresia Vogel and **Ingmar Höbarth**
Management Austrian Climate and Energy Fund, Austria

Ladies and Gentlemen,
Dear participants of the Sustainable Built Environment D-A-CH Conference 2019,

acting sustainably is a law of our time. The Fridays For Future movement shows impressively how vehemently especially young people demand to take determined action for climate protection in all societal, political and economic areas. Sustainable building as part of the national climate and environmental strategies in Germany as well promotes climate protection. Sustainability in the construction sector, on the one hand, means environmentally suitable and energy-efficient building to minimise negative impacts on the climate. On the other hand, we have to adapt our buildings to the climate change to keep damages to the built infrastructure as low as possible.

As a research institution of the German Federal Government, the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) advises and supports the German Federal Ministry of the Interior, Building and Community in a wide spectrum of construction-related issues, including climate protection, energy and resource efficiency, planning quality, cost-effective housing construction and demographic change. A special focus is on interdisciplinary research and development projects. The projects create a bridge between research and construction practice. All measures have the aim to promote a sustainable development in the construction sector as a whole.

With the Guideline for Sustainable Building and the Assessment System for Sustainable Building (BNB), the Federal Building Ministry has developed instruments to put its ambitious climate goals into practice. The goal behind was to realise the Federal Government's construction projects sustainably thus acting as an example to other public owner-builders. The Guideline for Sustainable Building and the BNB pursue an approach combining climate protection and climate change-adapted building in terms of sustainable building. In the context of their „Future Building" research initiative, the Federal Building Ministry and the BBSR have developed many action guidelines for planners and architects or builders.

With an exhibition and various lectures during the Sustainable Built Environment D-A-CH Conference 2019, the BBSR will provide an overview of the Guideline for Sustainable Building and the Assessment System for Sustainable Building (BNB), its supporting instruments as well as of model projects of the Federal Government's construction activities. Our Special Forum "Level(s) and its place in the tool box for sustainable construction" shall enable the discussion about how a division of labour between Level(s) as the European Union's voluntary reporting context and other national assessment systems for sustainable building like the BNB might be realised.

The Conference serves to inform and exchange about sustainable developments in the construction sector. It offers an excellent basis for presenting and discussing research results. I wish the Conference all the best, a lasting success and many interesting conversations and findings.

Yours,

Dr. **Robert Kaltenbrunner**

Deputy Director of the Federal Institute for Research on Building, Urban Affairs and
Spatial Development, Germany

KEYNOTE SPEAKERS

Transition Towards a Net Zero Carbon Built Environment

KEYNOTE SPEAKERS

OPENING

1.5°C Climate Change - What are the Implications for the Built Environment?

Prof. Dr. **Diana ÜRGE-VORSATZ**
Department of Environmental Sciences and Policy at the Central European University, Budapest;
Vice Chair of Working Group III of the Intergovernmental Panel on Climate Change (IPCC)

Supporting, Challenging, Advising: Building Policy in the Light of Climate Change

MinDirig Dipl.-Ing. Arch. **Lothar FEHN KRESTAS**
Head of the Department of Building, Construction Industry and Federal Buildings at
the Federal Ministry of the Interior, Building and Community

Sustainability Assessment of Buildings in the Focus of EU-Taxonomy for Sustainable Finance

Ursula HARTENBERGER
Global Head of Sustainability, RICS, Member of the Technical Expert Group on
Sustainable Finance, Chair of Buildings Sector Group

Building Related Environmental Impacts - the Hidden Aspects

Dipl.-Ing. Dr.techn. **Peter HOLZER**
Institute of Building Research & Innovation ZT GmbH


credit: Nepszava


credit: Roland Horn


credit: RICS


credit: P. Holzer

CLOSING

SBE19 Graz Highlights

Richard LORCH
Editor in Chief, Journal Buildings & Cities

From Challenge to Mission - Make Sustainable Cities a Reality

Prof. Dr.-Ing. **Holger WALLBAUM**
Full Professor in Sustainable building, Dep. of Architecture & Civil Engineering, Chalmers University of Technology, Gothenburg, Sweden and host of the World Sustainable Built Environment (WSBE2020) conference in June 2020 entitled BEYOND 2020


credit: Clare Park


credit: Holger Wallbaum

1.5°C Climate Change - What are the Implications for the Built Environment?

Prof. Dr. Diana **ÜRGE-VORSATZ**
Department of Environmental Sciences and Policy at the Central European University, Budapest; Vice Chair of Working Group III of the Intergovernmental Panel on Climate Change (IPCC)

The first keynote speech will guide us from the broad topic of climate change to our specific topic „Transition Towards a Net Zero Carbon Built Environment".
Diana Ürge-Vorsatz will present recent developments from IPPC (especially from Working Group III Mitigation of Climate Change) and will inform us about the implications for the built environment.

Supporting, Challenging, Advising: Building Policy in the Light of Climate Change

MinDirig Dipl.-Ing. Arch. Lothar **FEHN KRESTAS**
Head of the Department of Building, Construction Industry and Federal Buildings at the Federal Ministry of the Interior, Building and Community

Megatrends such as climate change, resource scarcity, demographic change and a shift in values towards a greater sense of responsibility to society and the environment are currently presenting additional challenges to politics at federal and regional level. Taking as an example the need and opportunities for German federal politics to act and support sustainable development in the construction, housing and real estate industries, I will in the following consider how governmental tasks and roles can be generally defined in this context.

One matter which has been a subject of discussion for some time now is whether politics has a key role to play when it comes to environmental and health protection issues and securing the future viability of politics, or whether the task of developing and implementing adequate solutions for promoting sustainable development should be left to market forces. Experience gained in Germany and elsewhere shows that a combination of governmental measures and individual or institutional initiatives holds great potential. Politics is thus called to take responsibility for developing medium- to long-term strategies, for setting the framework and boundary conditions, defining socially justified standards and determining requirements to be made in respect of environmental and health compatibility. These are the guideposts along which market forces can seek and find solutions. It is thus especially important that these requirements be formulated so that they are performance-oriented and do not give preference to any specific technologies. Market players all acknowledge that politics has a particular responsibility when it comes to safeguarding social and economic developments while at the same time protecting the environment and conserving resources in such a way as to safeguard our natural resource base. Increasingly, politics is also coming up against growing expectations on the part of businesses and the general public. These expectations have conflicting underlying objectives, though. One example is the struggle to reconcile the goal of securing a quantitatively and qualitatively adequate supply of affordable housing while at the same time improving the energetic quality of the building stock through wide-ranging modernization measures as a means of contributing to climate protection.

Politics takes on various roles when it comes to the planning, construction and operation of real estate based on sustainable development principles as well as when it comes to improving the current housing stock. Given that it is policymakers who are responsible for legislation, it is they who thus first set the regulatory environment. Simultaneously, policymakers create incentive and support schemes which help get new products on the market or close efficiency gaps. At the same time, though, federal institutions are the builders, owners, operators and users of real property. That opens up the opportunity and the need for them to set an example on the one hand and to test new options themselves on the other. In the following these roles will be briefly outlined in connection with the resulting tasks and possible courses of action.

Federal legislation has for many years now included direct references to sustainable development in the construction sector – from the Building Code (sustainable land use) to the Regulations on Determining Real Estate Market Values (including energy quality when determining a building's value). Sustainability is a cross-cutting issue in the building and real estate industries and thus needs to form part of a whole-of-government strategy.

One aspect which Germany has still not addressed when it comes to developing energy quality standards for buildings is the need to add climate action requirements to resource conservation targets. For the first time the Federal Government's Climate Action Plan 2050 sets sectoral goals for reducing greenhouse gas emissions in the building sector, and these could be interpreted as the remaining CO2-eq. budget for real estate utilization. The task now is to achieve those goals by implementing suitable strategies and packages of measures. At the same time, the Federal Government has adapted its national reporting and statistics in order to be able to record and thus assess the level of achievement of select sustainable development targets. The options available for creating fiscal incentives to reduce greenhouse gas emissions have not yet been fully exhausted – a carbon tax is currently under discussion, for example.

It is up to politics to promote beneficial developments by way of providing financial support, where possible and sensible from a macroeconomic perspective. For many years such funding programmes have been available in the building sector to improve the energy quality of buildings, provide advice and support to clients, put products made from renewable resources on the market and construct accessible buildings. How funding programmes can be adapted and improved to contribute even more to climate action is a current matter of debate in Germany and many other countries. The KfW Development Bank, for instance, is reviewing options for funding various building measures, ranging from green roofs as a means of reducing heat island effects to climate-neutral building designs.

As is the case in Switzerland and Austria, research and development in the field of sustainable planning and building, sustainable neighbourhood and urban development, and the development of products, tools and methods is receiving publicly funded support on a massive scale in Germany. Here, these programmes are coordinated and pooled in the Zukunft Bau (The Future of Building) programme, the outcomes of which will be made available to the public.

Building on the traditions of energy-efficient, healthy, and cost- and space-saving planning and construction, the federal ministry responsible for building tasks began implementing the principles of sustainable development back in 2000. Since 2001, this work has been coordinated with representatives of business and science as part of the Sustainable Building Round Table. The aim is to set an example when it comes to sustainable public procurement. The Round Table has not only produced guidelines and a system for evaluating the sustainability of federal buildings (Bewertungssystem Nachhaltiges Bauen für Bundesbauten, or BNB) and made these an obligatory requirement for building projects, the required data and tools have also been made freely available. In the case of building projects funded by the Federal Government, sustainability requirements must be formulated in the early planning stages and then recorded in a target agreement. Projects have to achieve the "BNB Silver" certificate level, though they often do better. The focus is presently on expanding climate action targets, as well as passing on experience gained at the federal level to the federal states and local authorities. The Federal Government is also enhancing the planning, construction and operator skills of staff in regard to energy-saving, resource-friendly, healthy and cost-effective planning through special training programmes.

It will only be possible to successfully implement sustainable development principles in the building sector if the focus is not only placed on so-called lighthouse projects. That is why one approach which is being resolutely pursued is to provide clients and planners with the necessary methods (BNB), data (oekobau.dat, WECOBIS) and tools (eLCA) free of charge in order to achieve a broad-based impact. These are based on European and international norms. Germany actively brings its positions to bear and puts forward ideas in this regard and – like Austria and Switzerland – is actively involved in improving and harmonizing these foundations. That makes it easier for planners, construction firms and product suppliers to cooperate across borders.

Information about sustainable building in Germany and about free-to-use data and tools is available on the www.nachhaltigesbauen.de platform, for example.

One good example of how common political goals can be pursued at regional level is the Alpine Climate Target System 2050 initiative (see https://www.bmu.de/pressemitteilung/alpenregion-soll-bis-2050-klimaneutral-werden/).

At a time when the real consequences of climate change are already being felt, it is important that policymakers step up the pace when it comes to translating scientific findings into policy action and adapting the framework and boundary conditions. Even though they recognize the particular relevance of this issue, the task remains to direct business and social development across the entire bandwidth of related issues so that a balance can be found. When defining and pursuing ecological, social and economic targets, conflicting goals can be identified and resolved, and the livelihoods of future generations safeguarded. In the truest sense of the word, politics itself must be sustainable, too.

Sustainability Assessment in the Focus of the EU-Taxonomy for Sustainable Finance

Ursula **HARTENBERGER**
Global Head of Sustainability, RICS, Member of the Technical Expert Group on Sustainable Finance, Chair of Buildings Sector Group

While initially the focus of legislative frameworks had been more on technical aspects of sustainable development, over the past few years, policy makers have been actively reaching out to and engaging with the finance community.

In this, COP21 in 2015, the signing of the Paris Agreement proved to be a decisive moment. As part of the agreement, signatories not only committed to climate targets, but also to aligning financial flows with a pathway towards low-carbon and climate-resilient development. No surprise then that sustainable finance has now also become a core element of EU policy initiatives, reflecting a growing awareness that this alignment is crucial for successfully addressing the complex challenges of climate change.

However, large-scale investment is needed for the EU to meet its 2030 climate targets, being clearly beyond the capacity of the public sector alone, especially in view of the short time-scale during which the changes need to be made.

The situation for energy efficiency investments in buildings is not dissimilar. According to the most recent Global Status Report[1] , annually published by the UN-led Global Alliance for Buildings and Construction Global Alliance[2] , the rate of investment flows towards more efficient buildings as a share of total investment when compared to previous growth rates is slowing down.

The financial sector thus has a central role to play in driving investments towards more sustainable businesses, technologies and products, including construction and real estate. But how to assess what is a sustainable business, technology or building?

This is where the EU Action Plan for Sustainable Finance[3] adopted in March 2018 which is setting out a comprehensive strategy to connect finance with sustainability comes into play.

One of the measures within the Sustainable Finance package is a proposal for a unified classification system or “Taxonomy”. The aim behind creating this Taxonomy has been to define what can be considered an environmentally sustainable economic activity.

Economic activities are screened for their contribution to six environmental objectives: (1) climate change mitigation, (2) climate change adaptation, (3) sustainable use and protection of water and marine resources, (4) transition to a circular economy, waste prevention and recycling, (5) pollution prevention and control and (6) protection of healthy ecosystems.

To be Taxonomy-eligible, an economic activity must contribute substantially to at least one of these environmental objectives and do no significant harm to the other five. It also has to meet minimum social

[1] UNEP and IEA, 2018, Towards a zero-emission, efficient and resilient buildings and construction sector, Global Status Report. Available at: https://www.unenvironment.org/resources/report/global-status-report-2018

[2] The Global Alliance for Buildings and Construction (GlobalABC), founded at COP21 in Paris in 2015, is a global platform for governments, the private sector, civil society and intergovernmental and international organizations to increase action towards a zero-emission, efficient and resilient buildings and construction sector. For more information: https://globalabc.org/about-gabc/introduction

[3] European Commission, 2018, Action Plan: Financing Sustainable Growth, available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52018DC0097

safeguards in line with ILO[4] standards.
Climate change mitigation activities are categorised by their level of contribution: (1) activities that are already on a low-carbon trajectory, (2) transition activities and (2) enabling activities.
Within construction and real estate, four economic activities have been included in the Taxonomy: the construction of new energy and resource efficient buildings as a low-carbon activity; the renovation of existing buildings as a transition activity and individual measures, such as the installation of efficient building components, i.e. new boilers, windows, insulation, etc., renewable energy technologies and associated relevant professional services as enabling activities. Criteria for the fourth activity, acquisition and ownership, refer to the low-carbon and transitional activities. The appropriateness of the thresholds set will be periodically reviewed and tightened to ensure getting to net zero carbon by 2050.

Except for buildings used by companies engaged in the extraction, transport and manufacture of fossil fuels, the Taxonomy is very inclusive as it covers virtually all buildings and renovations and. To facilitate smooth market entry, it is closely aligned with EU policy instruments, such as Energy Performance Certificates (EPCs) and nZEBs (nearly Zero Energy Buildings) and corresponding thresholds. These obviously only work in an EU context which is why potential proxies have been identified for application by non-EU investors.

Given the complexity of the sector and the issues at hand, developing the Taxonomy for construction and real estate has not been without challenges. The most significant challenge has doubtless been having to find a compromise between ambition and the desire to avoid so-called “greenwashing” and the need to give consideration to different levels of market readiness across EU Member States in different climate zones. Furthermore, the aim was also to enable already operational or emerging financing tools, such as Green Bonds or the Energy Efficient Mortgage Initiative (EEMI)[5] to continue to flourish.

Workability and acceptance have also guided the thinking behind the transitional approach regarding the choice of metrics. Initially, these are going to be based on annual operational primary energy demand as at present only a small part of the market is working with GHG metrics. In future, this will be extended to include operational GHG emissions and eventually also whole life cycle emissions. While there is consensus about the impact and importance of embodied carbon, at present, the embodied carbon data gaps are making any kind of meaningful benchmarking in this area extremely difficult.

However, regardless of these challenges and the fact that there is still some work to be done until the Taxonomy becomes operational in 2021, for the construction and real estate sector the Taxonomy could represent a quantum leap forward by both rewarding buildings that are already high-performing and by channelling investments to those needing upgrading to improve performance. With 97% of buildings in Europe stock requiring updating to achieve higher performance[6] , particularly in the case renovation, that investment is much needed.

What the EU Taxonomy has achieved is the creation of a common language around sustainable buildings, providing answers to questions that investors, their advisors and developers have been trying to come up with for years: what actually makes a building sustainable and how to assess this? This represents a major milestone for the sector and has a strong signalling function for the whole value chain.
Having a clearly defined set of criteria for sustainability performance characteristics will not only help investors to identify sustainable economic investments, it will also help professionals such as facility managers, valuers and brokers in their daily work and during conversations with investors and financing institutions.

[4] International Labour Organization
[5] Information on the EEMI is available at: https://energyefficientmortgages.eu/
[6] Buildings Performance Institute Europe (BPIE) Factsheet, available at: http://bpie.eu/wp-content/uploads/2017/12/State-of-the-building-stock-briefing_Dic6.pdf

Building Related Environmental Impacts - the Hidden Aspects

Dipl.-Ing. Dr.techn. Peter **HOLZER**
Institute of Building Research & Innovation ZT GmbH

SBE19 gathers an impressive number of most experienced, courageous and enthusiastic experts in the field of sustainable built environment. It does so in a series of international conferences which started back in the year of 2000. This year's conference' headline is nothing less programmatic than "Transition Towards a Net Zero Carbon Built Environment". [1]
Without any doubt this transition is a most urgent imperative on a desirable pathway to a generally sustainable development. It is in line with the Sustainable Development Goal (SDG) 11 – Sustainable Cities and Communities of the UN 2030 Agenda as well as with many other international and national targets. We may agree, that the target of a net zero carbon built environment is both crucial and ambitious. yet, encouraged by significant progress that have been made already, we may even agree that the target is realistically achievable. Still, parallel to consequently making this transition towards Net Zero Carbon happen, we have to be well aware of building related environmental impacts beyond carbon emission. I entitled them, somewhat mysteriously, the 'Hidden Aspects'.
Based on meta studies as well as own research activities I'd like to raise awareness to the impacts of buildings on two more alarming threats of sustainable development, beside climate change: Biodiversity Loss and Land Use Change.
Both trends – biodiversity loss and land use change – together with climate change, have basic qualities in common: They, without any doubt, predominantly result from human activities. They are severely threatening the chance of a civilized and desirable future of mankind. They are highly correlated to each other. Finally, they are significantly influenced by the way we design and operate our built environment.
The secured facts of biodiversity loss and land use change are alarming, the same as they are in case of climate change. There's no time left to address one challenge without and not even before the other. It is dangerous to address one aspect without considering consequences to the others.[2, 3, 4]
As a result of years and decades of collaborative and consistent effort, the assessment of carbon emissions of buildings, amongst many other environmental impact categories, has reached a mature and applicable methodological level, supported by databases, tools and coordinated by international standards. Quite different, biodiversity loss and land use change do not play an adequate, if any, role in the list of practically applied building related environmental impact categories.
This is a dangerous gap. Optimising one aspect (carbon emissions) without having the full picture nor an assessment methodology to consider aspects of equal importance (biodiversity loss and land use change) might lead to dangerously wrong decisions. I will take the chance of the keynote to draw your kind attention to these "Hidden Aspects", presenting learnings from meta studies as well as preliminary results of own research, inviting for further discussion:
In case of biodiversity loss I will present ongoing research towards a methodology to develop a mass-related impact factor, which possibly could be integrated into the existing system of Environmental Product Declarations (EPDs). As an encouraging starting point, the impact category of biodiversity loss is

[1] As a consistent next step, WSBE2020 in Gothenburg, Sweden will address the full mission of "Make Sustainable Cities a Reality".
[2] https://www.un.org/sustainabledevelopment/blog/2019/05/nature-decline-unprecedented-report/
[3] https://www.umweltbundesamt.at/umweltsituation/raumordnung/rp_flaecheninanspruchnahme/
[4] Österreichische Strategie Nachhaltige Entwicklung (ÖSTRAT) – ein Handlungsrahmen für Bund und Länder. Zl. BMLFUW–LE.1.4.5/0012-II/3/2010. Juni 2010

already mentioned in relevant international standards.[5, 6, 7, 8]
In case of land use and land use change, to our assessment, the consideration of the environmental impact from building activities has to be done on political level in a process of responsible spatial planning, well before the process of responsible building design.[9] Still, one could think of integrating an impact factor such as a site-usage-density. But such a factor would only highlight the usage intensity of a site, without considering spatial or environmental qualities of the specific site.
Summing up: Integrating the qualities of biodiversity loss as well as land use change into environmental assessment of buildings and communities calls for new research efforts in development of methodology, derivation of databases and development of tools. It will necessarily raise complexity of environmental building assessment, but, to our understanding, it is definitely necessary to draw decisions of far-reaching consequences in a complex environment.

[5] Hammer, Renate; Holzer, Peter et al.: Biodiversity Impact Assessment. Entwicklung eines methodischen Ansatzes zur Einführung der Wirkungskategorien Biodiversitätsverlust in die Ökobilanzierung, laufende Forschung im Auftrag der WKO – Fachverband steine und Keramik

[6] EN 15643 – 2 (2011): Sustainability of construction works. Assessment of buildings. Framework for the assessment of environmental performance, appendix B.2

[7] ISO 21931 – 1 (2010): Sustainability in building construction -- Framework for methods of assessment of the environmental performance of construction works -- Part 1: Buildings, chapter 5.6.2

[8] ISO 14025 (2006): Environmental labels and declarations -- Type III environmental declarations -- Principles and procedures, chapter 7.2.3

[9] Bundeskanzleramt Österreich (Hrsg.): Dritter Österreichischer Baukulturreport, https://www.baukulturpolitik.at/baukulturreport/dritter-baukulturreport/

SBE19 Graz Highlights

Richard **LORCH**
Editor in Chief Journal Buildings & Cities

This presentation draws together the key themes and ideas that emerged at SBE19 Graz conference. It comments on how the Graz conference may shape future research and policy agendas, particularly for the forthcoming WSBE Conference: Beyond 2020.

From Challenge to Mission - Make Sustainable Cities a Reality

Prof. Dr.-Ing. Holger **WALLBAUM**
Full Professor in Sustainable building, Dep. of Architecture & Civil Engineering, Chalmers University of Technology, Gothenburg, Sweden and host of the World Sustainable Built Environment (WSBE2020) conference in June 2020 entitled BEYOND 2020

At the Earth Summit in Rio de Janeiro in 1992[1], more than 178 countries adopted Agenda 21[2] as a plan of action to build a global partnership for sustainable development to improve human lives and protect the environment. At the Millennium Summit in September 2000, the UN Member States unanimously adopted the Millennium Declaration at UN Headquarters in New York. The Summit led to the elaboration of eight Millennium Development Goals (MDGs)[3] to reduce extreme poverty by 2015. The Johannesburg Declaration on Sustainable Development and the Plan of Implementation, adopted at the World Summit on Sustainable Development in South Africa in 2002, built on the Agenda 21 and the Millennium Declaration and put more emphasis on multilateral partnerships as well. At the United Nations Conference on Sustainable Development (Rio+20) in Rio de Janeiro in 2012, Member States decided to launch a process to develop a set of SDGs to build upon the MDGs. At the UN Sustainable Development Summit in September 2015, the subsequent adoption of the Agenda 2030 for Sustainable Development was decided. As we all know, the 2030 Agenda for Sustainable Development provides a shared blueprint for peace and prosperity for people and the planet, now and into the future. The main contribution of Agenda 2030 has to be seen in the 17 Sustainable Development Goals (SDGs), *"which are an urgent call for action by all countries a global partnership. They recognize that ending poverty and other deprivations must go hand-in-hand with strategies that improve health and education, reduce inequality, and spur economic growth – all while tackling climate change and working to preserve our oceans and forests."* [4] Although the SDGs build on decades of work by countries and the UN, including the UN Department of Economic and Social Affairs, the implementation of the SDGs to real actions remains a challenge. Today, the Division for Sustainable Development Goals (DSDG) in the United Nations Department of Economic and Social Affairs (UNDESA) provides substantive support and capacity-building for the SDGs and their related thematic issues, such as water, energy, climate, oceans, urbanization, transport and plays a key role in the evaluation of UN system-wide implementation of the 2030 Agenda. As stated by the UN, "in order to make the 2030 Agenda a reality, broad ownership of the SDGs must translate into a strong commitment by all stakeholders to implement the global goals."

The built environment is – without any doubts – one of the most relevant sectors for the implementation of the Agenda 2030. With the globally ongoing trend of urbanisation, cities play a major role for more sustainable development. Projections suggest cities will swell at an astonishing pace and it needs to be seen whether that means our salvation or an eco-disaster.It is very obvious that the current trend of planning, constructing and maintaining our cities put even more pressure on the planetary boundaries[5]. Hence, what is needed is a transformational plan on how to achieve "Sustainable cities and communities" in terms of concrete actions.

[1] https://sustainabledevelopment.un.org/milestones/unced (accessed August 15, 2019)
[2] https://sustainabledevelopment.un.org/content/documents/Agenda21.pdf (accessed August 15, 2019)
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[4] https://sustainabledevelopment.un.org/?menu=1300 (accessed August 15, 2019)
[5] Anders Wijkman & Johan Rockström. 2012. Bankrupting Nature - Denying Our Planetary Boundaries, Routledge, London, ISBN 9780203107980 and Rockstrom, J., et al. 2009. Planetary boundaries:exploring the safe operating space for humanity. Ecology and Society 14(2): 32.

Fig. 1: SDGs that are strongly connected to SDG 11 Sustainable Cities and Communities selected by BEYOND 2020.

The next version of the World Sustainable Built Environment conference that is entitled BEYOND 2020 will exactly focus on creating clear links between the most relevant UN SDGs and the built environment. Central to our discussion will be achieving UN SDG 11, Sustainable cities and communities by the 2030 deadline but from our perspective, the path towards SDG11 is only possible, if other relevant SDGs are fulfilled (Fig. 1).

Key points to achieve SDG 11 will, e.g.

- How can the building sector contribute towards the creation of Sustainable Cities and Communities (SDG11) of the future?
- What other UN SDGs (see below) should play a role in the pursuit of SDG11 from the built environment perspective?
- How does the role and importance of the UN SDGs (relevant for the built environment differ in various parts of the world?
- What challenges and opportunities result for the building sector from implementing the UN SDGs?

The next edition of the World Sustainable Built Environment conference will work on a transformational plan towards the Agenda 2030. Key elements will be addressed already at the SBE19 in Graz.

FULL PAPER

Transition Towards a Net Zero Carbon Built Environment

Stakeholder related fields of action for process optimization of nearly zero energy and plus energy buildings

Höfler R[1]

[1]AEE - Institut für Nachhaltige Technologien, 8200 Gleisdorf, Feldgasse 19, Austria

r.hoefler@aee.at

Abstract. In order to be able to guarantee a regulated process in the design of nearly zero and plus energy buildings, it is important that all relevant stakeholders are involved from the beginning of the project. This is particularly important because disagreements and lack of communication between the stakeholders often lead to problems, which delay planning and implementation and lead to additional costs. In order to prevent the resulting barriers, it is essential that the previous processes for such an implementation are analysed and the individual steps are optimized to such an extent that a goal-oriented and cost-efficient cooperation is possible. This is focused in the thesis "Stakeholder related fields of action for process optimization of nearly zero energy and plus energy buildings". In this way, an attempt is made to achieve process optimization with the aid of various methods from management consultancy. In order to achieve this, the focus of every construction project, especially nearly zero energy and plus energy buildings, must be on integral planning. The individual action steps must therefore be optimized in such a way that it is clearly defined for all stakeholders when and with which partner to interact.

1. Introduction

As buildings account for almost 40% of total energy consumption and 36% of greenhouse gas emissions in Europe, the European Commission has adopted a directive aimed at reducing the total energy consumption of buildings [1].

By the year 2019, many researchers were already working on the topic of implementing nearly zero energy and plus energy buildings (nZEB and PEB) due to the greenhouse gas emissions already mentioned, which reduce the quality of life. In the various fields of research, the content usually concentrates only on a concrete view of a group of stakeholders. In this way, strategies have only ever been developed from a specific discipline, a specific field of study, in order to be able to successfully implement nZEB and PEB. The focus was often on architectural and technical details [2]. No matter which perspective was used for the research, the different perspectives usually have one aim in common. The necessary solutions for building optimization should be as cost-efficient as possible and have a positive influence on the life cycle of a building.

In addition, energy consumption should be reduced as far as possible in order not to pollute the environment further [3]. For this reason, research in the past concentrated to a large extent on the development of new technical concepts in implementation in order to be able to address these goals as quickly as possible. However, this is made more difficult because the lack of knowledge about new technologies and thus the lack of specialist know-how, the working methods of the commissioned project partners and the decision-makers are limited. Problems arise when life cycle costs are not considered in their entirety, but only the respective costs for individual sub-areas, in the planning and implementation. The main reason for this is that it is unclear to many project participants that up to 40% of operating costs can be saved by using slightly higher construction costs (approx. 2%) [4]. Due to such misjudgements, existing potentials for cost reduction are often used only partially or not at all.

The term Integral Planning, through such misjudgements and problems in the transparency and cooperation of different stakeholders, achieves an important meaning in the planning and implementation of nZEB and PEB. This means the early integration of technical/functional aspects in order to additionally support the planning process. Methodological and technical aspects are an important focus for successful planning and implementation [5]. The core objective here is to highlight the different interests and perspectives of the stakeholders involved in order to optimize building quality as best as possible over the entire life cycle.

Of course, this aim should be pursued for all buildings, regardless of the requirements. However, it is particularly important for nZEBs and PEBs, as this approach is essential for the success of the project.

In order to ensure the quality of buildings, a passive house construction method has been aimed since the beginning of the 21st century and the associated integral planning in the building industry [6].This is due in particular to the far greater scope for influencing the quality of a building at the beginning of a construction project, compared with the constantly changing views of various actors, which must be integrated into the planning. For this reason, it makes sense to involve all participants from the outset in order to be able to represent all opinions in the best possible way and to prevent emerging conflicts in the future. In addition, the more the project progresses, the greater the change effort and costs required.

2. Problem identification and challenges in the implementation of nZEB and PEB

The implementation of projects with a high energy standard is currently often carried out using the same procedures as projects with lower requirements. This is a result of the fact that these processes have been tried and tested. This procedure, however, involves risks, as it is often not considered that the standardized processes cannot offer the best solution for the implementation of nZEB and PEB. Such procedures often generate additional costs in planning and implementation, although the high costs only become apparent very late and countermeasures can therefore only be taken late. For this reason, previous processes should be analysed and their sequence reconsidered in order to achieve the desired standards as quickly and as effectively as possible [7].

Previous projects and works dedicated to these themes usually only refer to parts or individual actors of a design project. This complicates the cooperation of all participants, since the different approaches and focal aspects are often not recognized and for this reason the required cooperation does not work out. It is therefore important to create a decisive overview for all actors involved in the project planning and implementation of nZEB and PEB.

Based on this necessity to implement integral planning, barriers were filtered out using the online survey tool Mentimeter [8] as well as the results of the CRAVEzero project of the research institute AEE INTEC, which complicate the planning and implementation of nearly zero and plus energy buildings. In the survey conducted during the ISAC Conference 2018 in Graz, Austria, 102 stakeholders participated, who, although coming from different professional groups, largely agreed on the influence of individual parameters on the planning and implementation of nZEBs. This is also shown by the research project CRAVEzero. The results of the survey can be seen in the graph below. According to the survey and the CRAVEzero project, the biggest deficits are too high costs [9], a lack of support from politicians, poor communication among themselves and a lack of knowledge about new technologies [10]. In addition, misjudgements are often made in demand planning [9] and no clearly defined minimum target values are given.

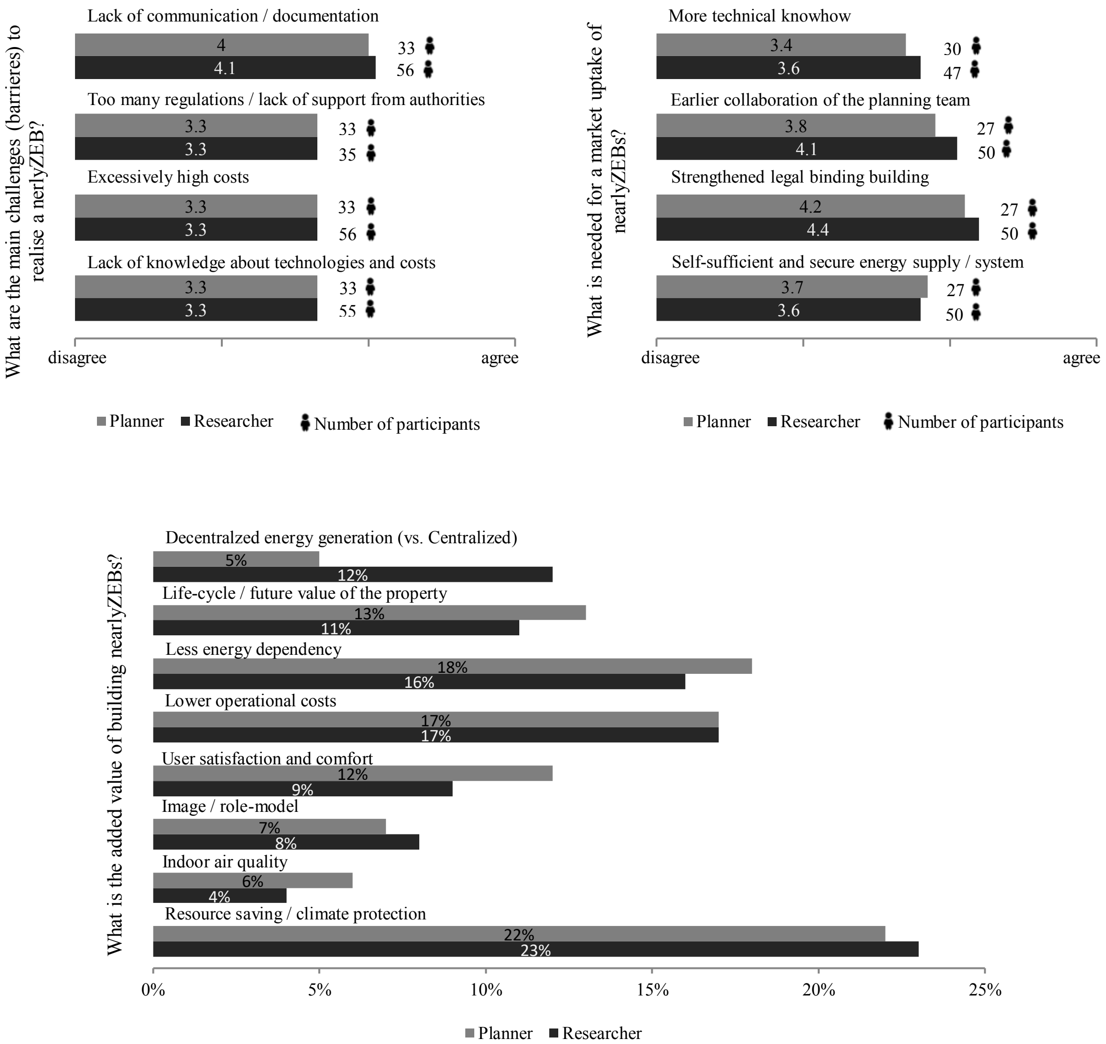

Figure 1. Results of the Mentimeter survey on the challenges, marketability and added value of nZEB and PEB (own illustration)

All these challenges are difficulties for the design and establishment of nZEB and PEB. In order to be able to handle them in the best possible way and thus guarantee error-free and time-efficient work, it is essential to clearly define which stakeholders are primarily responsible for which actions.

3. Methodology

In order to be able to carry out a successful optimisation of individual project processes, in addition to defining the circumstances causing the problems, it must be filtered out which stakeholder is responsible for which action and with which participants should be collaborated and communicated in order to promote constructive work. For this purpose, the filtered actions are divided into different project phases, prioritised and assigned to the stakeholders. In addition, the various dependencies of the actions dealt with are analysed.

By early recognition of interrelations between the individual actions, the actors can react quickly to changes and in the best case achieve a reduction in costs. However, the time savings that can be achieved in this way can also significantly influence the success of a project.

These positive effects are achieved, for example, when the thermal quality is coordinated with the heat output, since the heating system is often over dimensioned and therefore not economically viable. If, however, an early coordination between the responsible actors is aimed at, optimisations can be made in this area. Thus it becomes clear that these two parameters are interrelated and consequently influence each other.

These procedures are usually known in theory, but many of these steps are often circumvented in practice. This causes delays and errors in communication and processes. For this reason, it is necessary to sensitize and subsequently optimize in this respect.

In order to propose a process optimization, various existing optimization methods must be analysed and applied to construction projects. For this purpose, particular attention is paid to Business Process Reengineering, Total Quality Management, Lean Management and Artificial Intelligence since these methods of process optimization promise fast and targeted action with future-oriented solutions.

- Business Process Reengineering (BPR): This method pursues the approach of radically redesigning current business models or completely replacing them [11]. Thus every core process is questioned without considering the existing structures. The goal of this method is to achieve 30% of the four targets: Optimize quality, time, costs and service [12].
  This approach uses four process steps [13]:
  1. Uncover core processes
  2. Locate and identify vulnerabilities
  3. Radical restructuring of existing processes
  4. Adapt corporate structures

  The most important factors for the implementation of such projects are motivated and competent project partners, a systematic approach and clear guidelines to achieve the project goal.

- Total Quality Management (TQM): The aim here is to achieve an increase in processes. The satisfaction and motivation of the players are particularly important. The essential component, which is aimed at with the help of this method, is the increase of the execution quality. In particular, the active and independent action of all actors involved is assumed [14]. This is also made clear by Deming's 14 points on the characterisation of TQM [15]:

  - The will to continuous improvement
  - Creating awareness for quality
  - Preventive quality assurance
  - Check offers and pay attention to total costs
  - Continuous process improvement
  - Modern training methods
  - Cooperative management style
  - Open organization
  - Elimination of organizational barriers
  - Understandable goals and procedures
  - Qualitative target agreements
  - Identification with own activity
  - Continuing education
  - Create action plan

- Lean management: This involves organisational processes that aim to conserve resources and keep costs as low as possible. The focus is particularly on the "value-adding" processes. These are meant to identify waste and value-adding activities in order to save unnecessary processes and promote efficient procedures. The Lean Management method thus offers analysis possibilities for identifying non-value-adding activities and eliminating them [16]. When implementing lean management processes, it is important that all employees are involved in the new concept. The result is a new corporate philosophy that promotes cooperation and communication between all those involved [17]. The following objectives are decisive for the successful application of this method [11]:

- Process-oriented corporate management
- Highest possible efficiency
- Clearly defined processes and procedures
- Clearly distributed responsibilities and logical communication among each other

- Artificial intelligence: The fields of machine learning and artificial intelligence are expanding very rapidly and affect almost all technological aspects of society. One exception is the building sector [18]. Problems occurring in this area frequently require the use of optimization methods that enable the minimization or maximization of certain target functions. However, these problems cannot be solved precisely in most cases. For this reason, an approach is often more effective than a concrete solution to the problem at hand [19].
  This approach is particularly helpful in optimising the building sector. Intelligent systems can reduce the energy consumption of a building. This method is needed in order not to neglect not only energy savings but also the comfort of users [20].

The individual methods have their own character and rarely build on each other. This is because, depending on the method of optimization, there is a different focus on it. In TQM, for example, the focus is on independent action, while Lean Management is designed to promote communication among the participants. A more modern method is artificial intelligence, because it combines many factors, which are mostly considered individually in the planning, and shows how they can influence each other.

4. Results and Discussion

In the course of this research work, individual actions, which have a high priority especially for nearly zero and plus energy buildings, were analysed, assigned to responsible stakeholders and integrated into the already tested and known process flows. In this way, a clarity is created which should help all participants to integrate themselves into the processes. In this way, each participant sees by when which action must be completed and with whom he must contact in order to achieve this goal. This is important, because only together these often occurring problems can be tackled. In this way, the stakeholders involved are able to avoid problems at an early stage or solve them on their own.

These actions lay the foundation for the planning and implementation of nZEBs and PEBs. However, this does not eliminate the problems that have arisen so far. Here the methods for process optimization, which have already been explained in Methodology, are used. By the different approaches of the optimization methods best possible solutions can be found for the respective challenges. This corresponds to a learning process, which certainly takes a lot of time, but the knowledge gained in this way can significantly shape the future for the implementation of nearly zero and plus energy buildings.

5. Conclusion

Although the procedures for planning and implementing nearly zero and plus energy buildings are mostly known, individual steps are often skipped or only taken at a later stage. This has temporal, qualitative as well as financial consequences, since set goals are often delayed or not reached at all. In order to ensure the smooth planning and construction of almost energy free and energy efficient buildings, integral planning is indispensable for these reasons and should therefore be aimed at the very beginning of a project. In this way, initial communication difficulties can be avoided from the outset, as close cooperation already takes place between all parties involved.

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Life cycle cost reduction and market acceleration for new nearly zero-energy buildings

Weiß T [1], Pernetti R[2], Garzia F[2], Köhler B[3], Stobbe M[3], Meier K[4], Berggren B[5]

[1]AEE INTEC, Austria; [2]EURAC, Italy; [3]Fraunhofer ISE, Germany; [4]ATP Sustain, Germany; [5]Skanska Sverige AB

t.weiss@aee.at

Abstract. Cost optimal and nearly zero-energy performance levels are principles initiated by the European Union's Energy Performance of Buildings Directive, which was recast in 2010. These will be significant drivers in the construction sector in the next few years because all new buildings in the EU from 2021 onwards have to be nearly zero energy buildings (nZEBs); public buildings need to achieve the standard already by 2019 [1].While nZEBs realised so far have clearly shown that the nearly zero-energy target can be achieved using existing technologies and practices, most experts agree that a broad-scale shift towards nearly zero-energy buildings requires significant adjustments to current building market structures. Cost-effective integration of efficient solution sets and renewable energy systems are the major challenges [2]. The EU Horizon project CRAVEzero focuses on proven and new approaches to reduce the costs of nZEBs at all stages of the life cycle. The primary goal is to identify and eliminate the extra costs for nZEBs related to processes, technologies, building operation and to promote innovative business models considering the cost-effectiveness for all stakeholders in the building's lifecycle. As a result, an international database for benchmarking actual nZEB life cycle costs (LCC) including urban and building planning, construction, commissioning, operation, maintenance, management, end-of-life, has been developed. Furthermore, an operative methodology to achieve the best conditions towards optimal cost nZEBs has been set-up.

1. Stakeholder centred life cycle processes

In addition to legal and urban boundaries, buildings are essentially defined by the client. Owners or investors want to construct or renovate buildings for a specific purpose. Also, the buildings technical quality and the comfort standard have to be achieved within project specific budget limitations. Architects and specialist planners translate the client's ideas and wish into real plans and are responsible for the appropriate execution of the building project. Construction companies and craftsmen from numerous different disciplines are involved in constructing the building. There is a constant coordination process between the client, the planners and the contractors in order to prepare the construction of a building and if necessary, to react to changing conditions like costs, schedules, changed requests from the client, weather, etc [3].

Especially in the planning phase, the choice and combination of building materials and technologies and the execution on the construction site as well as the overall integral planning, construction and operation are of great importance. The range of services provided to buildings in the urban context today has also changed over time and gained new aspects. Nearly zero energy buildings increasingly become active participants of our energy supply infrastructure and raise new challenges concerning the quality of planning, construction and operational phase of a building. This results in new approaches to innovative energy concepts for both the building and districts. Innovations related to the realisation of nZEBs arise in different life cycle phases of buildings and at different points of the value chain in the building industry.

To reduce costs and accelerate processes, and assure the quality of nZEBs the right decisions have to be taken at the ideal time within the overall process.

In order to be able to optimise existing processes, technical qualifications, actions to be taken and roles must be known and tasks and functions of the stakeholders assigned.

The assessment of the process for nZEBs depends strongly on the perspective. Building owners, investors, tenants, the construction industry, providers of energy efficiency solutions and planners have different interests and are involved in different phases in the life cycle of buildings. There is a general lack of understanding, transparency and uniform methods when it comes to the overall process of nZEBs. Which costs and time horizons are significant for different actors and to what extent?

In the life cycle of a building, there are different interests of the actors and derived from this also different perspectives, observation periods and target values. There is the tenant/user, the real estate agent, the building contractor, planner, property manager, investor, owner and also the company which is directly or indirectly involved with the building. As shown in Table 1, these actors are involved in the overall process over a certain period of time. While the tenant is primarily interested in the operational phase, the planner is usually more likely to deal with the building only until its completion. If a property is financed and used by the tenant himself, the entire life cycle up to a change of use is usually of interest. Depending on the approach, this can be between about 25 years after repayment of the bank loan and up to 50 years after increased consideration of the use. For society as a whole, the entire service life of a building, including its demolition and disposal, usually counts.

The period under consideration must, therefore, be determined in advance with the parties involved. For most of the considerations of the entire building, between 25 and 50 years have proven to be reasonable.

Table 1. Stakeholders time expectancy of a project and optimization goals

STAKEHOLDERS	OPTIMIZATION CRITERIA		TIME EXPECTANCY
	Costs	Energy	
Tenant / user	Rental costs, operating costs	Final energy demand	3 – 30 years
Real estate agents	Market price	Energy performance certificate	1 – 2 years
Construction company	Building costs		1 – 5 years (Guarantee)
Planner	Planning costs, building costs	Energy performance certificate	1 years
Property management	Maintenance costs, renovation costs	Final energy demand	1 – 50 years (Contract)
Investor	Investment cost		1 – 5 years
Building owner / landlord	Financing costs	final energy demand	20 - 50 years
Building owner (public)	Net present value	Primary energy, final energy, CO_2	50 – 100 years
Society	Life cycle costs, climate protection	Primary energy, CO_2	> 100 years

In addition to low rental costs, the tenant is also interested in low operating costs and thus in a good energy standard, e.g. so that he has low heating costs. The building contractor is usually anxious to keep his building costs low. In the case of owner-occupied real estate, both cost components are important, the initial investment as well as the running costs. For the company, the total costs and also the effects such as CO_2 emissions are important.

In addition to the optimisation criteria and thus the benefits that can be directly assessed in monetary terms, there are also different benefits and additional benefits for the individual actors, which often cannot be assessed directly in monetary terms and therefore do not appear in the life cycle cost analysis. These benefits and additional benefits are shown in Figure 1. This concerns marketability, rentability, value development, comfort, but also image, climate protection or regional goals such as energy autonomy. Where possible, these benefits and additional benefits should be taken into account in the decision-making process. However, examples exist where increased productivity, higher revenue, reduced employee turnover, reduced absenteeism, etc. have been quantified [4]. Additionally, studies do exist which may be used as a basis for analysing added values.

Studies show that staffs in high quality nZEBs perceive a positive effect of their work environment and productivity [5] [4] [6]. In one case, a 10 000 m2 office building, increased productivity of 0.3 % were reported, equal to 8 €/m2a. Two studies have found reduced absenteeism in green buildings [5]. An American study showed that roughly 20-25 % of 534 tenants/companies reported higher employee morale, easier to recruit employees and more effective client meetings [7]. Additionally, 19 % reported lower employee turnover. In addition to well-being and productivity, higher revenues from rent or sales may be expected. Bleyl et al. reviewed previous studies and concluded that higher rent income might range roughly between 5 % and 20 %. Furthermore, higher market valuations may range from below 10 % to up to 30 %. It should be noted, in relation to nZEBs and productivity and wellbeing, that a recent study pointed out that social factors may have a greater impact, in monetary terms, compared to environmental factors [8].

The value of a positive news article about a specific building or a specific project could also be comparable to advertising costs in the specific source, in which the article is published [9]. One way to discuss the importance to investigate different co-benefits may be to rank them as presented in Figure 1. The classification is a subjective judgement, highlighting the relevance and the difficulty in valuing the co-benefits discussed above.

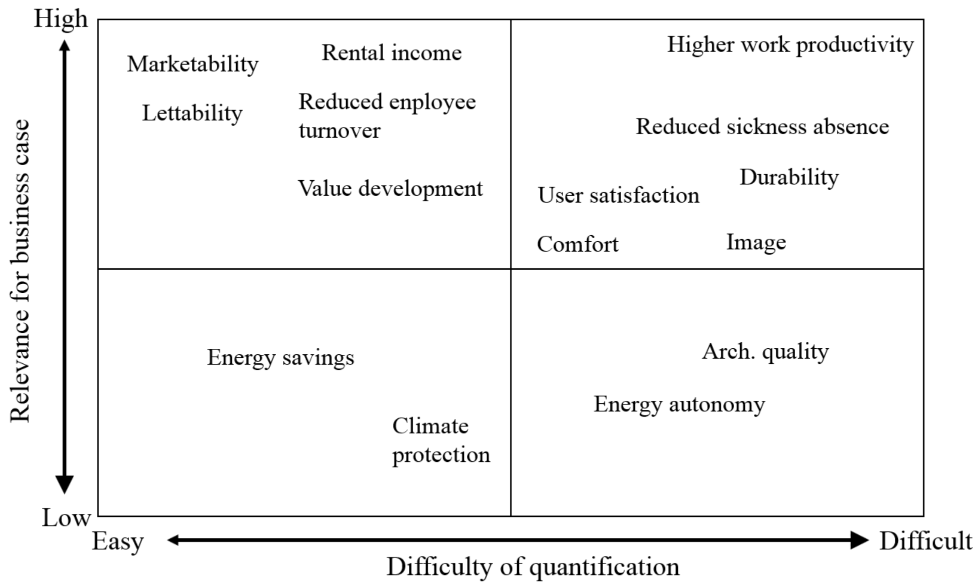

Figure 1. Co-benefits classifications, based on Bleyl et al. [1].

2. nZEB Technologies

For realising nZEBs, which are cost-efficient for all stakeholders throughout their lifecycles, the knowledge about possible cost developments of the most relevant technologies is essential. Furthermore, the identification of currently realised and promising technology sets for the future can help to reduce the cost of nZEBs and accelerate the respective market.

For the deduction of cost reduction potentials, there are in principle two approaches; the Top-down learning curve analysis and the Bottom-up analysis. Compared to the Top-down approach more detailed data and information is needed for the Bottom-up analysis. Therefore, the learning/ experience curve approach was chosen for the deduction of cost reduction potentials for all identified technologies, whereas the Bottom-up analysis was only conducted for three central technologies (PV, solar thermal, electricity storage). The calculation of cost reduction potentials with the experience curve approach is based on market and cost data as well as the determination of learning rates.

Even though the applied methodologies are widespread and established, it has to be mentioned that there are several uncertainties, which can influence the development of costs, especially over a relatively long period until 2050. The calculated market development can vary due to changing requirements or political changes, the actual learning rate can vary, and global commodity prices can fluctuate, which can also lead to price increases instead of decreases.

2.1. Top-down:

The various technologies analysed have different cost reduction potentials. The basis for the deduction of cost reduction potentials are current market and cost levels as well as market forecasts for each technology – if available for whole Europe and in case of limited data available only for Germany.

Established, fossil fuel-based technologies (oil and gas boilers) have the lowest cost reduction potential until 2050 (only about 1% and 9% respectively). A major reason is the comparably high CO_2-emissions, which contradict the climate protection targets of the European Union and will therefore lose market shares leading to only a small increase in the cumulative production volume. A slightly higher market share is predicted for biomass boilers which are more environmentally friendly as they use a renewable fuel. Biomass boilers have a cost reduction potential of approx. 14% until 2050.

Heat pumps are seen as a central heating (and probably cooling) technology in an energy system based on fluctuating renewable energies as they are one important technology for the coupling of the electricity and heating sector. Therefore, a strong market increase is expected to result in cost reductions of more than 20% by 2050.

Ventilation systems (central and decentralised) are of major importance for energy efficient buildings. They supply fresh air, reduce ventilation heat losses when equipped with heat recovery systems and assure good air quality by removing moisture, moulds, pollutants and vapours. Especially in airtight buildings assuring good air quality is almost impossible without mechanical ventilation. The market for ventilation systems will most probably grow in the coming decades leading to cost reductions of around 46% - 52% by 2050.

Thermal and electrical storages become more important in an energy system based on fluctuating renewable energies. Both storage types have substantial cost reduction potentials of about 29% (thermal) and 65% (electrical) by 2050.

With increasing indoor comfort requirements and further global warming, the need for air conditioning/ cooling is increasing leading to a strong market increase and associated cost reduction potentials of about 29% by 2050.

PV is an established renewable energy source with a global market, but still has the potential for optimisation. In all future scenarios with low green-house gas emissions, PV plays a key role in meeting emission targets and generating the required amount of renewable electricity. High cost reduction potentials are expected as fast market development is indispensable until 2050 for the achievement of the climate and emission targets of the Paris Agreement. The estimated cost reduction potential is around 49% by 2050. In addition to the established use on the roof, building-integrated PV (BiPV) is a promising and growing new field.

Solar thermal systems – even though already widespread – still have cost reduction potentials of 38% by 2050. Like for PV systems, there is the possibility to integrate solar thermal systems in the building envelope (e.g. the façade) and replace elements leading to overall lower costs for realising nZEBs.

For the building sector, insulation plays an important role in reducing overall energy demands especially concerning the heating demand in moderate and cold climate regions. However, for established and widespread insulation materials no further cost reduction is expected; cost reductions are only expected for new/ innovative materials and by improved mounting processes.

Besides insulating a building, there are additional passive strategies such as night cooling or natural ventilation, which reduce the end energy demand of a building and become increasingly important for the realisation of nZEBs. However, deriving cost reduction potentials is not possible based on the available data.

The derived cost reduction potentials of the Top-down approach are summarised in Figure 2.

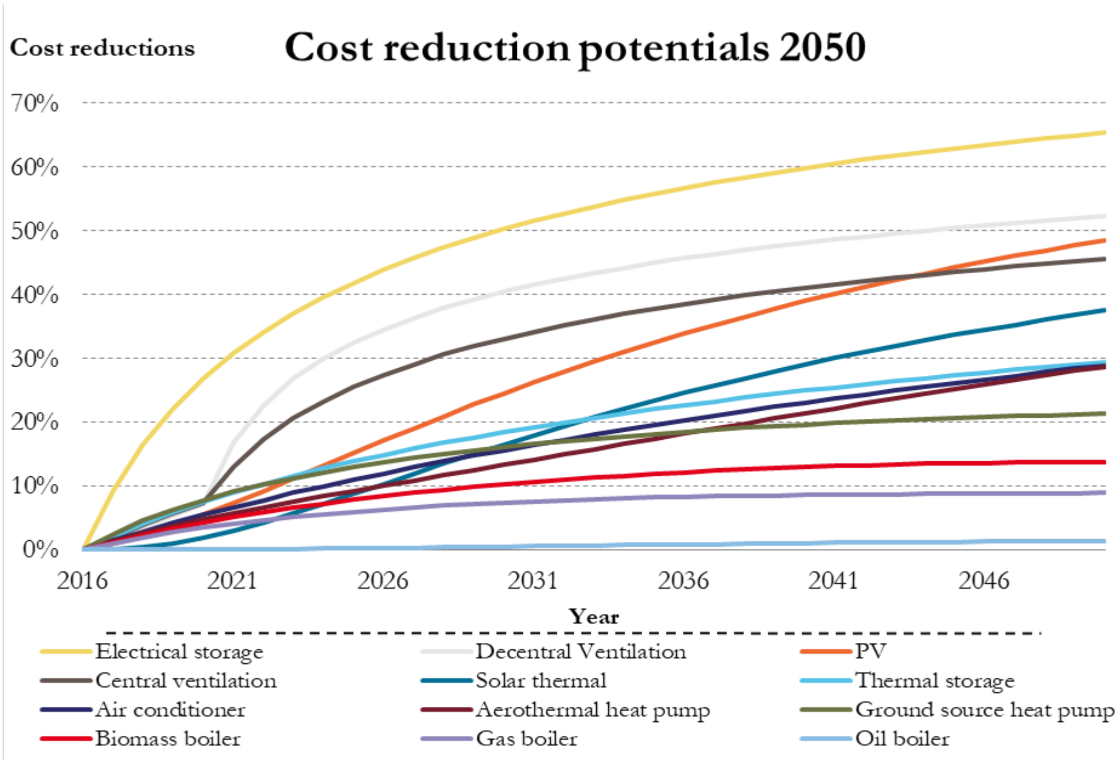

Figure 2. Cost reduction potentials till 2050 of major nZEB technologies calculated with the Top-down learning curve approach.

2.2. *Bottom-up:*

With the Bottom-up approach, specific cost drivers were determined for PV, solar thermal and electrical storages. For PV, cost reductions of up to 57% are estimated in different studies. Increased efficiency and material savings are the main possibilities for future cost reductions.

For solar thermal, the factors identified for possible cost reductions are the amount of material used, material changes, simplification of the system, faster assembly and changes in production methods; efficiency shows no high potential for further optimisation. Until 2030, cost reductions of up to 43% are described. For stationary batteries, the bottom-up analysis show cost reduction potentials of up to 65%. The main drivers are economy of scale and technological improvements such as an increased energy density, material savings and use of cheaper material.

Environmental pressure and policies on energy-efficient buildings with lower greenhouse gas emissions are probably the main reasons for the focus and increase in local renewable energy and energy-saving technologies powered by electricity instead of fossil fuels. The building sector plays an important role in reducing total greenhouse gas emissions and is currently still responsible for 32% of the world's final energy demand. Today, the energy supply is mainly based on fossil fuels causing CO2-emissions. Market demand for efficient and renewable technologies is a key factor for realising cost reduction potentials. The EPBD is thus an important factor in boosting the market for technologies like solar thermal, heat pumps, thermal insulation, PV and storages.

3. Life Cycle Cost Analysis

In the CRAVEzero project twelve case studies all over Europe, as can be seen in Figure 3 have been evaluated. The ISO 15686-5 [10] provides the main principles and features of an LCC calculation, while the European Code of Measurement one describes an EU-harmonised structure for the breakdown of the building elements, services, and processes, in order to enable a comprehensive evaluation of the building life costs.

The tool PHPP [11] has been used for the energy performance analysis. This tool summarises all the information dealing with the energy-related features of the building components and services and provides a comprehensive overview of the technologies installed.

Figure 3. CRAVEzero case studies

3.1. Life Cycle cost calculation

According to the ISO 15686-5:2008, the LCC of a building is the Net Present Value (NPV), that is the sum of the discounted costs, revenue streams, and value during the phases of the selected period of the life cycle.
Accordingly, the NPV is calculated as follows:

$X_{NPV} = \sum_{n=1}^{p} \frac{C_n}{(1+d)^n}$	C: cost occurred in year n; d: expected real discount rate per annum (assumed as 1.51%); n: number of years between the base date and the occurrence of the cost; p: period of analysis (40 years).

The analysis within CRAVEzero is based on standard values from EN 15459:2018 that provides yearly maintenance costs for each element, including operation, repair, and service, as a percentage of the initial construction cost. For the passive building elements, an average yearly value accounting for 1.5% of the construction cost has been assumed for the evaluation. The value has been cross-checked with average values coming from the experience of the industry partners.
The analysed case studies are located in different European countries, i.e. Austria, Germany, France, Italy, and Sweden, with specific characteristics in terms of climate conditions, construction, and energy market. Therefore, in order to compare the results of the case studies and to draw a general overview of the costs of the current nZEB practices, a normalization of the collected data is needed. In particular, the construction costs have been normalised considering the data from the ECC (European Construction Costs) that calculated a European construction cost index that quantifies the ratio among the construction costs of EU countries. For the climate conditions, the normalisation has been carried out considering the Heating Degree Days of the building locations. Concerning the energy
process, a common value has been adopted, accounting for 0,160 €/kWh of final energy consumed.

3.2. Presentation of the results – case studies comparative analysis

The second part reports an overview of the results, with the comparison of relevant indicators, costs, and performances among the case studies considering the effect of local specificities, different context and use of the buildings (i.e. normalised results).
Figure 4 shows an overview of the average impact of all the phases on the LCC, the investment costs for design, material labor and other initial expenditures is around 60% of the LCC, while the energy and maintenance account for around 40%.
As it was expected, the energy costs during the life cycle of a nZEB represent a minor contribution to the LCC, with an average of around 15%. Figure 5 shows the absolute values in €/m^2 of the LCC. It is important to point out that the contribution from the renewable energy systems like PV is accounted as a reduction of the energy cost of the overall life cycle (calculated as a balance between energy consumed

and produced). In case of "Greenhome", the energy costs reported in the chart assumes a negative value, since the energy produced is higher than the energy consumed, considering the large PV field installed.

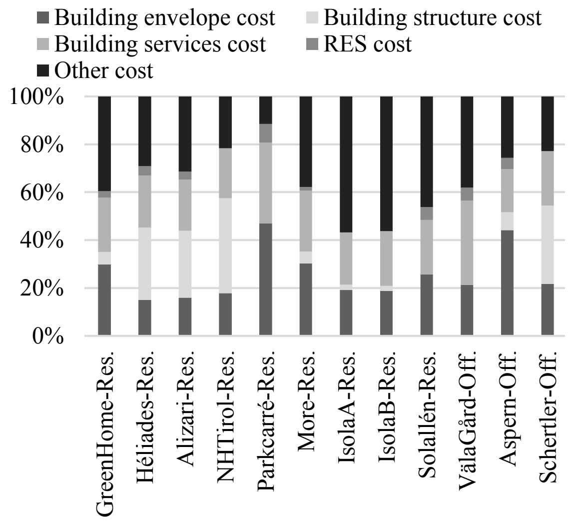

Figure 4. Construction cost breakdown

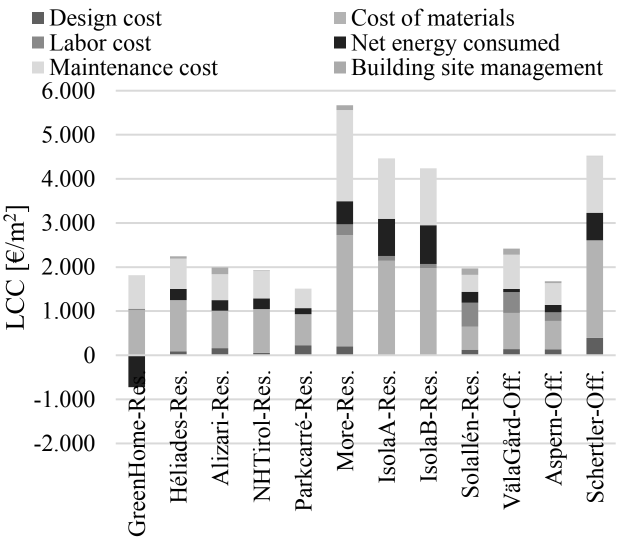

Figure 5. Life-cycle cost breakdown – normalized values.

Figure 4 reports the breakdown of the cost for the building elements, highlighting the impact on the construction costs. It shows that in some cases the structural elements represent a significant contribution to the construction, according to the complexity and the dimension of the building. On the other hand, nZEB related technologies have a small impact on the construction costs, although in comparison to a traditional building the cost for the HVAC system and the integration of renewables is more significant.

4. Multi- objective energy and life cycle costs analysis

The identification of suitable methods for the energetic-economic optimisation of highly efficient buildings in all life-cycle phases is a prerequisite for the broad market implementation.

As we have seen in the energetic-economic optimisation of buildings, there are different interests of the actors and, derived from this, different perspectives, time expectancies and goals. The term "multi-objective parametric analysis" in this report defines a method in which series of calculations are run by a computer program, systematically changing the value of parameters associated to one or more design variables. The key feature of this approach is that it allows evaluating the effect of individual design variables on energy, costs and environmental parameters in one step.

The multi-objective approach is based on the concept of Pareto frontier: a solution is optimal when no other feasible solution improves one of the objectives without affecting at least one of the other. In that case the multi-objective algorithms generate a set of solutions, known as the Pareto front. If the problem includes only two objectives, the Pareto front is a two-dimensional curve. This concept can also be applied to three or more objectives, although the results are more difficult to analyse. It is also important to note that this approach, rather than finding a single optimal solution, seeks to explore a set of optimal solutions and evaluate various trade-offs among them [12].

This approach was prototypically implemented in the case study Solallén based on the already gathered lcc data shown in the previous chapter. According to the defined general parameters in the previous chapter a set of ten different parameters with three to four levels are defined. The parameters consist of passive actions (Insulation standard, air-tightness, window U-values), active actions (ventilation-, PV-, heating-, cooling- and solar thermal system), user behaviour and economic sensitivities.

The analysis is performed for each parameter individually and in combination.
In total more than 31,000 different variants of different nZEB technology solution sets were calculated.
Figure 6 shows the overall results of the case study Solallén. In Figure 6 the financing costs of all investigated parameters are shown in relation to the balanced CO_2 emissions.
Figure 6 allows following short analysis:

- The financing costs range between 2100 Euro/m² and 2500 Euro/m². This is a range of ~ 20%.

- The balanced CO_2 emissions range between 14 kg/m²a and 52 kg/m²a. This is a range of ~70%.

Furthermore the analysis shows that similar financing costs can be achieved by the variants leftmost in the diagram and the variants rightmost. With these similar financing costs the balanced CO_2 emission can be reduced by nearly 70%.

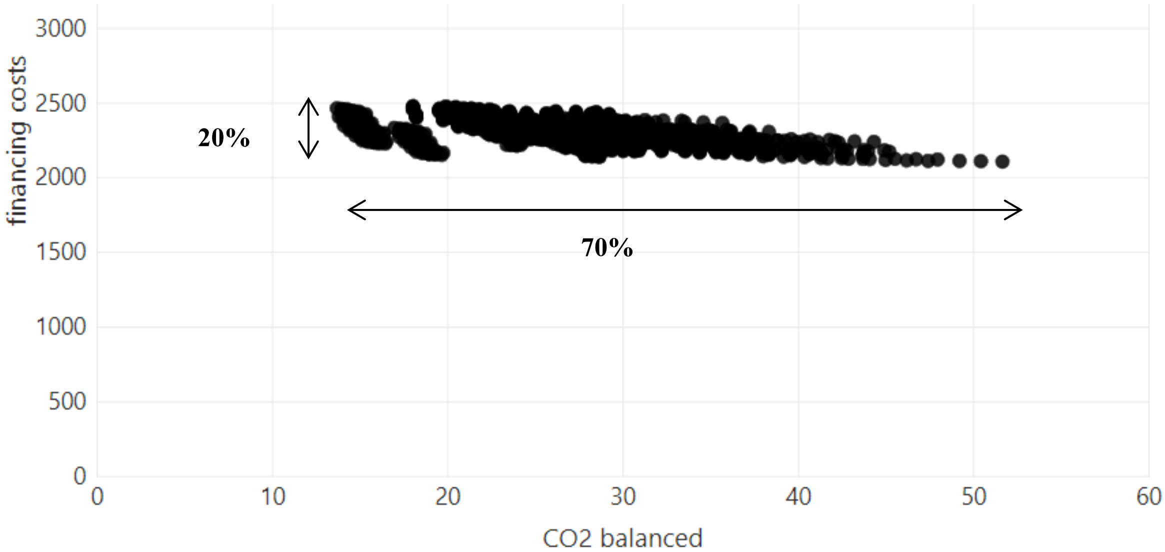

Figure 6. financing costs in relation to the balanced CO_2 emissions of all variants of the case study Solallén (related to treated floor area of the PHPP / CO_2 factors PHI/ without consideration of subsidies / no CO_2 credit for electricity fed into the grid)

5. Summary

On the basis of the results, the statement is confirmed: nZEBs are economical. It can now be shown that the additional costs of efficiency measures are so low that highly efficient buildings have the lowest life-cycle costs.

- In nZEBs, low energy demand is achieved through insulation and passive strategies is essential in order to be able to provide the remaining energy demand for the building operation (heating, cooling, ventilation, domestic hot water, and lighting) with onsite renewable energy.
- nZEB measures only have a small percentage influence on construction costs, but can reduce CO_2 emissions many times over.
- The energy standard has a small influence on the building and construction costs. Energy efficiency is therefore not a major cost driver in construction.
- The additional construction costs of nZEBs are compensated in the life-cycle of most technologies even without subsidies.
- The cost optimum of primary energy demand and CO_2 emissions is in the range of nearly zero and passive houses. Highly insulated envelopes and highly efficient windows are usually economical even without subsidies. This is also due to the long service life of these components in comparison to HVAC systems.
- The cost optimum curve in relation to CO_2 emissions is very flat. Low emissions and energy requirements can therefore be achieved with different energy concepts as long as the envelope is very efficient. This means architectural and conceptual freedom.
- The cost reduction potentials for nZEB technologies until 2050 vary from approx. 1% to 65%. Stationary batteries have the highest potential with 65%, followed by decentralised ventilation, PV, centralised ventilation with 52%, 49%, 46% and 38% respectively. Oil and gas boilers have the lowest potential of less than 10%.
- In many cases the return of investment in energy efficiency measures to reach the nZEB target is around 25-40 years, if calculated only in terms of energy cost saving. Nevertheless, as assessed by Berggren, Wallb, and Togeröc [13] the cost-effectiveness of nZEB construction becomes more apparent if the co-benefits and revenues are included in the analysis.

Acknowledgements

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Life-Cycle Costs of a Minimally Invasive Refurbishment Approach in Comparison to a Standard Refurbishment

Heidenthaler D[1], Gnigler M[1], Leeb M[1], Embacher M[2], Schweizer P[2]

[1] Smart Building, Salzburg University of Applied Sciences, Markt 136a, 5431 Kuchl, Austria
[2] Paul Schweizer Architects, Franz-Josef-Straße 35, 5020 Salzburg, Austria

daniel.heidenthaler@fh-salzburg.ac.at

Abstract. The decision on constructing or renovating buildings is often based on construction costs; consequently, follow-up costs are not considered. *Life-cycle cost analysis* is a common method for assessing the economic viability of buildings over their entire life-cycle. In this project, life-cycle costs of a minimally invasive refurbishment with component activation are compared with those of a standard refurbishment approach with an external thermal insulation composite system (ETICS) and radiators. Although the follow-up costs approximate the life-cycle costs after a period of 50 years in this analysis, the additional erection costs of the minimally invasive refurbishment approach cannot be compensated. In order for the system to become economically competitive, the erection costs regarding the façade system and the associated building technology must be reduced by 36 %, assuming that the nominal follow-up costs remain the same. Since the current implementation is still a prototypical one, cost-saving potential is expected on basis of the experience of the executing companies. However, in addition to the economic efficiency, the non-monetary added value of the system in the form of a more homogeneous heat output, more ecological building materials, less stress for the inhabitants due to the minimally invasive approach, reduced use of floor space and increased sound insulation due to the sound insulation façade, should also be taken into account in the decision-making process.

1. Introduction

Due to the climate policy in the European Union and consequently in Austria, the energetic renovation of buildings is becoming more and more important. According to Statistics Austria, an average of 21252 new buildings were built each year between 2011 and 2017 [1]. In addition, 49.5 % of the existing buildings in Austria and 43.4 % in Salzburg were constructed between 1945 and 1980 (as of 2011) [2]. The age structure of these buildings will cause various problems and challenges in the near future. The object of investigation, an apartment building with twelve apartments, can be assigned to the early post-war architecture of the 1950s. The challenges and problems which need to be overcome concern the energy standard of the building envelope, building technology, sound insulation and the comfort of the occupants of the buildings. A thorough examination of the existing building stock will therefore be indispensable. The analyzed object is characterized by a lack of thermal insulation and the windows were last replaced in 1993 and require renovation. This is accompanied by high transmission heat losses and thus a high heating energy demand of 241.6 kWh/m²a (according to the energy performance certificate) in the existing building. Moreover, the heat supply system of the considered object is heterogeneous. Seven apartments are equipped with individual stove heating and five apartments are connected to the district heating grid. The refurbishment is currently in progress, but has not yet been completed.

The erection costs as well as the follow-up costs associated with such renovations vary over the entire life-cycle of a building depending on the chosen construction method, components and technologies. In most cases, the choice as to which components and construction method to use takes place without considering the follow-up costs and the decision is made solely on the basis of the investment or erection costs [3]. The refurbishment measures for this object are carried out in the course of a research project focusing primarily on a novel façade technology. A minimally invasive multifunctional façade is being tested, which combines thermal insulation, sound insulation, heat dissipation and façade cladding in prefabricated wooden elements. This contribution wants to compare the life-cycle costs of a minimally invasive refurbishment with those of a standard refurbishment (see description of the approaches in chapters 4.1 and 4.2), in which the refurbishment costs are kept as low as possible.

2. Objectives

Life-cycle costing is a widely used method for assessing the economics of a whole building or individual components over its entire life-cycle. Accordingly, the literature on life-cycle cost analysis (LCCA) in general is extensive, but there are only a few detailed studies on the analysis of facade systems. Floegl and Ipser [4], for example, examine the life-cycle costs of six different residential complexes of different construction years and sizes. Höfler and Kunesch [3], on the other hand, compare the life-cycle costs of different refurbishment concepts in the course of the e80^3 project. Furthermore, a facade module and a building services module have been developed and implemented in a demonstration building. One of the objectives was the prefabrication of energy-efficient elements. The present research project differs from the described system as it integrates the heating system within the façade in the form of a component activation, as well as the installation of wood cement panels as sound absorbing elements. Schmidt et al. [5] have developed and tested an external component activation in the course of the research project "LEXU" and "LEXU II". In this case, the system was combined with an external thermal insulation composite system. Höfler et al. [6] have investigated prefabricated systems for the refurbishment of residential buildings in the course of the IEA ECBCS Annex 50 and developed prefabricated modules with a focus on thermal refurbishment for a demonstration object in Graz-Dieselweg. A life-cycle cost analysis has not been carried out for the latter two projects. At the moment, the available data for a detailed LCCA is insufficient; therefore, the basis for this contribution is a rough estimate of the costs of the refurbishment method currently being carried out with a prefabricated multifunctional façade and component activation on the basis of an apartment building in Hallein, Salzburg. The chosen renovation method represents a prototype and is planned to be applied to other buildings with similar characteristics. The life-cycle costs are calculated on the basis of the tool Lekoecos, which in turn is based on the corresponding standards ÖNORM B 1801-1 [7] for the calculation of the erection costs and ÖNORM B 1801-2 [8] for the calculation of the follow-up costs. The applied calculation method uses the present values of the follow-up costs for the selected period of 50 years. The costs for the minimal invasive refurbishment are to be compared with those of a conventional renovation with a similar energetic standard.

3. Research process

In this chapter, basic data for the calculation of the life-cycle costs as well as the boundaries of the treated costs are expounded.

3.1. *Basic data*

The considered life-cycle costs are based on data about the minimally invasive refurbishment still under construction as well as the estimation of the renovation costs of a standard approach. Based on the current data situation, the estimated costs are thus made up in part of actual costs, obtained offers and estimated costs. The following documents are available for the calculation and input:

- as-built and execution plans (architecture and building technology)
- energy performance certificates (stock and renovation)
- simulation of heating demand
- invoices of measures already carried out including redensification by adding a story in solid wood construction, multifunctional façade, building technology of the minimally invasive refurbishment, renovation of the existing bathrooms and planning services
- offers and estimates of the work still to be carried out and the standard refurbishment including façade cladding of the added story, roofer and plumber, electrician, dry construction, outside facilities, measurement and control technology, external thermal insulation composite system (ETICS), building technology of the standard refurbishment

The calculation parameters are based on the tool LEKOECOS of the Danube University Krems in beta version 1.3. The input of the object parameters refers to the execution and as-built plans as well as the energy certificate. In addition, the respective invoices, if available, are used to determine the construction costs. With regard to the minimally invasive refurbishment, the existing offers serve as a basis for the input of construction measures that have not yet been carried out. If there is neither an invoice nor an offer, a cost estimate based on the ÖNORM B 1801-1 [7] is made. The calculation of the erection costs for the standard refurbishment is also done on the basis of existing offers as well as cost estimates based on the ÖNORM B 1801-1 [7]. The heating energy demand results predominantly from the simulation of the two divergent heating- as well as construction variants. Furthermore, the heat losses of the heating system are obtained from the respective energy performance certificate, since only the simulation of a part of the building and the building technology system is carried out. The energy required for hot water preparation is similarly obtained from the energy certificate. Any energy gains from the photovoltaic system are not taken into account. The assessed costs per kWh for heat supply correspond to the costs actually charged. The operational life spans for calculating the usage costs of technical building systems were obtained from the VDI 2067-1 [9], and the operational life spans of the building components originate from the Federal Ministry of the Interior, Building and Community Germany [10].

3.2. Boundaries

The ÖNORM B 1801-4 [11] divides life-cycle costs into erection costs and follow-up costs, the latter in turn includes usage costs as well as object removal and demolition costs. The following economic efficiency comparison is drawn for selected cost groups on the basis of LCC (Figure 1). In this project, the erection costs thereby include those cost groups according to ÖNORM B 1801-1 [7] that are actually generated during the renovation process, namely costs for the building shell (E2), building technology (E3), building extension (E4), outside facilities (E6), planning services (E7) and reserves (E9). In addition, standard refurbishment costs for incidental expenses (E8) are taken into account, since it is assumed that the occupants must be resettled during the renovation. Therefore, this cost group includes the loss of rent during the renovation as well as one-off relocation expenses. Because of the observation of two façade systems and the associated heat release systems, the follow-up costs are limited to the relevant usage costs of the cost groups technical building operation (F2), supply and disposal (F3), cleaning and maintenance (F4) as well as overhaul and modification (F7). Owing to the current data situation, costs for object removal and demolition (F9) are not considered. In addition, according to Höfler and Kunesch [3], when a dynamic calculation method is applied, object removal and demolition costs lose much of their significance when observed for longer periods of time.

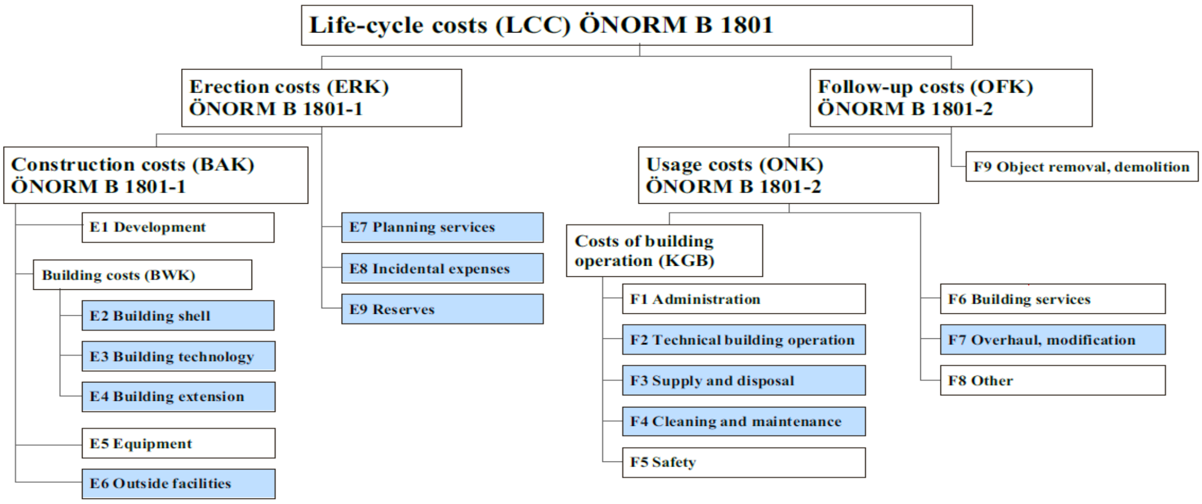


Figure 1. Selected cost groups of the considered life-cycle costs according to the ÖNORM B 1801.

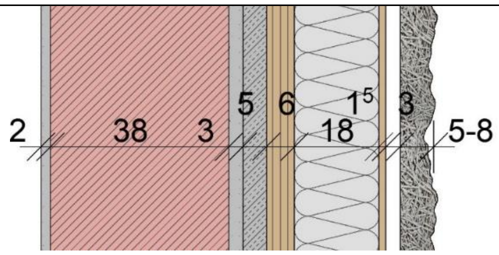
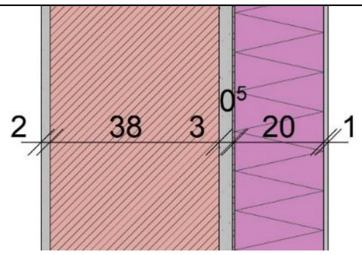
4. Life-cycle analysis

In this chapter, a description of the considered renovation variants is given. In principle, the costs of the entire renovation are included in the consideration of the life-cycle costs, whereas differences between the two variants only affect parts of individual cost groups. The basis for the two renovation variants is an apartment building in solid brick construction, which contained twelve apartments before the renovation. In the course of the refurbishment, the building gets extended and seven apartments are added, resulting in a total of 19 apartments after the refurbishment. The differences between the two variants are limited to the chosen façade and heating system. The two variants share the following measurements regarding to the construction costs:

- redensification by adding a story in solid wood construction
- roofer and plumber
- electrician
- renovation of the existing bathrooms and planning services
- installation of a photovoltaic system
- installation of home transfer stations in each apartment
- outside facilities
- district heating connection
- dry construction

Below, the differences between the two variants are explained and the considered construction systems (Table 1) and technologies are described.

Table 1. Comparison of the selected variants.

	Minimal invasive refurbishment	Standard refurbishment
Component structure		
U-Value	0,182 W/m²K	0,182 W/m²K
Thickness	81,5-84,5 cm	64,5 cm
Heat dissipation	Component activation	Radiator

4.1. *Minimally invasive refurbishment*

The exterior walls of the existing building are constructed as externally and internally plastered standard format brick walls. The so-called *multifunctional façade* comprises a thermally activated mortar layer (8 cm), in which the heating coils for the external component activation are positioned, a composite wood panel (6 cm), cavity insulation using cellulose (18 cm), and all-over MDF-cladding (1.5 cm). Externally, there are both a ventilation level (3 cm) and sound-absorbing wood cement panels (5-8 cm). A schematic structure of the actual wall structure can be seen in Table 1. This wall structure reaches a U-value of 0.182 W/m²K.

The façade elements, i.e. the composite wood panels, the cellulose insulation and the planking, are prefabricated and displaced as floor-to-ceiling elements. The resulting space between the existing masonry and the prefabricated façade element is filled with injection mortar after the installation. This layer contains the heating coils for the component activation. The distance between the coils is usually 20-25 cm. These are multi-layer composite coils with an outer diameter of 20 mm and a material thickness of 2.25 mm, and are attached to the existing wall before the façade modules get displaced.

4.2. Standard refurbishment

In order for the standard refurbishment to be compared to the minimally invasive refurbishment, a wall structure is chosen that has a similar U-value to that of the minimally invasive refurbishment. Thus, the external thermal insulation composite system, which is often used in renovation procedures, represents the standard refurbishment. This variant comprises a façade insulation consisting of expanded polystyrene (20 cm) and reinforced synthetic resin plaster (1 cm) attached to the existing wall. The wall structure described above obtains a U-value of 0.182 W/m²K. A schematic structure of the standard refurbishment can be seen in Table 1.

In minimally invasive refurbishment, the building is heated via the façade, whereas in standard refurbishment heating is provided by radiators. The additional costs for the standard system cover the installation of the surface-mounted heating pipes and the radiators as well as the corresponding material costs. Since risers and transfer stations in the individual residential units are installed as part of the bathroom refurbishment, additional costs in standard refurbishment have to be taken into account only for the distribution pipes within the apartments, as opposed to the minimally invasive refurbishment, where additional distribution pipes need to be installed starting from the distribution stations in the basement.

4.3. Comparison of life-cycle costs

The results of the minimally invasive refurbishment are now compared with those of the standard refurbishment. Therefore, the life-cycle costs of selected cost groups are displayed in the following figures.

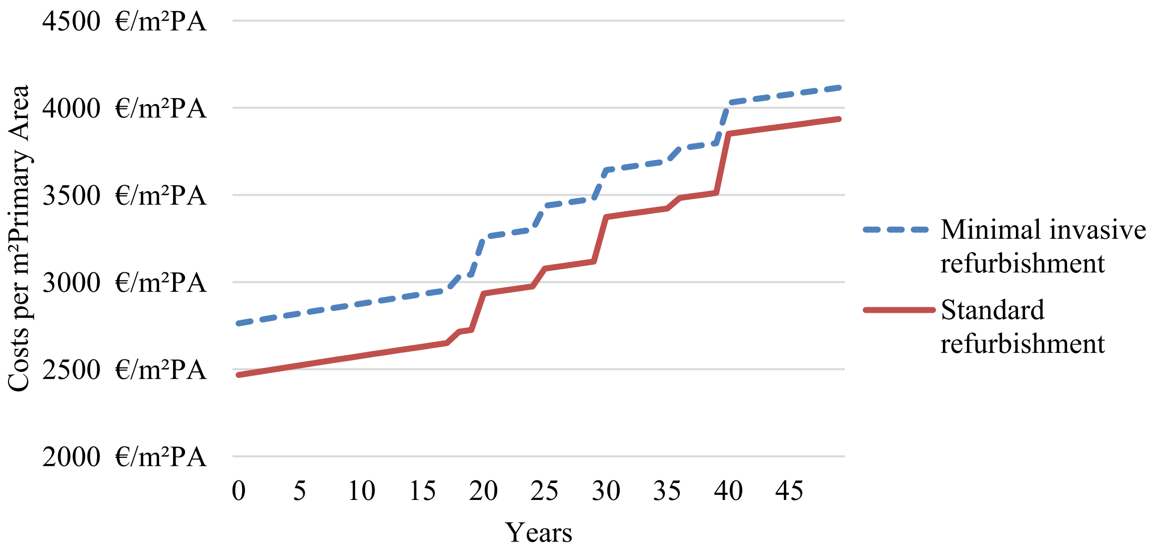


Figure 2. Trend of the life-cycle costs of selected cost groups over a period of 50 years.

Figure 2 shows that the minimally invasive refurbishment is more expensive as far as construction costs are concerned, but not regarding usage costs. Yet the benefits as a result of the lower usage costs over the considered 50-year period are not sufficient to offset the higher construction costs. In principle, three major rises can be observed in the course of life-cycle costs. First, the rise in usage costs after 20 years due to required renewals of some building technology components. Second, after 30 years it is assumed that it will be necessary to replace windows. The standard refurbishment involves higher costs, since a renewal of the heat release system is included. Third, after 40 years, the investment once again mainly relates to the renewal of some components of the building technology. The refurbishment of the thermal insulation composite system is taken in standard refurbishment, too. This results in a discrepancy in the rise of the two systems regarding usage costs.

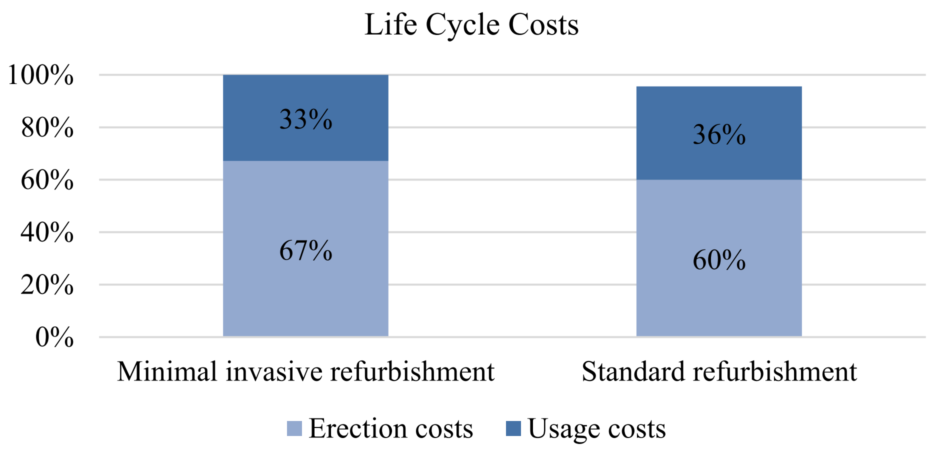


Figure 3. Life-cycle-costs in percent based on the minimally invasive refurbishment.

As can be seen by the ratio of construction costs and usage costs in Figure 3, usage costs of the minimally invasive refurbishment are 3 % lower and construction costs 7 % higher than in standard refurbishment. These differences relate to the cost groups technical building operation (F2), supply and disposal (F3) and overhaul, modification (F7). Standard refurbishment only bears lower costs in the cost group supply and disposal (F3), since the minimally invasive refurbishment entails higher heat losses due to the positioning of the building component activation on the outside of the existing wall. With regard to the erection costs, the costs of the minimally invasive refurbishment in the cost groups building technology (E3) and building extension (E4) are 2 % and 7 % respectively above those of the standard refurbishment. Standard refurbishment in turn includes additional costs of 2 % regarding incidental expenses (cost group E8). This results in the aforementioned difference of 7 %. Overall, the lower costs of standard refurbishment thus amount to 4 % in comparison to the minimally invasive refurbishment.

5. Conclusion

The results of the life-cycle cost analysis, excluding the cost group of object removal and demolition (F9), show that the additional costs of the minimally invasive refurbishment concerning construction costs cannot be compensated by the incurred additional costs of standard refurbishment due to the relocation of the tenants and the associated rent loss. Although usage costs of standard refurbishment with regard to the thermal insulation composite system and the heat dissipation system are now somewhat higher, mainly due to the shorter operational life spans, at the end of the considered 50-year period a difference in life-cycle costs of 4 % remains. In order for the multifunctional façade and the building service system to be economically competitive with a standard refurbishment as described, cost savings regarding construction costs are required. If the construction costs of the façade and the associated building services system could be reduced by 36 %, the difference of 4% in life-cycle costs of the two variants could be compensated, assuming that the nominal follow-up costs remain the same. The calculation of follow-up costs in Lekoecos is in some cost groups based on a percentage of the construction costs. This results in the problem that the advantage of high-quality, innovative components and systems leading to lower follow-up costs cannot be expressed [12].

In addition, it is important to consider the added value of the system, which cannot be monetized. It includes the reduced burden on the tenants due to the minimally invasive refurbishment. The minimally invasive refurbishment approach allows residents to remain in the building during conversion work. This is based on the demands of the building operator (the city of Hallein) and the tenants, surveyed during the stocktaking analysis of the project area [13]. The heat dissipation through component activation instead of isolated radiators and the reduced use of floor space due to the piping on the outside add another aspect. The installation of sound absorbing wood-cement panels has the potential to reduce noise levels in open spaces throughout the district, getting more effective by the number of surrounding buildings reconstructed with absorbing elements. The sound behavior was examined in detail and a potential sound level reduction of 1 to 3 dB was determined [14]. The use of wood-based materials and good decomposability make the variant more sustainable and ecological compared to a thermal insulation composite system. All these added values cannot be taken into account in a purely monetary valuation and analysis.

The life-cycle cost analysis did not take into account any advantages in terms of subsidies.

6. Outlook

Due to the fact that this system still is in a prototypical state, a future optimization and cost reduction is quite foreseeable. It is difficult to estimate the extent of possible cost reductions, but savings can basically be achieved by optimizing both the building service system and the construction of the façade. In the course of the research project, further optimizations of the multifunctional façade will be tested in a similar building, starting in autumn 2019.

7. Acknowledgments

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Towards the definition of a nZEB cost spreadsheet as a support tool for the design

Pernetti R[1], Garzia F[1], Paoletti G[1], Weiss T[2]

[1]Institute for Renewable Energy – eurac research, Italy;

[2]AEE INTEC, Austria

federico.garzia@eurac.edu

Abstract. The 2010 Energy Performance of Buildings Directive (EPBD recast) [1] established that all new buildings have to reach, by the end of 2020, the nearly-Zero Energy (nZEB) target as set by the Member States. In order to achieve the nZEB standards, while keeping investments sustainable, it is strategic to focus more on the operational phase and to guide the decision-support with a lifetime perspective. In this regard, a crucial step is to adopt a shared methodology for evaluating the Life-Cycle Cost (LCC), in order to minimize the effect of uncertainties, the impact of calculation approach and the variability of the boundaries at EU level. The H2020 CRAVEzero project developed a LCC spreadsheet, aimed at calculating a set of relevant indicators for assessing the cost during the investment phase (design, labour and material costs) as well as during the operational phase of a building (energy and maintenance costs). The LCC spreadsheet implements an approach for normalising the results according to the main relevant boundaries that can affect the comparability at EU level (e.g. energy prices, the national construction costs, the climatic conditions, etc.). Moreover, it introduces a sensitivity analysis that aims to provide the impact that the boundary conditions can have on the results, reducing the uncertainties in the LCC calculations due to a long-term perspective (*http://www.cravezero.eu/lcc spreadsheet/)*. This paper presents the structure of the LCC calculation approach defined within the project, the structure of the spreadsheet and the main indicators as evaluated for a set of relevant nZEB case studies across Europe.

1. Introduction

Despite the EPBD 2020/31/EU [1] that established the nearly Zero Energy Buildings (nZEB) target for all the new buildings by 2020, there are still many barriers affecting the update process of the construction markets towards nZEB. In fact, even though the MS established minimum nZEB requirements according to the cost-optimal principles indicated by the EPBD, the extra-cost of investment for nZEB technologies is rarely accepted by stakeholders. This is mainly because the investor usually adopts a reduced time-horizon for evaluating the cost-optimality of an investment, and this strongly affects the building design and the reachable targets, as stated in [2].

H2020 CRAVEzero project aims at changing the approach, identifying the costs of nZEBs in a life cycle perspective in order to propose solutions for cost optimisation or cost shifting.

In this regard, a structured methodology for assessing building Life Cycle Cost (LCC), with benchmarks, exemplary cases and standard values is needed. This paper presents the results of the work carried out within the CRAVEzero "Cost Reduction and market Acceleration for Viable nZEBs" as a starting point for developing a structured and EU-wide approach for LCC evaluations, including data collection templates, references and standard costs to be adopted for preliminary evaluations.

The approach has been traduced in the so-called "CRAVEzero nZEB spreadsheet" implementing a comprehensive and structured methodology to evaluate the LCC, which was used for analysing a set of 12 exemplary nZEBs representing current best practices across Europe.

The paper also presents an overview of the results, including the comparison of relevant costs and performance indicators among the case studies and a differential Sensitivity Analysis (SA), aimed at identifying the main boundaries and inputs affecting the LCC of a building.

2. Case studies and data collection

The first step of the analysis is to set-up the framework for the data collection. Following a series of workshops and feedback loops with project partners and potential stakeholders, we developed a reference template structured in three main parts:

1. General project information: it includes the main information of a case study (i.e. building features, context, principles for the business model),
2. Non-construction costs: it deals with the enabling and preliminary costs for the building construction,
3. Life-Cycle Costs: it reports all the costs for building elements and services from the design phase until the construction and operation, including maintenance and energy costs.

The data collection template is structured according to the approach provided by two primary sources: the Standard ISO 15686-5 (Buildings and constructed assets - Service life planning - Part 5: Life-cycle costing) [2]; providing the main principles and features of an LCC calculation and the European Code of Measurements [3], defining an EU-harmonised structure for the breakdown of the building elements, services, and processes, in order to enable a comprehensive evaluation of the LCC.

The defined approach has been implemented for the analysis of the 12 exemplary case studies, representative of the best nZEB practices across Europe (Table 1).

Table 1. Case studies main features.

Case study	Location	Year	Typology	NFA [m^2]
Green Home	Nanterre (France)	2016	Residential	9267
Les Héliades	Angers (France)	2015	Residential	4590
Résidence Alizari	Malaunay (France)	2015	Residential	2776
NH - Tirol	Innsbruck (Austria)	2008/2009	Residential	44959
Parkcarré	Eggenstein (Germany)	2014	Residential	1109
More	Lodi (Italy)	2014	Residential	128
Isola Nel Verde A	Milan (Italy)	2012	Residential	1409
Isola Nel Verde B	Milan (Italy)	2012	Residential	1745
Solallén	Växjö (Sweden)	2015	Residential	1778
Väla Gård	Helsingborg (Sweden)	2012	Office	1670
Aspern	Vienna (Austria)	2012	Office	8817
I.+R. Schertler	Lauterach (Austria)	2011/2013	Office	2759

The following sections present an overview of the methodology for the case study analysis and the main results from the application.

3. Methodology for calculating Life Cycle Cost

The ISO 15686-5:2008 standard provides a structured methodology for calculating LCC of buildings, setting the general principles, phases, and assumptions of the evaluation. It defines two main indices:

1. The Life Cycle Cost (LCC), focused on design, construction, and operation phase
2. The Whole-Life Cost (WLC) including the initial non-construction costs for enabling the building.

Table 2 shows the phases and contributions to be included in the analysis of LCC and WLC

Table 2. Phases and costs in WLC and LCC

			Life cycle processes	**Included costs**
WLC			1. Political decision and urban design phase	Non-construction cost (cost of land, fees and enabling costs, externalities)
	LCC	**Initial Investment**	2. Building design phase	Building design costs
			3. Construction phase	Construction and building site management costs
			4. Operation phase	Energy and ordinary maintenance costs
			5. Renovation phase	Repair and renovation costs
			6. Recycling, dismantling and reuse phase	The residual value of the elements

Although both LCC and WLC evaluation includes all the cost until the end of life, the presented analyses neglected both dismantling and residual values, since no structured and relevant data from the case studies was available.

Following the framework of ISO 15686-5:2008 standard, the first step for the calculation of the LCC is to set the time period, according to the purpose of the analysis. The standard indicates that the largest period to be selected is 100 years. On the one hand, shorter periods allow more reliable assessments, since the time-uncertainties are less affecting. On the other hand, longer periods, while having more uncertainties in the results, allow for more comprehensive evaluations, including maintenance costs. As stated in [4] "the International standard ISO 15686-5:2008 recommends that the estimated service life of a building should not be less than its design life". Furthermore, [5] suggested an analysis period between 25 and 40 years, since the present value of future costs, which arise after 40 years might not be consistent because of a large number of uncertainties. Therefore, for the purposes of this analysis, a period of 40 years has been selected. Regarding the actualisation of future costs over the 40 years lifespan, a common value of interest rate for all the case studies has been adopted. The selected value is taken from FRED Economic Database [6], which provides an average interest rate of 1.51% for the time period going from 2008 (year of construction of the oldest case study) to 2017.

According to the ISO 15686-5:2008, the LCC of a building is the Net Present Value (NPV), that is the sum of the discounted costs, revenue streams, and value during the phases of the selected period of the life cycle.

Accordingly, the NPV is calculated as follows:

$$X_{NPV} = \sum_{n=1}^{p} \frac{C_n}{(1+d)^n} \quad (1)$$

- C: cost occurred in year n;
- d: expected real discount rate per annum (assumed as 1.51%);
- n: number of years between the base date and the occurrence of the cost;
- p: period of analysis (40 years).

Finally, costs are grouped according to the life cycle phases: design, construction, building site management, operation, and maintenance. The effective estimation of energy and maintenance costs required a set of assumptions, described in the following sections.

3.1. Determination of the energy costs

In order to provide a homogeneous and comparable estimation of the energy costs of the case studies, since the official bills were not available in most of the cases, the evaluation was based on the calculated energy demand. As stated before, energy performance analysis was carried out by using the PHPP tool [7], which allows the implementation of the data dealing with the energy performance of a building, including the features of the envelope, HVAC system and renewables installed.

In particular, energy costs (C_{energy}) were estimated through a the difference of the cost due to the energy consumed ($C_{consumed}$), including heating, domestic hot water production, cooling and household/auxiliaries electricity and the revenues from the energy produced ($C_{produced}$) thanks to the renewables installed, (i.e. the contributions of final energy generated by a photovoltaic system and solar thermal system), both calculated on monthly base during month i (Equation 2):

$$C_{energy} = \sum_{i=1}^{12} C_{consumed,i} - C_{produced,i} \quad (2)$$

For each country the unitary energy prices (€/kWh) applied to calculate the costs for the energy consumed and produced, have been taken from Eurostat [8], considering the average values in the period 2010 – 2017. Most of the case studies are supplied by electricity, since the most common technology adopted is the heat pump. Nevertheless, for other energy fuels, the same approach the costs definition has been adopted.

As a general assumption, for the evaluations described in this report, a common value for considering the increase of the energy price has been adopted. According to the data reported in [8], the inflation of electricity prices in CRAVEzero countries from 2010 to 2017 amounts to 1.0%, and this value is used in the LCC evaluation.

3.2. Maintenance costs

Maintenance costs for the case studies were not fully available with a relevant level of accuracy and detail. In fact, the analysed buildings were built between 2009 and 2016, and only minor maintenance had already taken place. Therefore, the analysis within CRAVEzero is based on standard values from the literature. In particular, the standard EN 15459:2017 “Energy performance of buildings - Economic evaluation procedure for energy systems in buildings” [9] provides the life span and the yearly maintenance costs for each element, including operation, repair, and service, as a percentage of the initial construction cost. For the passive building elements, an average yearly value accounting for 1.5% of the construction cost was assumed for the evaluation, while the standard reports more detailed figures for the HVAC components (for both life span and annual maintenance). The value was crosschecked with average values coming from the experience of the industry partners.

4. Approach for the normalisation of Life Cycle Cost in the EU

The analysed case studies are located in different European countries (Table 1), i.e. Austria, Germany, France, Italy, and Sweden. Each country presents specific characteristics in terms of climate conditions, construction, and energy market. Therefore, in order to compare the results of the case studies and to draw a general overview of the costs of the current nZEB practices across Europe, a normalisation of the collected data is needed. In this regard, the following sections present an overview of the normalisation factors adopted for comparing the data of the case studies for construction, climate conditions and energy prices.

4.1. Construction cost

The impact of the construction costs on the life cycle is affected by several country-related factors. In fact, the price of the materials can be influenced by several national and international economic factors, as well as the costs of transports, strongly affected by the fuel costs, and the labour cost. In order to reduce the perturbations of the results caused by these national specificities, it is essential to find a common factor to normalise the construction costs.

Table 3. Construction cost index for CRAVEzero countries according to ECC [10].

Construction cost index				
France	**Austria**	**Germany**	**Italy**	**Sweden**
103.87%	100.67%	96.62%	93.63%	134.19%

The ECC [10] has calculated a comprehensive European construction cost index that quantifies the ratio among the construction costs of EU countries, considering the above-mentioned factors. Table 3 reports the normalisation factors of the construction costs adopted within CRAVEzero.

4.2. Year of construction

Another factor influencing the costs of investment and operation is the adopted reference year for the actualisation, usually the year of the construction. For this analysis, considering that 10 out of 12 case studies were built between 2012 and 2015, in order to simplify the evaluation process, the normalisation of the year of construction was neglected.

4.3. Climate

It is important to normalise the energy costs according to the climate conditions of the building location, to neglect their effect on energy consumption. In this regard, the heating degree days (HDD) was assumed as a normalisation factor. The values were derived from the report “U-value and better energy performance” [11], which provides the HDD for a set of reference cities of the EU-countries.

4.4. Energy price

Finally, in order to compare the energy costs, a normalisation, which considers differences in energy prices among countries, was implemented. 0.16 €/kWh has been assumed as the average energy price for the normalisation. This value was calculated considering the average price for each energy vector and its weight among the other energy vectors according to the technology installed.

5. Key performance indicators and sensitivity analysis

To display the results of the data analysis of each case study, a set of key performance indicators is proposed. A list of performance indicators was submitted to the project partners, with the request to rate the KPIs on a scale of 1-3 (“3 - very interesting”, “2 - interesting” and “1 - not interesting”). According to the ranking, it has been decided to include in the final list the KPIs with an average score ranging from 2 to 3. Table 4 presents the selected indicators.

Table 4. Rated key performance indicators.

KPI	Rating	KPI	Rating
LCC / usable floor surface	3	Cooling energy demand for cooling	2.4
Investment cost / usable floor	2.8	Energy demand for hot water production	2.4
Operation cost / usable floor	2.6	Annual renewable energy generation	2.4
Renewable energy share	2.6	Maintenance cost / usable floor surface	2.2
PV annual electricity yield	2.6	Maintenance cost / investment cost	2.2
Annual CO2 emissions	2.6	Final energy consumption	2.2
Life-cycle CO_2 emissions	2.5	Specific heating demand	2.2
LCC	2.4	Specific cooling energy consumption	2.2
WLC	2.4	Specific hot water energy consumption	2.2
Investment cost	2.4	Specific Electricity energy demand	2.2
Operation cost	2.4	LCC / renewable energy installed capacity	2
Maintenance cost	2.4	Operation cost / PV energy production	2
Primary energy consumption	2.4	Electricity energy demand (lighting,	2
Heating demand for heating	2.4	Energy demand for ventilation	2

5.1. Sensitivity analysis

One of the main drawbacks of the LCC analysis is the high level of uncertainty affecting the evaluation of the costs during the building life cycle. In fact, on the one hand, the calculation requires a series of simplifications and assumptions for defining the input parameters, and, on the other hand, the complex cost structure and the uncertainties in predicting future events that may affect the results [12, 13]. A proper cost analysis requires the quality of input data and accurate long-term forecasts of these values over the analysed lifespan [12]. The difficult access to this type of data leads to uncertainty in LCC methods, limiting their application. Hence, to tackle the uncertainty issue, the CRAVEzero LCC evaluation includes a sensitivity analysis to define the impact of the uncertain boundaries and input values on the LCC. SA measures the effect on the outputs, caused by input variation, due to uncertainty or risk. In this way is it possible to define uncertainty-adjusted LCC ranges, allowing decision makers to concentrate on the analysis of the most critical parameters [13].

The present paper reports the outcome of differential SA. This method belongs to the class of the "One factor At a Time" (OAT) screening techniques, since it evaluates the effect of the variation of a single input parameter on the output, while the other set of inputs are set equal to their baseline value:

$$s\% = \frac{\frac{\Delta O}{O_{un}}}{\frac{\Delta I}{I_{un}}} \quad (3),$$

Where:

- S%: Sensitivity index
- O_{un}: Baseline value
- ΔI: Input variation
- ΔO: Output variation
- I_{un}: Baseline value

Figure 1 and Figure 2 report the results of the SA for one of the case studies, i.e. Résidence Alizari, in terms of Sensitivity Index and LCC variation around the baseline. In particular, the analysis focused on boundary conditions and general assumptions that are mainly affected by uncertainty issues: interest rate, energy cost and its inflation rate, maintenance cost (evaluated as a % of the construction cost) and operational cost. As shown in Figure 1, the maintenance and the lifespan of the buildings have the highest impact on the LCC, that can range from 2610 and 2675 €/m² according to the variation of the inputs.

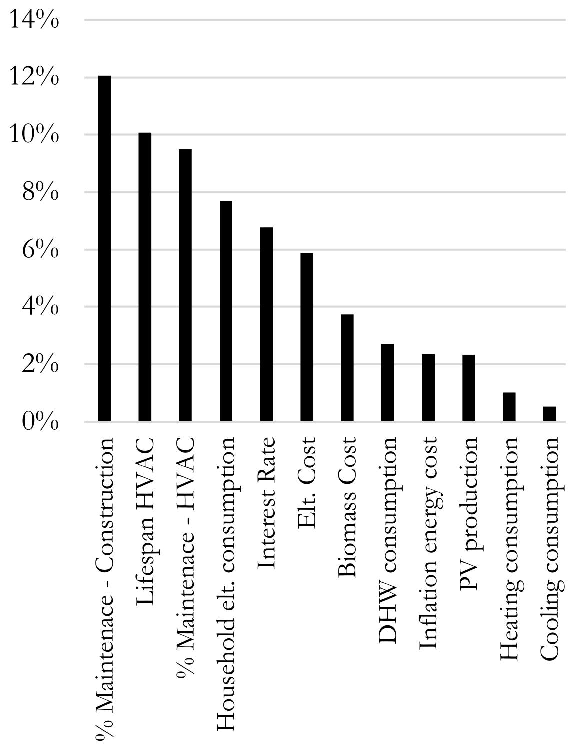

Figure 1. Sensitivity index (s%) of boundary and assumptions – Résidence Alizari.

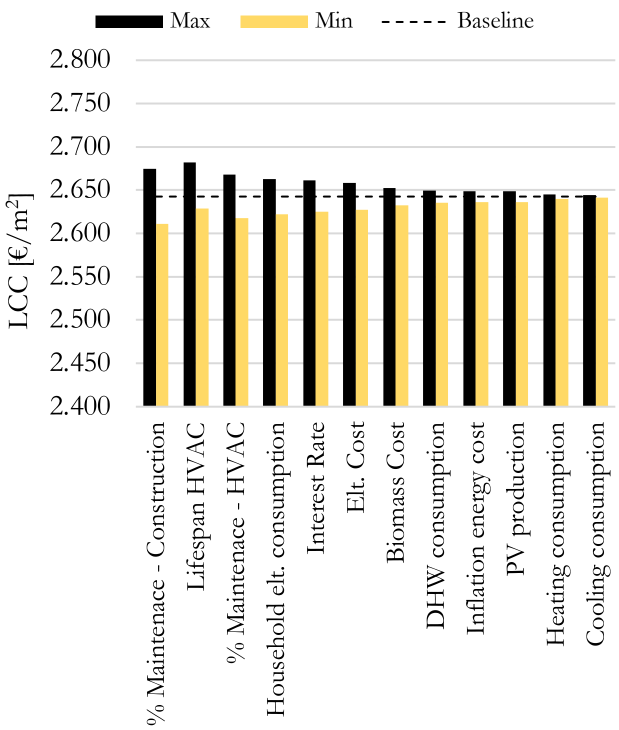

Figure 2. LCC variability according to the variations of boundaries and assumptions

6. Spreadsheet

The set of selected KPIs, shown in Section 5, have been combined in the CRAVEzero nZEB spreadsheet describing, in both numerical and graphical form, the normalised life cycle cost of nZEBs for an EU-wide comparison of the results.

Figure 3 shows the first page of the CRAVEzero spreadsheet, including an overview section of the main features of the case study and the KPIs related to investment costs and energy consumption. In particular, it reports the investment cost with the breakdown and a special focus on design and construction, and a detailed analysis of labour and material cost for each building and HVAC element with the impact on the investment. Finally, there is a section dedicated to the energy performance of the nZEB, including specific energy demand, consumption CO_2 emission and production from renewable energy sources. The second page (Figure 4) focus on life-cycle cost KPIs, with a general overview of the cost during the life span (40 years), a distribution according to the phase with a special focus on the maintenance and a detailed breakdown of the specific costs for each unit surface during all the phases of the life cycle.

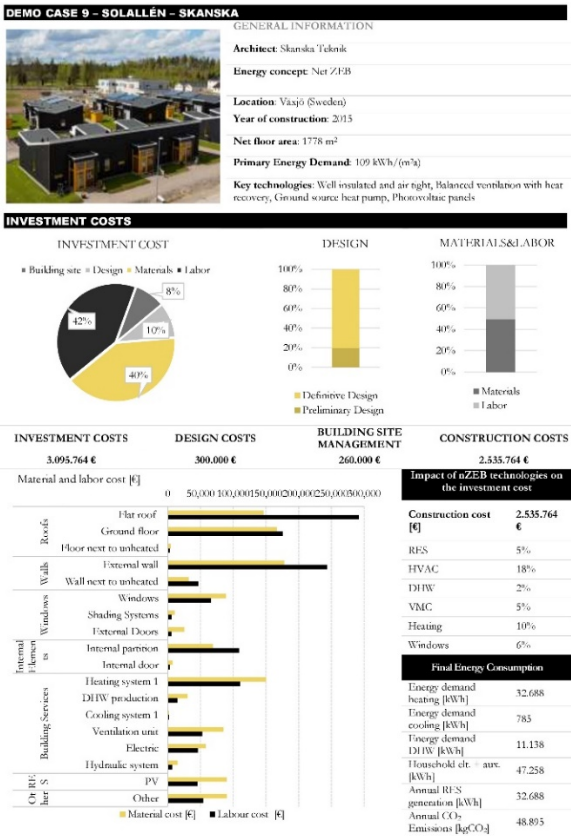

Figure 3. Investment KPIs.

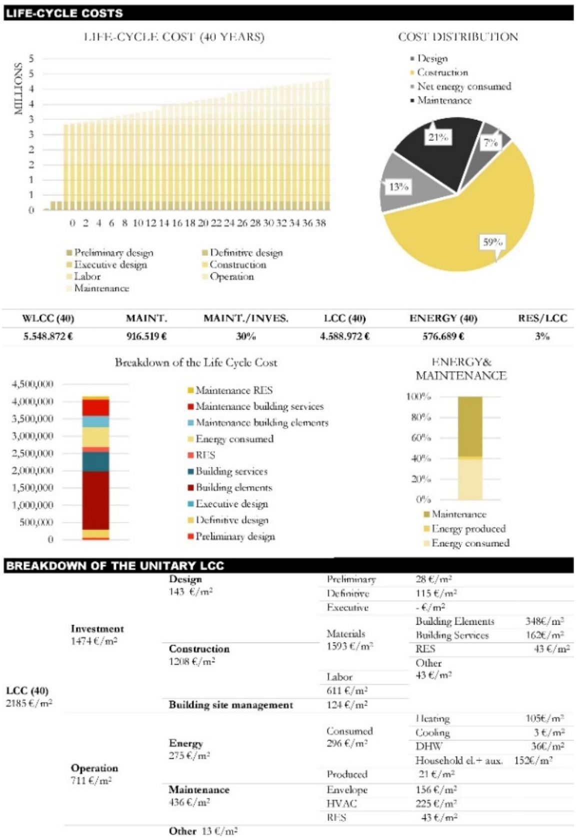

Figure 4. Life-cycle cost KPIs.

7. Comparative analysis

This section reports a general overview of the application of the methodology described in Section 3 and 4 to the CRAVEzero case studies, providing a comparative analysis highlighting the impact of the different phases on the overall LCC is provided. It is important to point out that the results are normalised according to the criteria illustrated in Section 4, in order to ensure the comparability of the indicators. Figure 5 shows the overview of LCC calculated considering a period of 40 years for the twelve case studies, with a breakdown of the cost for each phase. It is possible to point out that design cost has a reduced impact on the LCC, ranging from 3% (Case NH-Tirol) to 15% (Parkcarré), but with an average value of 5%. Cost of materials ranges from around 27% (for the case study Solallén) up to 53% (i.e. Les

Héliades). Since labour costs were in most cases, either not available or included in the cost of materials, a reliable breakdown of the construction costs into materials costs and labour costs was not possible.

As it was expected, for the analysed case studies the energy costs during the life cycle of an nZEB represent a minor component of the LCC, with an average of around 12% (Figure 7). It is important to point out that the contribution from the renewable energy sources (RES) is accounted for as a reduction of the energy cost (calculated as a balance between energy consumed and produced).

Figure 6 shows an overview of the average impact of all the phases on the LCC, the investment costs for design, construction and other initial expenditures is around 54% of the LCC, while the energy and maintenance account for around 44%.

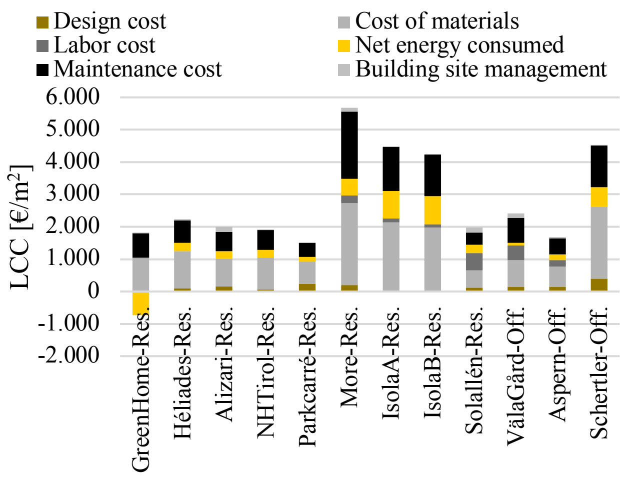

Figure 5. LCC breakdown.

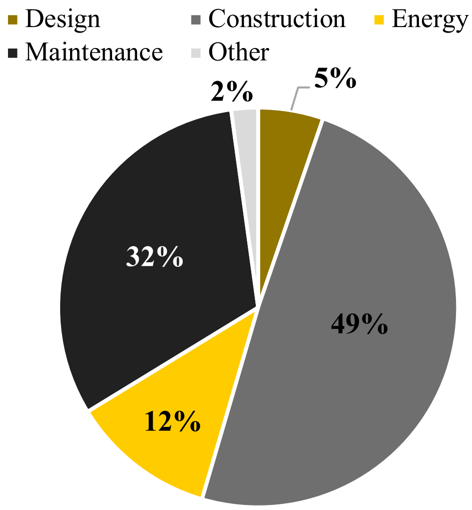

Figure 6. LCC breakdown – average.

Figure 7 displays the energy cost in relation to the average U-value of the opaque components. Figure reports the breakdown of the cost for the building elements, highlighting the impact on the construction costs. It shows that in some cases the structural elements represent a significant contribution to the construction, according to the complexity and the dimension of the building. On the other hand, nZEB related technologies have a small impact on the construction costs, although in comparison to a traditional building the cost for the HVAC system and the integration of renewables is more significant.

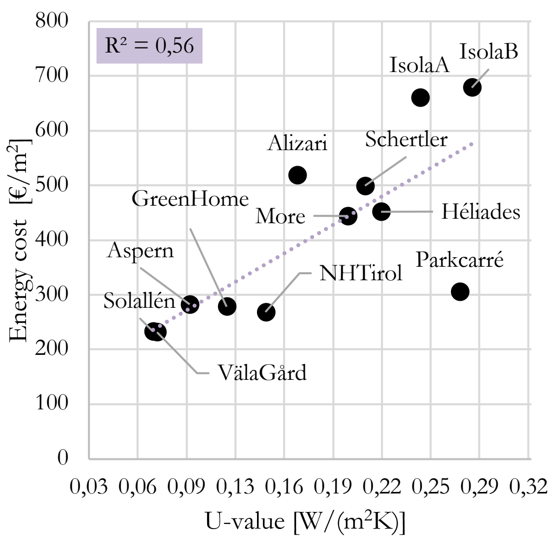

Figure 7. Correlation between energy cost and U-value.

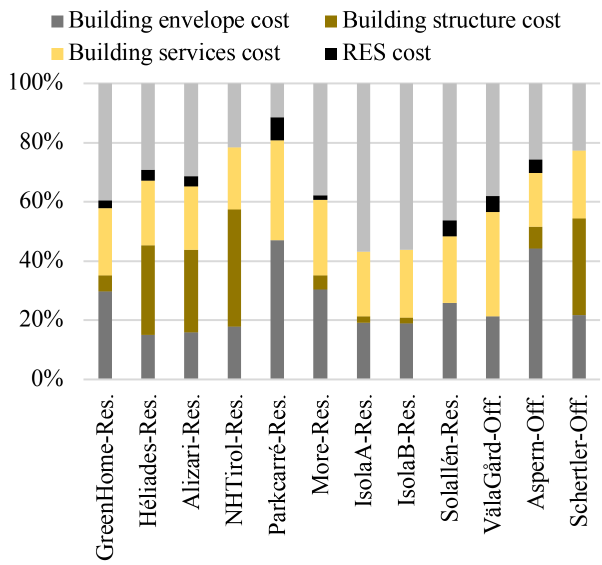

Figure 8. Construction cost breakdown

8. Conclusion and further development

This paper presents an operative methodology for an EU-wide evaluation of Life Cycle Cost, including boundary conditions, reference values, normalisation factors and sensitivity analysis. In addition, it reports an overview of the main results for 12 exemplary case studies analysed within the H2020 CRAVEzero project. The H2020 CRAVEzero project, is going to release an effective tool for producing the nZEB spreadsheet, including all the main indicators for analysing in detail the performances in terms of cost and energy of a building, identifying the main phases and elements affecting both the investment and the Life Cycle Costs. At EU level, a shared and operative LCC methodology and a comprehensive database with detailed building Life Cycle Cost evaluation represent the strategic references for a broader implementation of LCC analyses, providing useful benchmarks for comparison and increasing the reliability of LCC. The broad application of the LCC analysis will foster the market uptake of nZEBs, highlighting the cost-effectiveness and benefits during the life cycle. More information are available on the project website: http://www.cravezero.eu

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Energy and cost optimization in the life cycle of nearly zero energy buildings using parametric calculations

Venus D[1], Weiss T[1], Moser C[1], Hatt T[2], Ploß M[2], Roßkopf T[2]
[1]AEE INTEC, Feldgasse 19, 8200 Gleisdorf, Austria
[2]Energieinstitut Vorarlberg, CAMPUS V, Stadtstraße 33, 6850 Dornbirn, Austria

d.venus@aee.at

Abstract. Possible cost saving potentials in the planning and construction of future building standards are often not sufficiently assessed, as only a few possible variants are considered in the traditional planning process. Often planning and analysis are not carried out in parallel, and the various possibilities are discarded at an early stage. If, on the other hand, several variants are realistically compared in the planning phase, including life-cycle costs, a profound decision can be made. Therefore parameter studies were carried out as part of the national research project "KoPro LZK+" (cost and process optimization in the life cycle of nearly zero energy buildings) for seven buildings, five multi-family buildings, a school and an office building. For this purpose, a VBA macro was programmed in MS-Excel©, which automatically carries out energy demand calculations in the "Passive House Planning Package" (PHPP) and life-cycle cost calculations in the tool "econ calc". A total of more than 216,000 variants were investigated in this way, whereby on the one hand a variety of technologies, such as insulation of the building envelope, ventilation or electricity and heat supply, and on the other hand a variation of the boundary conditions (such as observation period, user behaviour, energy price increases or CO_2 costs) were carried out. The results were analysed energetically and economically over the life cycle (separately from each other and combined) with the objectives of identifying coherences, deriving trends and optimizations over the life cycle.

1. Methodology

In the traditional planning process client, architect and technical planners develop a building with the relevant technical equipment and building services. In many cases, everyone optimizes in "his/her" area, and thus the building project as a whole is being lost out of sight. Thus, it can happen that at the end a building is built and in operation, it turns out that, e.g. the running costs are extremely high. If, on the other hand, several variants are being compared in the planning phase, including life-cycle costs (LCC), a sound decision can be made already in advance. Research and demonstration projects show that it is already possible today to construct new or to renovate buildings to near zero and plus energy standards that achieve extremely low energy consumption and CO_2 emissions and can be operated economically. [1]

The term "parametric analysis" in this paper defines a method in which series of calculations are run by a computer program, systematically changing the value of parameters associated with one or more design variables. The key feature of this approach is that it allows evaluating the effect of individual design variables on energy, costs and environmental parameters in one step. This so-called multi-objective optimization analysis has become more popular in recent years. [2]

The multi-objective approach is based on the concept of Pareto frontier: a solution is optimal when no other feasible solution improves one of the objectives without affecting at least one of the other. In that case, the multi-objective algorithms generate a set of solutions, known as the Pareto front. If the problem includes only two objectives, the Pareto front is a two-dimensional curve. This concept can also be applied to three or more objectives, although the results are more difficult to analyse. This approach seeks to explore a set of optimal solutions rather than to find a single optimal solution. [3]

The difference between a conventional optimization method and the parametric optimization is clearly shown in following figure 1. With the conventional method, only selected technology combinations are checked and compared with each other. The optimization, therefore, takes place within this selection but does not include all possible combinations. This is the big difference between the conventional method and the parametric analysis and optimization. Here, all possible combinations are calculated, analyzed and the optimal variant is determined.

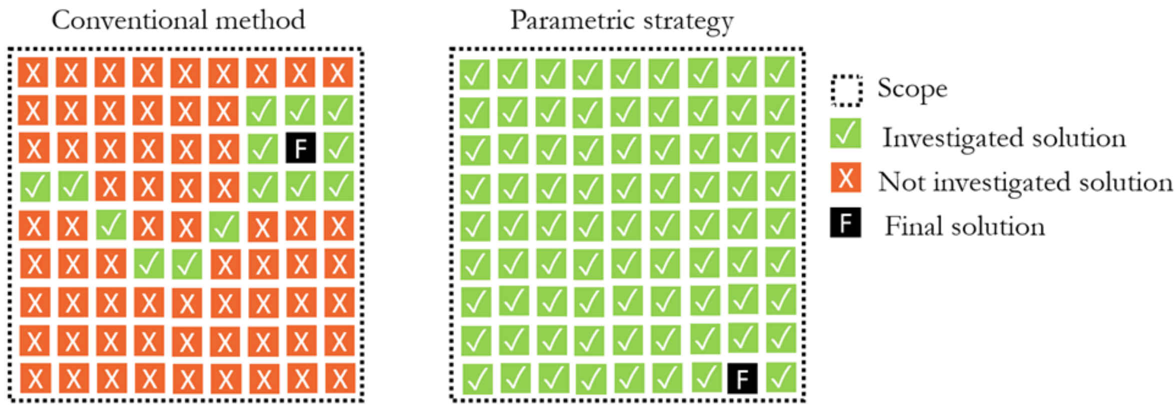

Figure 1. Comparison of conventional optimisation method vs. parametric optimisation [4]

The method of parametric analysis and energy-economic optimization in the research project "KoPro LZK+ - cost and process optimization in the life cycle of nearly zero energy buildings" (https://nachhaltigwirtschaften.at/en/sdz/projects/kopro-lzk-plus.php) follows the order below:

- Design
- Determination of target values and goals
- Determination of the parameters to be varied and their levels e.g. envelope quality, heating system, window size, window quality.
- Energy demand calculations with the "Passive House Planning Package (PHPP)"
- Calculation of the life cycle costs of each variant, taking into account operating costs, maintenance, replacement investments and residual values, using the LCC tool "econ calc"
- Evaluation and presentation of the results.

With this method, more than 216,000 different variants could be calculated in a manageable amount of time for seven prototypical case studies.

2. Investigated Case Studies

In the KoPro LZK+ project, seven buildings were investigated in detail. These case studies were selected so that they reflect a limited cross-section over different uses (multi-family residential, office and school) and include new as well as renovated buildings.

All buildings have already been completed and are in operation, except for one multi-family building, which was still in the construction phase at the beginning of 2019. The investigation of the buildings was therefore carried out after completion of the building. This procedure was chosen because in the short time of the project duration it was not possible to find several real buildings, which were in the planning phase at this time and that can be managed within the research project. However, the examples can be used to show the potentials and commonalities of the projects and to identify the levers and influencing variables. In future construction projects, however, the method shown should be used in the planning process of the building.

To give a short overview of the investigated case studies, table 1 summarizes some facts and figures of the buildings. Table 1 also gives some information about the investigated parameters.

Table 1. Overview of the case studies and the investigated parameters.

parameter	case study 1	case study 2	case study 3	case study 4	case study 5	case study 6	case study 7
use	residential	residential	residential	residential	residential	office	school
gross floor area [m²]	1,495	589	1,822	2,845	1,450	1,283	3,243
treated floor area [m²]	1,212	432	1,421	2,091	1,025	822	2,580
year of completion	2019	2013	2017	2014	2015	2012	2013
utilisation units	15	6	19	32	16	28	-
investigated parameters in all case studies							
building envelope	✓	✓	✓	✓	✓	✓	✓
ventilation	✓	✓	✓	✓	✓	✓	✓
heating system	✓	✓	✓	✓	✓	✓	✓
solar thermal system	✓	✓	✓	✓	✓	✓	✓
PV	✓	✓	✓	✓	✓	✓	✓
energy tariffs	✓	✓	✓	✓	✓	✓	✓
observation period	✓	✓	✓	✓	✓	✓	✓
investigated parameters in selected case studies							
user behaviour	✓	✗	✗	✓	✓	✓	✓
heat distribution	✓	✓	✓	✗	✗	✗	✗
heat emission	✗	✗	✓	✗	✗	✗	✗
construction	✗	✗	✓	✗	✗	✗	✗
household electricity	✓	✗	✗	✗	✗	✗	✗
PV credit	✓	✓	✓	✗	✗	✓	✓
battery storage	✗	✓	✗	✗	✗	✗	✗
electricity tariff model	✗	✓	✗	✗	✗	✗	✗
funding model	✗	✓	✗	✗	✗	✗	✗
CO_2 follow-up costs	✗	✗	✗	✗	✓	✗	✗
number of investigated variants							
variants	53,000	49,000	75,000	7,300	5,800	23,000	3,500

The construction costs for the seven example buildings were provided by the project partners. The costs for the investigated technology options were provided directly by the property developers or building services planners or derived from other reference projects. The costs for the PV systems were derived exclusively from current market prices, as there has been a significant cost reduction in recent years. All costs are stated as net costs, excluding VAT. Furthermore, land costs were not taken into account in all projects, as they can strongly distort the life cycle cost analysis.

As the buildings were built between 2013 and 2017, the costs cannot be directly compared. To ensure some comparability, the costs for all case studies have been index-adjusted to the year 2017. Since the costs in the KoPro LZK+ project are viewed more from the buyer's or user's point of view, the construction price index was used. The indices are given with different reference years (2015, 2010, 2005, 2000, 1996...).

The interest rate for the bank rate has been set at 3.0% nominal for the 25 year credit period. The current rate for the 10-year fixed rate is around 1.8%. The inflation rate is set at 1.7%. The principal or discount rate is set at 3.0% nominal, similar to the bank rate.

3. Example multi-family building “+ERS” (case study 5)

3.1. Description of the case study. The project “Plus Energy Network Reininghaus Süd (+ERS)" is an integral part of the "Energy City Graz-Reininghaus (ECR)" project and follows the specifications of the overall urban planning framework. The project is divided into two sections: part 1 is an office and business complex with residential use on the upper floors, part 2 consists of 12 multi-family houses with 162 residential units in total. In the national research project KoPro LZK+, one of the 12 multi-family buildings was investigated in detail. All results in chapter 3.3. refer to this building, which is shown in figure 2.

Figure 2: +ERS - Plus Energy Network Reininghaus Süd (source: Martin Grabner)

3.2. Variants and sensitivity analysis. Table 2 shows an overview of the investigated technologies. For each technology, different parameters were varied, which can be classified into a maximum of three levels.

Table 2. Overview of the investigated technologies and parameters.

Parameter	level 1	level 2	level 3
building envelope	passive house standard	national regulation	-
ventilation	mechanical ventilation with heat recovery	window ventilation	-
heating system	ground source heat pump + earth piles	ground source heat pump +ground collector	air source heat pump
photovoltaics (PV)	no PV	medium-sized PV	large-sized PV
solar thermal system	no solar thermal system	solar thermal system for DHW	solar thermal for DHW + heating

In addition to the technologies also some boundary conditions were varied like user behaviour, the energy tariff, energy tariff increase, the calculation period and CO_2 follow-up costs. Table 2 shows, for example, the assumptions for the investigated user behaviour.

Table 3. Investigated user behaviour and assumptions.

user behaviour	room temperature in winter	DHW demand (60°C)	additional shading in winter due to misuse of external blinds	additional window ventilation in winter due to misuse
ideal	21°C	25 L/pers/d	+ 0%	+0,00 1/h
standard	22°C	30 L/pers/d	+10%	+0,05 1/h
inefficient	23°C	35 L/pers/d	+20%	+0,10 1/h

3.3. Results. This chapter contains some selected results of the many calculations available. All results with detailed descriptions can be found in the final report of the national research project under the link: https://nachhaltigwirtschaften.at/en/sdz/projects/kopro-lzk-plus.php and on the website of AEE INTEC (https://www.aee-intec.at/index.php?params=&lang=en).

To analyse the energy performance in combination with cost efficiency scatter plots were used. Each technology was analysed separately and in combination with other technologies.

For every single technology, the net present value was compared to the balanced CO_2 emissions and the balanced primary energy demand. The results of this analysis are shown in following figure 3. "Balanced" in this case means that the self-consumption of the PV system was considered, transferred into CO_2 emissions (and in into primary energy) by the conversion factors for electricity and then subtracted from the calculated CO_2 emissions (respectively primary energy demand).

Written as a formula, the balanced CO_2 emissions were calculated as follows:

$$CO_{2\_balanced} = CO_2 \left[\frac{kg}{m^2a}\right] - PV\ selfconsumption \left[\frac{kWh}{m^2a}\right] \times electricity\ conversion\ factor\ [\frac{kg}{kWh}]$$

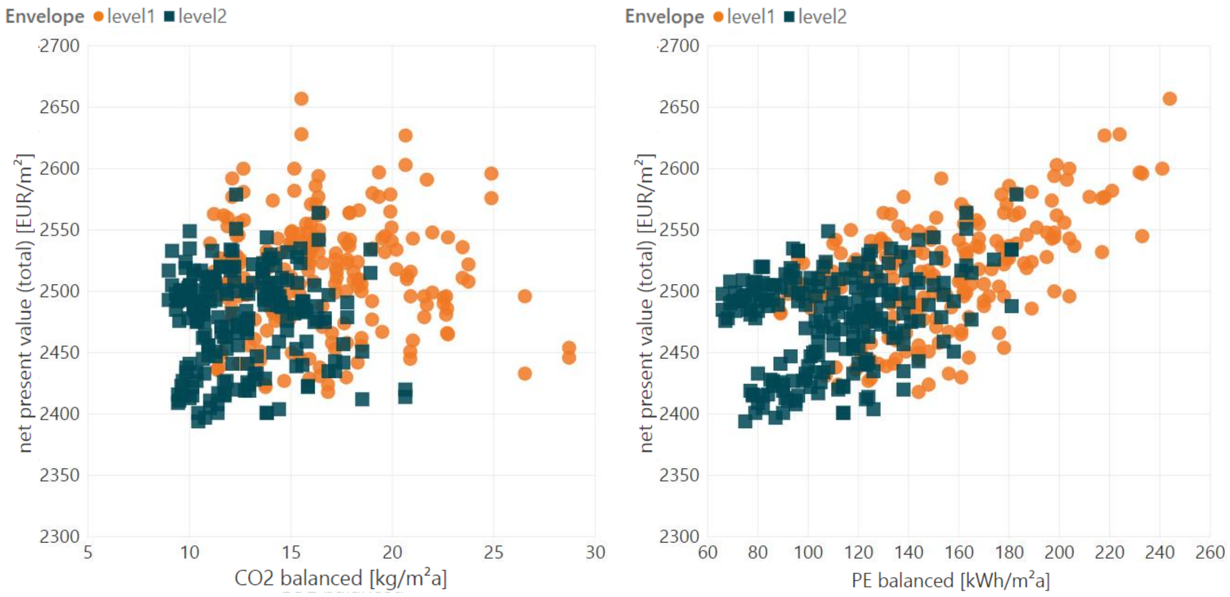

Figure 3. Analysis of the influence of the building envelope on the net present value, the balanced CO_2 emissions (left) and the balanced primary energy demand (right) (related to treated floor area of the PHPP / energy tariff standard / user behaviour standard / CO_2 and PE factors OIB RL-6 2015 / without consideration of subsidies / no CO_2 or PE credit for electricity fed into the grid).

Figure 3 shows the influence of the building envelope on the net present value, the balanced CO_2 emission and the balanced primary energy demand. The analysis shows that the improvement of the insulation from level 1 to level 2 leads to a reduction of the CO_2 emission and the primary energy demand, and also to a reduced net present value. Looking at the whole life cycle of the building it is, therefore, advisable to improve the quality of the building envelope, in this case to passive house standard.

In further consequence, the sensitivity of the individual technologies to the indicated performance indicators "balanced CO_2 emission", "balanced primary energy demand", "financing costs" and "net present value" was investigated. For this purpose boxplots were produced to show the sensitivity of all investigated technologies on the named indicators. These results indicate the sensitivity of the investigated performance indicators for the multi-objective building life-cycle cost and performance optimisation.

The analysis was done in two parts:

- Part 1: Technologies that could be counted as "energy efficiency measures" or "passive measures", like insulation of the building envelope or mechanical ventilation.
- Part 2: Technologies counted as part of the "energy supply system" or "active measures", like heating system, solar thermal installation and PV system.

When the difference in median value and the standard deviation is small, it is assumed that the indicator is not sensitive.

Figure 4 shows as an example the sensitivity of the energy supply measures on the defined indicators.

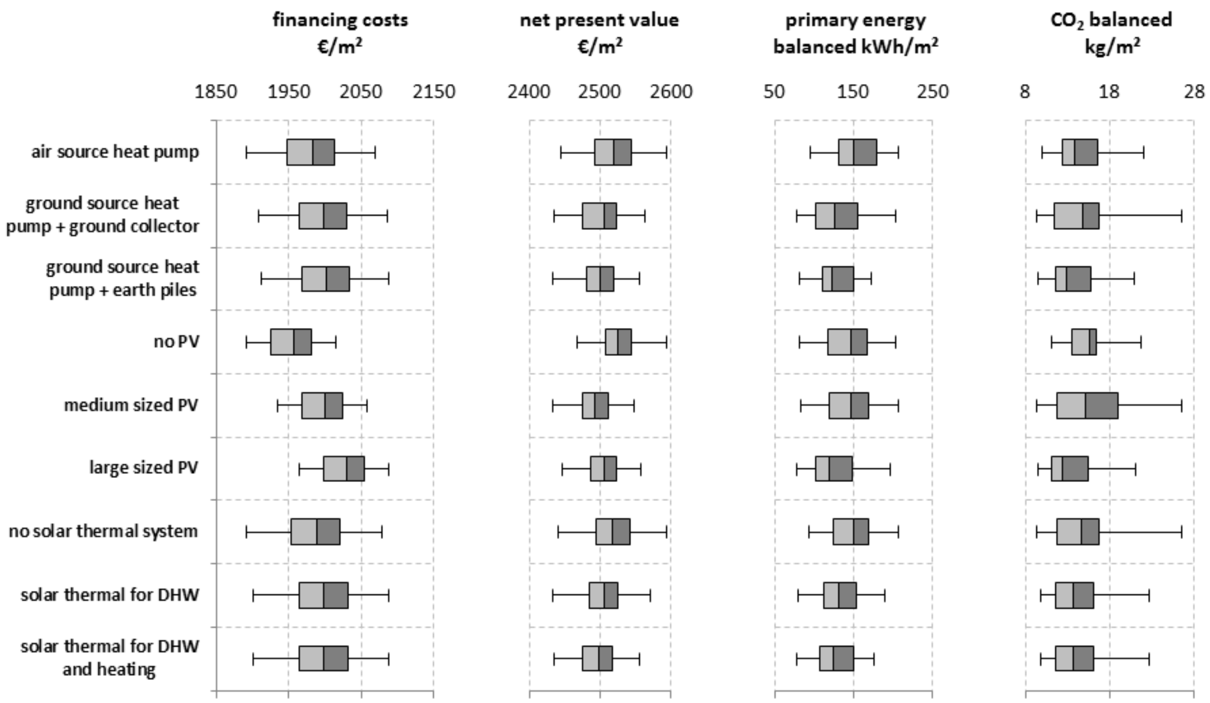

Figure 4. The sensitivity of the financing costs, the net present value, the balanced primary energy demand and the balanced CO_2 emissions to the energy supply measures (heating system, PV and solar thermal system)

All results from the project were integrated into an interactive web-based guideline for zero and plus energy buildings, which makes it possible to evaluate all variants individually. This means that estimations of cost and energy reduction potentials can be analysed at an early stage of the project using the example buildings (see https://www.aee-intec.at/kostenreduktion-plusenergiegebaeude-n-koprolzk-p218).

4. Lessons learned

Determining the best global solutions for nearly zero energy buildings design variables, in terms of energy, environmental and cost performance, is not an easy task, mainly because the variables affect each other through processes that are often not linear, and the optimisation goal of each variable can change significantly based on the optimisation goal and the importance of the key performance indicators (e.g. financing costs, net present value, primary energy demand, CO_2 emissions).

The assumption that the additional costs of energy efficiency measures are so low that energy efficient buildings have the lowest life-cycle costs can now be confirmed by the investigation of seven example buildings (with different use / new constructions and renovations). Energy efficiency measures have only a small percentage influence on construction costs but can save many times more CO_2 emissions. Regarded over the whole life cycle of the building, these efficiency measures are then usually cost-neutral or even economical.

In detail the results of the evaluations within the national research project KoPro LZK+ can be summarized as followed:

- The energy efficiency level has only a small influence on building and construction costs. Energy efficiency is therefore not a significant cost driver.
- For most technologies, the additional construction costs of energy-efficient variants are compensated over the life cycle of the building even without subsidies.
- Considering the life cycle costs, the primary energy demand and the CO_2 emissions the optimum is in the range of passive houses. Passive house envelopes and highly efficient

windows are in most cases economical even without subsidies. This is due to the long service life of these components in comparison to the building services.

- The optimum for life-cycle costs and CO_2 emissions are very flat. Low emissions and energy consumptions can, therefore, be achieved with different energy concepts as long as the building envelope is very efficient. This allows creative and conceptual freedom.

It is shown that energy efficiency and economic efficiency are not contradictory strategies, but can complement each other very well. The selection of variants according to life-cycle costs, therefore, makes sense and should be increasingly used as a decision criterion.

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Contradictions of low-emission nZEB buildings

Severnyák K

University of Debrecen, Hungary

severnyakk@yahoo.co.uk

Abstract. Based on the EPBD 2010 directive and the mandated method of cost-optimum calculation the forthcoming national regulations require “nearly zero energy buildings” which have high energy performance, significant share of renewables in covering the low energy need and harmonizing the requirement system and the cost-optimum all over in Europe. Known intention of the EU Member States as well as some research reports create the impression that predominant use of biomass in the forthcoming years will be the right way to fulfil the above requirements of nearly zero energy buildings. Taking advantage of regulations in many Member States, the amount of yearly primary energy demand is favourably influenced by the low primary energy conversion factor determined by the very states; besides the delivered energy does not decrease. The CO_2 neutrality of biomass is not real. It is true that the emission of gas firing far exceeds that of wood firing, but emissions from the production of natural gas might be lower than that of the production of certain wood products. Overall, the lifecycle-based emission of biomass firing for the most converted fuels is already significant. In the case of wood combustion, the local pollutant emissions, which occur in cities, are significant, while the CO_2 constraint take place in the forests.

1. Introduction

Based on the European Parliament’s directive published in 2010[1], all new buildings built after 31 December 2020 within the EU should meet the requirements of nearly zero-energy buildings.
According to the definition, these buildings must be characterized by low energy consumption and extensive use of renewable energy. The European Union has entrusted the Member States to set a maximum primary energy consumption requirement for nearly zero-energy buildings, which varies from one Member State to another.

The maximum value of the energy consumption of nearly zero-energy buildings is determined per year and floor area in primary energy. The method of calculating the yearly energy consumption is determined by the Member States individually (figure 1).

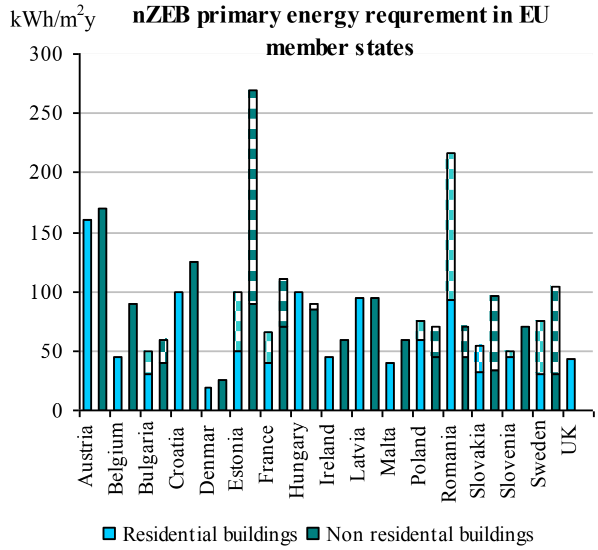

Figure 1. The primary energy demand for NZEB buildings in some EU Member States BPIE [2] (including renewable energy use).

The regulation gives Member States a broad opportunity to define the criterion, and this criterion can be met in a number of favorable computational ways.

2. Primary energy calculation mode interpretation in the EU

Buildings use heat, electricity, or mechanical energy. Different forms of useful energy must be converted into primary energy for comparability. Renewable and non-renewable energy sources such as coal, crude oil, natural gas, water energy, wind, and solar radiation found in nature are so-called primary energy carriers. Most of them are not used directly, but after conversion. The conversion into a directly usable energy carrier, such as gasoline, diesel, electricity, involves energy use and losses. The magnitude of the loss depends on the degree of conversion and the technology used. In Hungary, for example, the primary energy conversion factor for electricity (e) equals with 2.5 determined by the current regulation, which means that by investing 2.5 kWh of primary energy we get 1 kWh of useful electricity.

Member States of the European Union use primary energy conversion factors (e) with different values for the same energy carrier, that is, they determine their primary energy consumption individually depending on the energy, loss and other factors of the conversion of energy carriers[3]At the same time, these conversion factors may conceal central subsidies or other incentives that may cause energy consumption results to be subjectively distorted in individual Member States. The e-factor is set by the Member States on a subjective basis, mostly according to their own energy policy[4]. However, this should be an energy statistics parameter that could be determined by statistical measurements by tracking energy paths to territorial and / or consumer groups.

Most decision-makers in the EU are convinced that the nZEB requirement could be met with a widespread use of biomass [5]. As an example, the conversion factor for biomass energy is 0.6 in Hungary, 1.08 in Austria and 0.2 in Slovakia. Considering an example building, the same amount of fuel on the opposite sides of the border shows a completely different level of total primary energy consumption in Hungary, Austria and Slovakia. In many Member States, the primary conversion factor for biomass is surprisingly low (figure 2), which results in low total primary energy consumption simply by conversion factors. This way only the total primary energy use is reduced, not the heat demand.

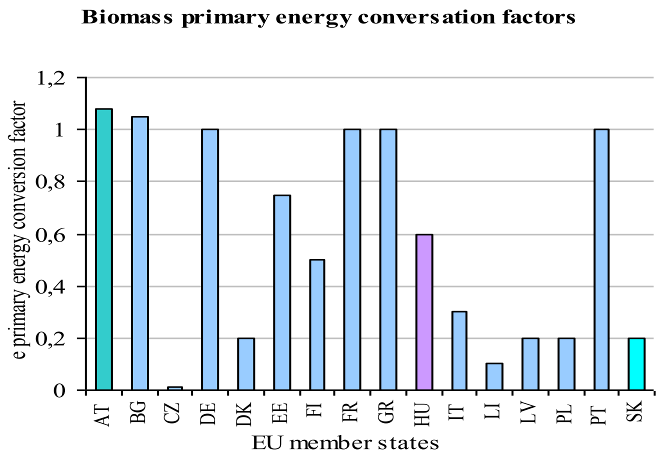

Figure 2. Primary energy conversion factors for biomass in some Member States

Let us calculate [6] [7] and compare the primary energy need of identical buildings on the opposite sides of the Hungarian-Austrian and Hungarian-Slovak borders. The sample building is a one-storey single-family house with a floor area of 100 m^2 made from manually built building blocks, widely used in Hungary between 1960 and 1980. Assuming the same environmental conditions the primary energy demand for heating the building is not the same in the three countries if biomass is used. The buildings were just a few meters away from each other on the opposite side of the border, and locally processed forest tree was used as fuel, which requires minimal processing (figures 3,4).

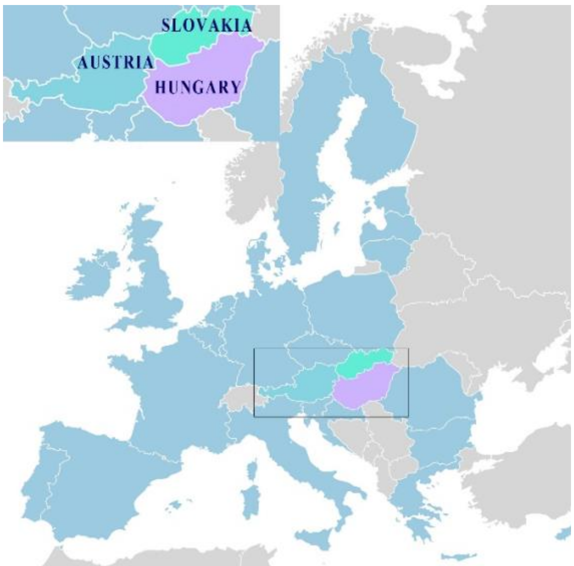

Figure 3. Austria-Hungary-Slovakia neighbouring countries

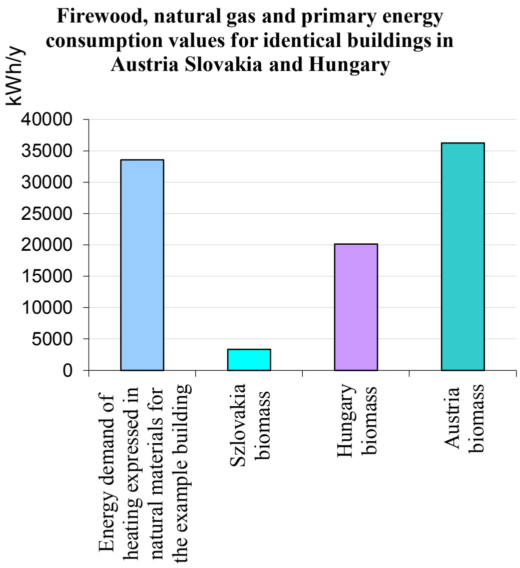

Figure 4. Energy need in identical buildings in identical climatic zone- from left to right: in delivered energy, in primary energy in Slovakia-Hungary-Austria

The truth is when different fuels are used, consumption of the sample Hungarian building shown in figure 5, taking into account the efficiency of the system, and the primary energy conversation factors more primary energy carrier is needed when using biomass.

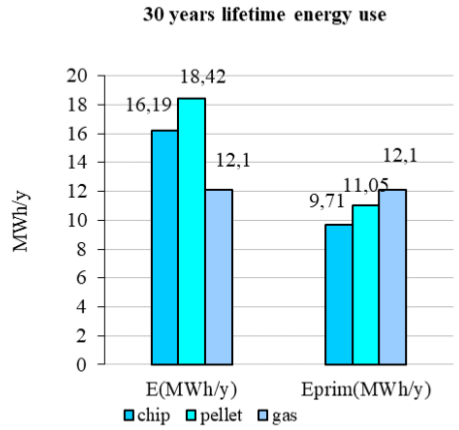

Figure 5. Primary energy and energy carrier consumption of the sample building

3. Fulfilment of nZEB building criteria in EU member states

Biomass use is expected to be the key to solving the problem of high renewable share of nZEB buildings. Biomass as an energy source can be renewed, but it has limitations. If we only look at the heat demand of buildings, it is likely that the growing demand for biomass poses a risk to resources and will result in rising prices (not to mention the biomass needs of thermal power plants, which is an important source of green electricity in Europe) [8].

Scientists, looked at the dynamic simulations of a single-family house and an office building in four representative European climates [2]. The results of each study put biomass use in the centre. This approach is reflected in the plans of some Member States which includes the share of the various renewable energy sources planned to be used in the future.

With some simplification, Member States distinguish renewable sources for heat production for example: solar, geothermal, biomass, heat pump, (the amount of heat or electricity generated above the needed auxiliary power).

Although this classification is not considered consistent, these data are available (figure 6).

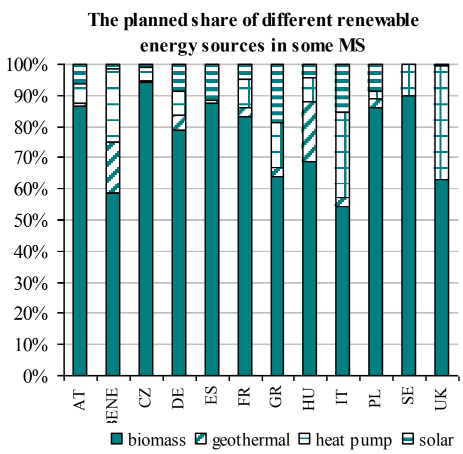

Figure 6. The planned share of different renewable energy sources in some member state [9]

However the acquisition of biomass fuel in the European Union is difficult for many Member States, e.g. GB imports from the USA, whilst Denmark from the Baltic States. [8].

4. Cost optimum requirements within the EPBD

"EPBD Recast" sets additional criteria for increased energy efficiency. EU Member States were asked to draw up action plans by 2020 and radically reduce energy consumption according to specific milestones. Member States shall regulate their own national energy criteria, which should be reviewed every five years. The Commission has published its regulation in support of the review and the Member States were asked to take into account the methodology and the criteria [10].

The methodology requires the identification of cost-optimal energy criteria for buildings and building elements. The primary energy consumption of buildings found in the energy certificate and the global cost of buildings, which consists of the sum of the present value of the initial investment costs, sum of running costs, and replacement costs (referred to the starting year), as well as disposal costs if applicable., are considered as the basis for the determination of the optimum.

Based on this method, the Member States calculated the costs of building renovating and maintaining optimum-including operation costs. The calculations had to take into account the national legislation in force in the Member States. Under the EPBD Regulation, the national minimum energy performance requirements should not deviate from the cost-optimal calculations by 15%. The cost-optimal level shall lie within the range of performance levels where the cost benefit analysis calculated over the lifecycle is positive [11] figure7.

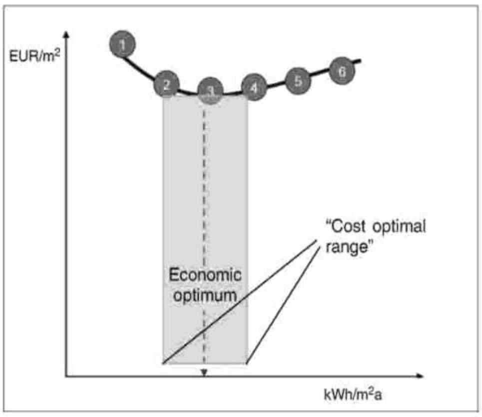

Figure 7. Cost optimum range by the EC

Based on the results, biomass use was highlighted by several advisory organizations supporting the Commission. Hungarian calculations also showed that progressive passive renovation and the complex renewal of engineering system to biomass use should be optimal. [6]

5. Cost aspects

In Hungary, the calculation underlying the report was prepared by Energiaklub Climate Policy Institute and Applied Communications; we studied a total of 15 reference buildings. [6]

The biomass fuel based optimum of nearly zero-energy buildings is shown through the cost optimum analysis of one of the reference buildings.

This type of building is typically a cube-shaped building constructed of B30 blocks, so-called "Kádár kocka" or "Kádár cube" (Hungary's leader between 1956(1961)-1988) based on the survey of the Energiaklub Negajoule2020 [11]. Built between 1960-1980, two-bedroom house with gas convector heating, gas-boiler hot water producing equipment. The typical annual energy consumption of the building is 38,520kWh / year, the CO2 emissions are 7.82t / year, calculations based on the 7/2006 Decree by the Minister without Portfolio of Hungary. [12]

The B30 block was a modern building unit in the Hungarian building materials market from 1960 to 1980. According to the data of the Hungarian Central Statistical Office based on the 2011 census data, of the stone, masonry unit buildings (2.48 M), more than 800,000 buildings could be built masonry units, therefore it can be considered a typical type of building in Hungary's single-family housing stock (figure

8). According to the result of the analyses, the optimum renovation of this building will result in an nZEB building.

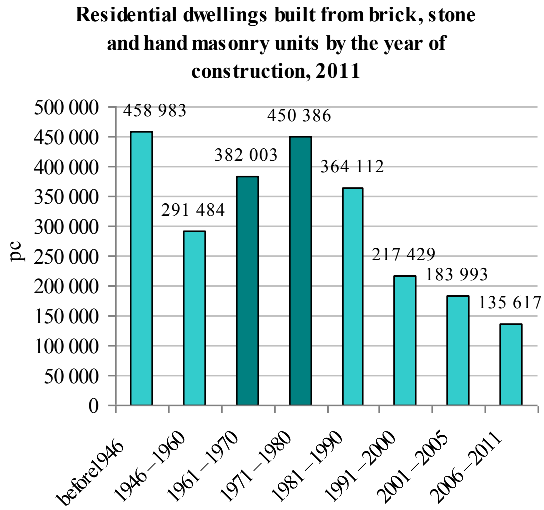

Figure 8. According to the data of the Hungarian Central Statistical Office, the census data prepared in 2011: by the building material of residential homes

According to the published methodology, Member States had to determine energy performance requirements for buildings in order to optimize costs. Examination was mandatory both at the level of the annual energy consumption of buildings and that of building elements.

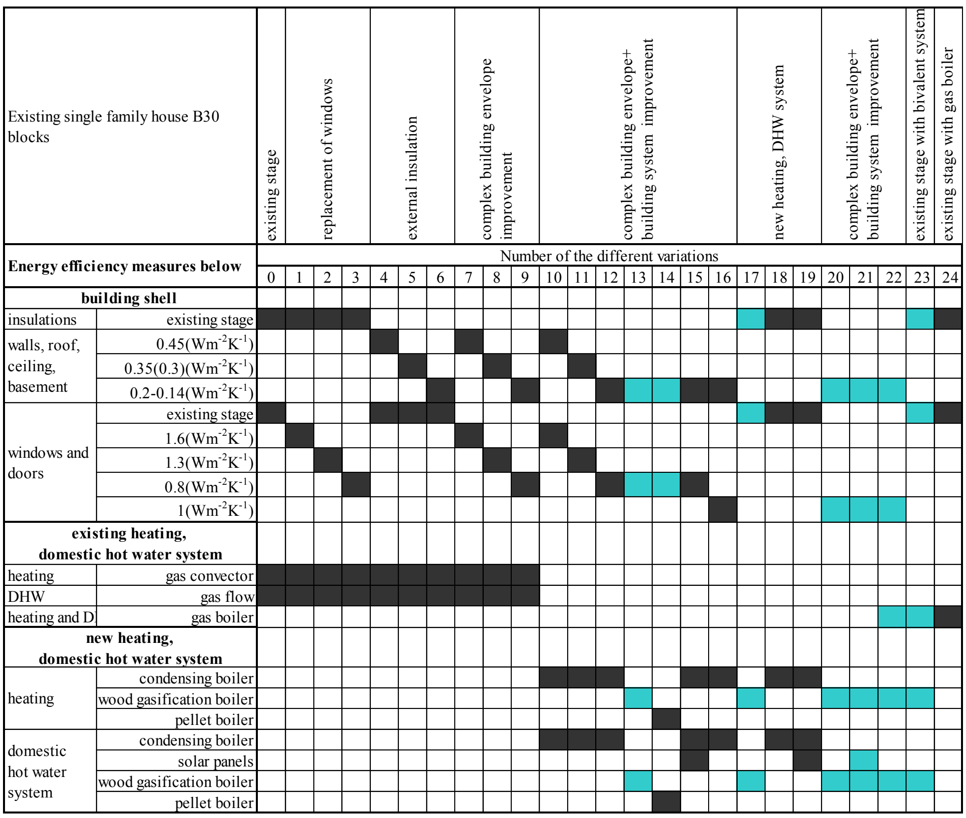

Table 1. Building shell and energy system versions for a reference single family house

The examination followed the next steps:

In the first step, the heating demand was reduced from the moderate to the progressive level by modernizing the energy performance of the building shell (wall, attic, cellar thermal insulation and replacement of windows), by building elements and their combination, and then such combinations were examined. Following the reduction of heat demand, combined alternatives were analyzed with various engineering solutions and the use of mandatory renewable energy sources. calculations based on the 7/2006 Decree by the Minister without Portfolio of Hungary. [12]

In the reference single family house, we looked at 24 really feasible alternatives for modernization. For combinations, see table 1. The results of the analysis are given in figure 9. The optimum solution No.20 is a complex refurbishment, based on wood heating.

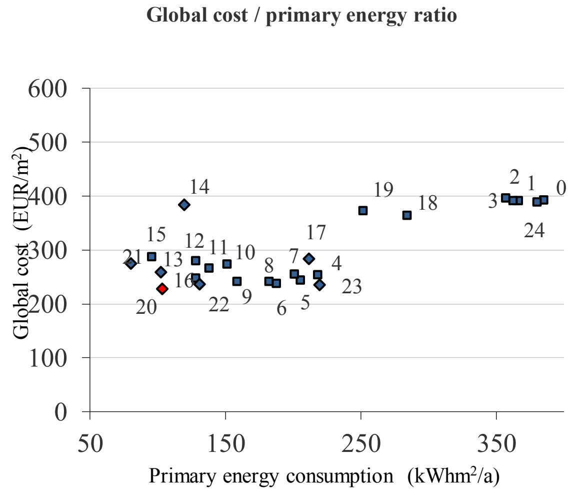

Figure 9. Global cost (EUR) in function of building shell and energy system combinations. Numbers identifies the combinations in Table 1.

However, the life-cycle CO2 emission examination of biomass firing, it can be established that it is by no means CO2 neutral. Depending on the fuel, fuel production and transport may show significant CO2 emission values which might be even higher than those of the production of natural gas.

During our research, we have examined whether life-cycle CO2 emissions show higher values for biomass or natural gas use, considering different transport distances.

Harmful emissions of buildings calculated by life cycle have been determined in two parts.

5.1. Emissions from fuel production and transport

a, CO_2 emissions during biomass production and transport (pellet, chip) was calculated on the basis of the Solid and Gaseous Biomass Carbon Calculator 2.0. [13] The calculator uses the Life Cycle Analysis defined in Renewables Obligation Order [14] and in the Renewables Obligation, in the Ofgem Sustainability Criteria Guide [15].

Our calculations were carried out with the delivery of the fuel to the house included.

During the calculation, the following phases can be considered in the user chain:

Chip production:
1, Corp production (fully for firing)
2, Harvesting
3, Drying (artificial, natural)
4, Raw material transport (by land to place of processing)
5, Biomass processing / conversion to chip
6, Fuel transport (by land to storage)

7, Storage
8, Fuel transport (by land to place of use)

Pellet production
1, Corp production (fully for firing)
2, Harvesting
3, Raw material transport (by land to place of processing)
5, Biomass processing / conversion to pellet
4, Drying (artificial,)
5, Biomass processing / conversion to pellet
6, Fuel transport (by land to storage)
7, Storage
8, Fuel transport (by land to place of use)

In the production of chips and pellets, the following CO_2 emission values were received taking into account the production-specific production chain. (figure10).

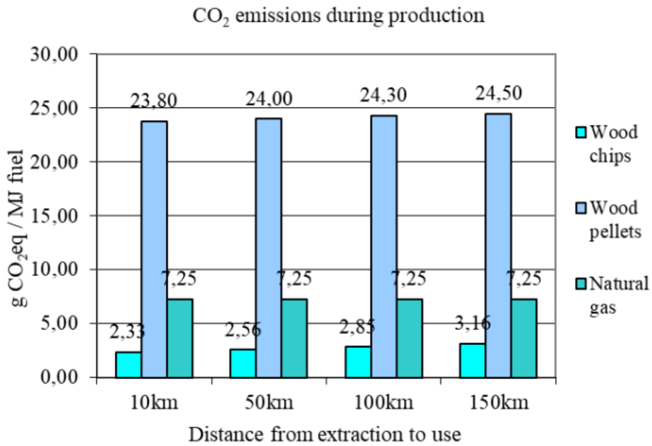

Figure 10. CO_2(g) emission of biomass production

b, Emissions from the production and transport of natural gas come from the SHALE GAS UPDATE FOR GHGENIUS study by (S&T)2 Consultants Inc. [16]. The emission value given in the report is as in Table 2.

Table 2. Emission value for producing natural gas

Natural Resources Canada	g CO_2eq / MJ fuel
Natural gas upstream emissions	7, 25

The method of calculating the emission values of natural gas production and the size of the final result vary by country, but for comparability, the above two results are accepted because of the available and traceable calculation method.

5.2. Annual CO_2 emissions of the reference building according to EPBD calculations

a, When using chip
b, When using pellet
c, For natural gas

The calculation methodology is based on the EPBD directive. The amount of carbon dioxide produced during the combustion of wood was constraint during the growth of tree. This constraint in the forest has improved the air quality of the environment. During combustion, emission happens in a residential environment (if not power plant use), so that the emitted pollutants return to the living environment and pollute it. The final results are aggregated to give CO_2 emissions values for producing natural gas and biomass during 30 years lifetime of the sample building (figure 11) as it is calculated in Table 3.

Table 3. Emission value for producing natural gas

Domestic hot water + Heating production	Energy demand E(MWh/y)	Energy demand E(MJ/30yrs)	Fuel carbon intensity (g CO2eq / MJ fuel)	CO2 emission of fuel production of sample building during 30 years (g CO2eq)
chip	16,19	1748520	2,33	4 074 020
pellet	18,42	1989360	23,80	47 346 768
gas	12,1	1306800	7,25	9 474 300

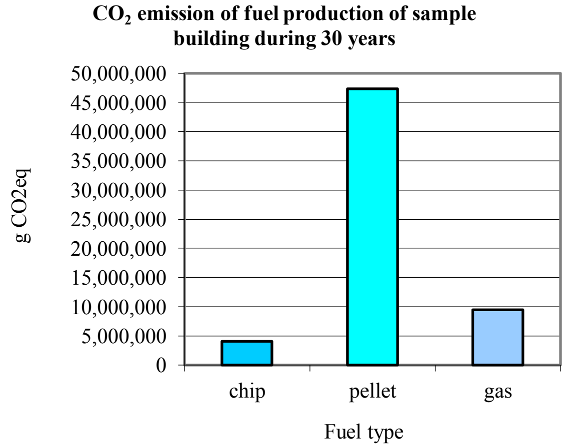

Figure 11. CO_2 emission of fuel production of sample building during 30 years

6. Summary

Cost-optimal calculations, as defined by the European Commission, have in many cases resulted in a biomass renewal version as cost-optimal, on the basis of which EC advisors recommend the use of significant biomass at nZEB buildings.

These studies do not take into account that:

Biomass production has territorial limits in many EU countries.

Taking advantage of regulations in many Member States, the amount of yearly primary energy demand is favorably influenced by the low primary energy conversion factor determined by the very states; besides the annual heat demand does not decrease in naturals. Therefore, nZEB buildings may use more energy through biomass firing than in gas heating.

The Commission advisers suggest that biomass fuel should be used to reduce CO_2 emissions, even if the availability of this fuel is limited in Europe. The CO_2 neutrality of biomass is not real. It is true that the emission of gas firing far exceeds that of wood firing, but emissions from the production of natural gas might be lower than that of the production of certain wood products. Overall, the lifecycle-based emission of biomass firing for the most converted fuels is already significant. In the case of wood combustion, the local pollutant emissions are significant, while the CO_2 constraint occurs in the forests.

Acknowledgements

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Design transformation from standard conformity to Net Surplus Energy

Trinius W

Ingenieurbüro Trinius GmbH, Barmbeker Str. 9a, 22303 Hamburg, Germany

trinius@trinius.de

Abstract. The energy performance of buildings directive requires all new buildings to be near zero by 2020. With that target year approaching, the lacking definition of what "near zero" actually means becomes increasingly prominent. While a weak definition threatens to undermine credibility of near zero claims, it is both environmentally profound, technically feasible and beneficial with regards to user qualities and indoor comfort aspects to plan and build net surplus energy and carbon neutral houses.
One goal of the project was to demonstrate that established building developers can shift their building practice to deliver surplus energy homes – without leaving their range of experience.
After analysing the base-line-design, incremental improvements focused on optimising the building envelope, including thermal bridges, air-tightness, fault-free insulation. The remaining energy demand is covered entirely from locally available renewable sources. Key elements are building integrated PV and power storage, geothermal heat pump for heating and warm water, ventilation system with heat recovery and LED lighting.
The PV installation is designed to generate more than twice the energy needed by the building and the users, providing that surplus to electric mobility applications. Displacing electricity purchased from the grid and displacing fuel combusted in vehicles is key to life cycle carbon and cost optimisation.
Energy efficiency is not in conflict with user comfort, especially not with daylight aspects or with architectural design. The successful merger of a wide range of sustainability aspects was highlighted by this building being category winner of the international activehouse awards 2018.

1. Introduction

Buildings account for 36% of global final energy consumption and nearly 40% of total carbon emissions [1] [2]. These generalised numbers include the energy demand in building operation as well as material-related contributions. Despite increasingly restrictive regulation on the energy demand of buildings in operation, the use stage typically remains being the main contributor to the life cycle environmental impacts of buildings.

Consequently still, the key strategy to reduce building related environmental impact remains to optimize the building layout to create a profound basis for energy efficiency; to energy demand in operation and to optimize the supply of the remaining energy demand, preferably under consideration of locally available renewable energy sources. While successfully optimizing the building however, material-related environmental impacts will increase in their relative importance, and from a certain energy performance level on, the strategy for further improvements will need to increasingly consider the materials.

The European energy performance of buildings directive [3] defines the target that all new buildings are to be “nearly zero energy buildings” by 2020. Currently, there appear to be two major problems associated with that target. Firstly, it is not defined what “nearly zero” actually is. This leaves room for interpretation when national or regional authorities are to apply the directive in their building regulation. Further, if buildings are to be nearly zero by 2020, this would need to be planning reality today. Planners ought to design buildings with highest levels of energy performance as standard practice. Meanwhile planning reality appears to be far behind.

2. Practice Case

This built case is based on the rather unique setting, that we as sustainable building consultant are the owner and user of the building. Often claimed lack of interest of the building client being a core obstacle to design and develop energy efficient buildings here obviously was not the case. Due to contractual agreements of the former owner of the plot, the building site was linked to a building developer, neither the selection of an architect or the building company was free.

The initial key task was to find a route that would enable the owner to get the desired surplus energy building without forcing the construction company into solutions, obligations or liabilities beyond their experience. Not including these performance goals into the contracts and at the same time acting as consultant to the designers and buildings solved these concerns. Consequently, the design optimization started with an analysis of the typical construction solutions applied by the company, and by acting as energy and sustainability consultant to the design team.

3. Conceptual Design

Besides the initial design and room concept, the ambition to create at least a net zero energy building, was set.

The ambition on energy performance was paired with the explicit vision on the future living environment, with key aspects of a melting interior-exterior boundary where rooms would expand from the inside to the outside, and where the availability of daylight with the experience of daytime and seasonal shiftings was a paramount interest.

The distribution and orientation of rooms followed a detailed discussion and analysis of how and when rooms would mainly be used. At those times, they ought to have daylight access and views to preferably at least two directions. The orientation to access to sunlight as well has a positive influence on the energy demand, where however care must be directed to both the winter-case as well as the summer-case.

The L-shaped footprint with rather narrow dimensions allows all rooms with a residence function (living room, kitchen/dining room, master bedroom) to be flooded with daylight from two opposing directions. The living room features a floating gallery, open to the second floor’s roof top, including north-faced skylights. The shape of the room acts as a light-chute.

Inspired by the active house concept [4], health, comfort and wellbeing, energy performance, environmental aspects and an overall feasible economy were the paramount objectives for the building design.

4. Active House Concept and Sustainable Building

The active house vision states that “Active Houses are buildings that create healthier and more comfortable lives for the occupants without negative impact on the climate – moving us towards a cleaner, healthier and safer world.” [4] Compared to sustainable building assessment schemes, like for instance DGNB [5], the scope of considered aspects is focussed on selected aspects, but still addressing a wide range of issues, a full comparison can be found in [6].

A stand-alone single family building is often challenged from a sustainability perspective, as an array of aspects are typically difficult to mitigate. Due to their extensive use and their typical location, single family buildings show disadvantages in terms of area demand, influence on urban sprawl, generation of traffic load, demand in infrastructure and - measured per useful floor area – relatively high material and energy demand.

On the other hand, smaller houses often show a realistic potential to supply their energy demand from building or site integrated renewable energy sources. The relatively large roof areas and the site here provide advantages.

The ambition in terms of sustainability was that the building would generate the building related energy demand locally from renewable sources, would supply the users energy demand as well, and would generate an additional surplus to provide electricity for a significant share of the commuter traffic to be carried out by electric mobility solutions.

5. Design Transition and Result

The beforementioned starting situation included a selected construction company having no practice in the design or construction of zero-energy buildings. The applied material and construction method rely on massive construction, including concrete slabs and sand-lime bricks. The energy performance of their standard building would outperform German energy performance regulation by roughly 15 to 20%.

Based on the conceptual design of the building, an early energy demand calculation based on the builder's standard solutions was carried out. Key features of the changes then were:

- Increased insulation thickness (+20%) in all construction elements in the thermal envelope
- Increased thermal resistance (+10%) of all insulation materials
- Controlled mechanical ventilation system with heat recovery
- Windows and external doors according to passive-house performance levels
- External solar shading to prevent summer-heat loads
- Careful design of thermal bridges
-

While all these measures are far from radical, they are highly effective. The selection of where to apply which changes has always been discussed with the construction company and the craftsmen involved. That way, both avoidance of exorbitant cost increases and practical applicability on site could early be integrated in decision making.

The optimisation resulted in a heating energy demand of 17 kWh/(m^{2}a), the share of the building related energy demand is provided in figure 1 below.

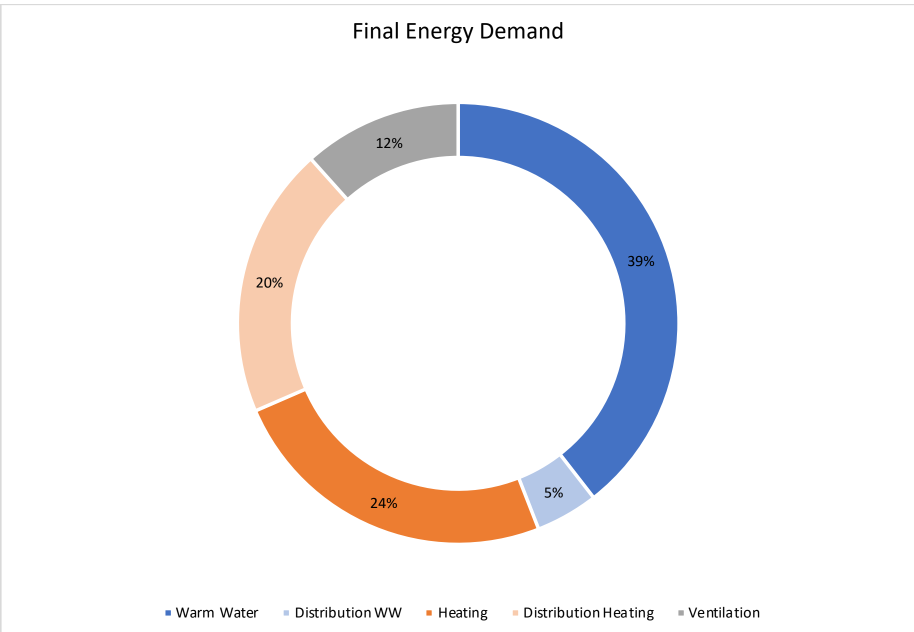


Figure 1 – final energy demand expressed as share of the total building demand in kWh per year

The following step of the design was to implement an energy supply based entirely on locally available renewable energy sources. In this case, the system features:

- Geothermal heat pump system with a COP-factor of 5.2
- Natural cooling function of the heat pump system to ensure summer comfort
- PV installation with 8.8 kWp
- electricity storage system
- domestic hot water storage system

The PV installation geometrically suits the roof shape. For prediction of the annual energy generation, several tools have been applied, amongst them the passive-house planning package [7].

According to the calculated energy demand and supply, the building will have a net-energy demand in November to February, all other months will provide a surplus energy. In reality, the PV generated the energy required for heating and hot water throughout November 2018, but could not supply the user-related electricity demand. After a few months of building operation, the real energy balance appears slightly better than predicted. Figure 2 below shows the calculated energy balance of the building, where the amount of energy available for e-mobility is assumed to apply all net-remaining energy. As the electricity storage is currently not at maximum capacity, but possible to be expanded to 40kWh capacity, some of that energy might actually by fed to the grid instead.

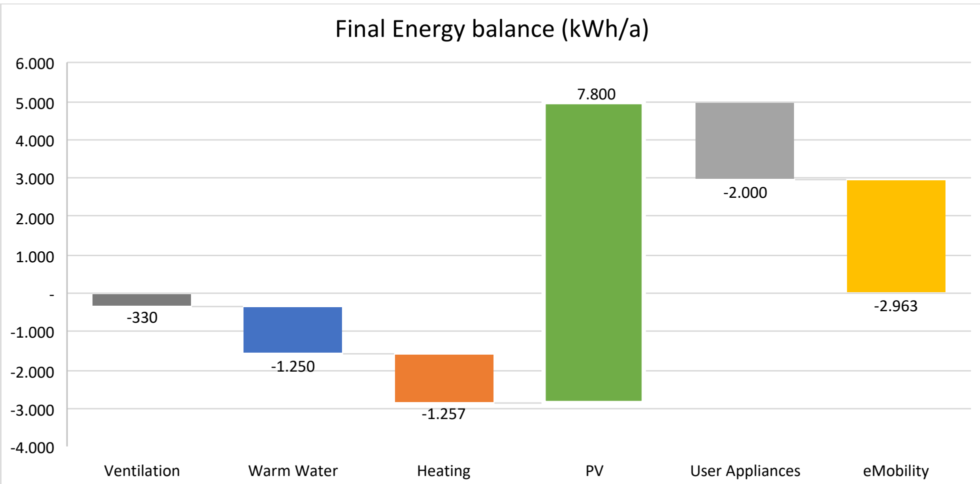


Figure 2 – final energy balance including building energy, PV generation, user and mobility

The energy surplus can basically be applied in two ways, it can either be fed to the grid, or be used for e-mobility applications. The latter is largely preferable, as the feed-in-tariffs for feeding electricity to the grid are not as attractive as a couple of years ago, with current feed-in tariffs lying at about 10ct (EUR cent) per kWh, while purchasing electricity from the grid lies at about 30ct. The more attractive option is to use the electricity for e-mobility, effectively replacing fuel combusted in cars.

The effect can be highlighted by figure 3, showing the CO2 emissions or savings associated with applying PV power instead of the German electricity grid mix.

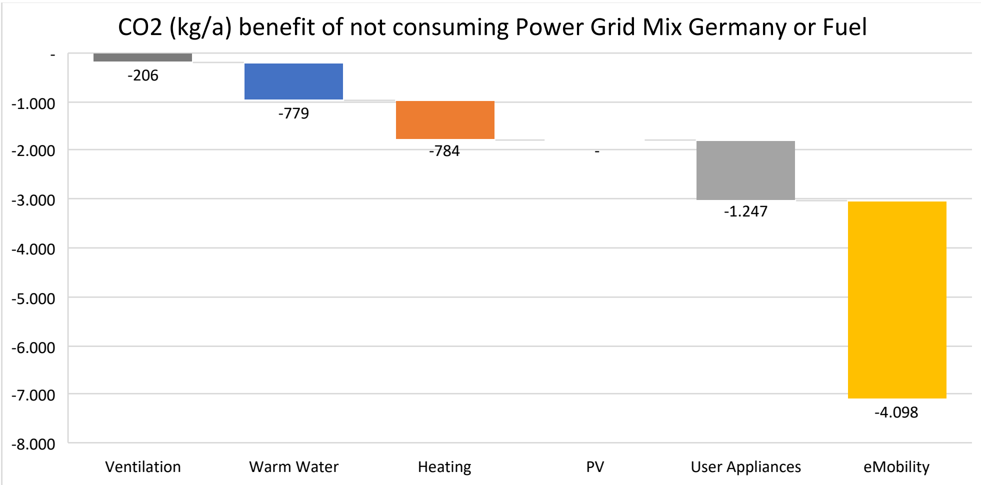


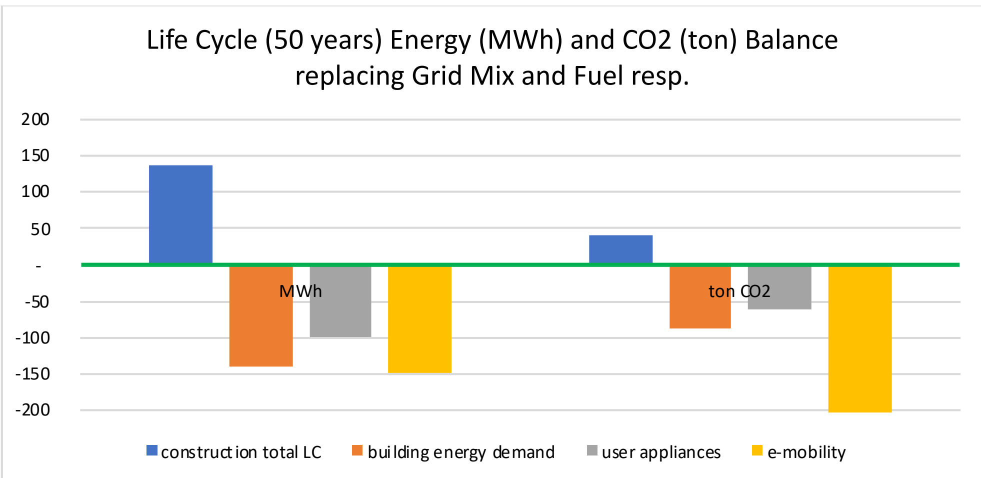
Figure 3 – CO2 benefit of replacing German Power Grid mix, respectively fuel (gas) for mobility, based on energy amounts from figure 2

For a consideration of the life cycle impact of the design transition, a building LCA according to the DGNB calculation parameters has been carried out. The LCA includes the construction of the building, future impacts related to deconstruction and waste management (including potential benefits of material recycling or incineration) and includes the use stage calculated for an assumed operating period of 50 years.

Below, the carbon indicator (global warming potential GWP) is presented as an example for the LCA results. The building construction results in a significant carbon footprint, mainly related to concrete, massive mineral materials, glazing etc. Figure 4 presents three lines starting from that initial carbon footprint. The first (orange) line including construction and building related energy demand for heating and domestic hot water (this corresponds to the scope of energy performance of buildings regulation). The line continues horizontally, as the energy demand is covered by PV, not contributing to CO2 emissions.

The second (grey) line includes user appliances. The line tilts to negative, as the energy is provided by PV and replaces German electricity mix and its associated emissions. With that scope the building is carbon neutral after roughly 35 years or operation

The third (yellow) line additionally includes the remaining energy surplus being fed to mobility and replacing fuel and its standard emissions. The electricity as well as the fuel consumption are calculated from the real consumption data of the user (not based on test cycles) and the CO2 emissions are read from data published by [8].



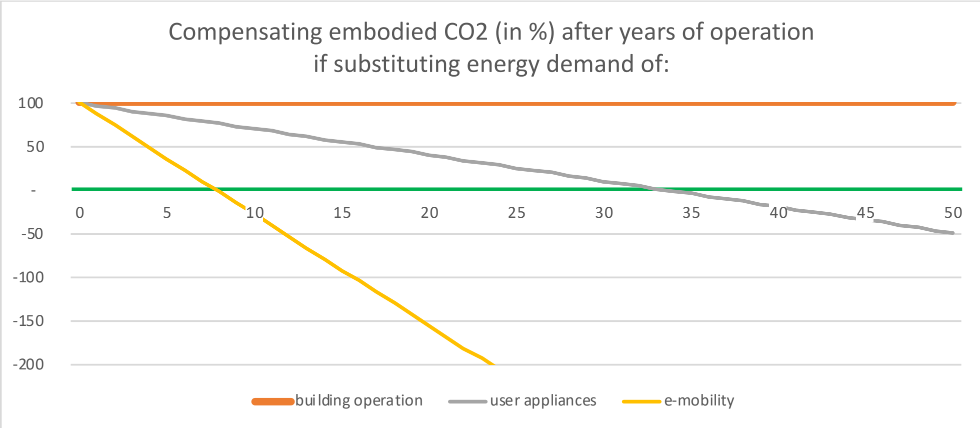


Figure 4 – Life Cycle Energy and Carbon balance, Time to Carbon Neutrality

6. Conclusion and Discussion

The presented building clearly demonstrates that it is without doubt possible and feasible to not only build nearly zero energy buildings, but surplus energy buildings. Not in the future, but today. The building demonstrates that it is possible to achieve that goal without needing to rely on a specific building and construction concept, but that it rather is possible to reach that performance level with a standard builder applying their normal but refined building concept. Also, the active house concept indicates a route that combines energy efficiency with quality and wellbeing aspects, demonstrating that there is no other side of the coin of energy performance.

Meanwhile required of course is that the building client has clear ambitions and that the planners are able to or supported in delivering to these goals.

Conducting cost assessments of design options and environmental assessments of the options as well as of the finalized building design allows to direct resources to where they are most efficiently and most effectively being used. In our case, the expansion of the system view – to include non-building related aspects of the users life, in this case the demand on mobility, clearly indicates that the surplus energy being applied in mobility currently spurs the carbon payback as well as the cost effectiveness.

The building has been awarded as category winner of the international active house alliance 2018.

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Analysis and Cross-Comparison of Business Models for nearly Zero-Energy Buildings in Europe

Köhler B[1], Quast A[1], Andaloro A[2], Dinkel A[1], Knotzer A[3]

(1) Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstraße 2, 79110 Freiburg, Germany

(2) Eurac Research - Institute for Renewable Energy, Via A. Volta 13/A, 39100 Bozen/Bolzano

(3) AEE – institute for sustainable technologies , Feldgasse 19, A-8200 Gleisdorf, Austria

benjamin.koehler@ise.fraunhofer.de

Abstract. Nearly Zero-Energy Buildings (nZEBs) will be the standard for new constructions in Europe from 2019 (public buildings) and 2021 (private buildings). Even though several technologies for realizing nZEBs are already available, their market penetration in Europe is still low. This can be ascribed to both high initial investment for nZEBs and limited adequate business models for several stakeholders along the buildings' lifecycle. The aim of this paper is to present and analyse examples of existing business models for nZEBs in different European countries. A broad overview of these business models, accompanied by evidence of their key factors and strengths is essential for developing new business models that ensure a cost-optimal nZEB implementation and adequate profitability for all stakeholders involved. Therefore, at first business models of different European markets and nZEB lifecycle phases are searched for and described in a profile-like manner. Secondly, the key factors and strengths of each business model are pointed out. In the end, a cross-comparison of the business models is done according to some key parameters, such as involved stakeholders and covered life cycle phases. This knowledge serves as a basis for the development of innovative nZEB business models. The work presented in this paper is developed in the frame of EU funded project CRAVEzero – Cost Reduction and market Acceleration for Viable nearly zero-Energy buildings which is co-funded by the Intelligent Energy Europe Programme within the Horizon 2020 Framework Programme of the European Union.

1. Introduction and Objective

1.1. Introduction

High investment costs and the lack of business models that are both reliable and economically viable for companies have been identified to be among of the main obstacles to nearly Zero-Energy Building's market-uptake [1]. Thus, in order to allow for the nZEB market acceleration needed to ensure Europe decarbonization objectives, solutions and innovative business models need to be developed. They should be reliable and predictable in terms of costs and thereby reduce a company's uncertainties and economical risks. Simultaneously, these models should be efficient enough to provide offers at reasonable price or/and with convincing benefits for customers.

The aim of this report is to give an extensive overview on the different kinds of business models that exist in the major European markets today. Therefore, CRAVEzero project partners contributed with descriptions of both their own and additional business models found on the internet. Additional business models were retrieved through interviews with companies not directly involved with the project. A comparative analysis of the findings is conducted in order to evaluate whether there are patterns according to different stakeholder perspectives that indicate success potential. Different stakeholder perspectives analyzed include planner, real estate/urban developer, construction companies, general contractor, facility manager building operators. Thus, in this report the business models introduced are actually practiced ones instead of general categories and therefore give more insight. Based on results generated with the analysis, main features useful to attract customer and strategic partnerships to create efficient win-win-situations emerge clearly, as well as phases along nZEBs' life cycle that are still lacking appropriate business models. This knowledge then serves as a basis for profiling new business models focused on nZEBs.

1.2. Objective

A business model is a simplified depiction of the way a complex and profit-oriented system generates, delivers and captures value. It illustrates the systems essential elements. With the term being relatively new in academic discussions and not formally defined yet, business modeling has not reached sophisticated maturity in many companies, especially in the construction sector. As a matter of fact, a number of companies developed certain business ideas and sections that work successfully. However, they often have not defined a complete and exhaustive business model including all necessary parameters required to describe its functioning. Usually, looking at one's own business from that perspective can be eye-opening. Gathering business ideas of companies, as it is done for this report, has a similar effect. It broadens the horizon of what is possible and in which manner. Most importantly, though, it spots business areas that are not covered yet or parts of business models that either help companies to be successful or cause the opposite. Thereby, the objective of this paper is collecting and analyzing existing business models, an essential preparatory step for generating innovative business models.

2. Scope and Methodology

In order to describe existing nZEB business models, a standardized blank profile has been developed. It includes parameters described in Table 1. The parameters are mainly based on the deliberations of Osterwalder and Pigneur [2] and their so called business model Canvas.

Table 1: Parameters of the business model profiles and their description

PARAMETER	DESCRIPTION
Value Proposition	Products, services, features, benefits creating value for the customers
Customer Relationship	Intensity of customer-provider relationship, channels to reach the customers
Customer Segment	Typical Customer group that the product/services is directed at
Activities and Capabilities	The most important activities a company needs to conduct in order to provide the offer and necessary resources required
Revenues	Type of streams a company generates revenues with
Costs	Most important expenditures that incur for the provision of the offer
Maturity	Stage a company is situated in regard to how elaborated and integrated a business model is.
Key Factors and Strengths	The most important factors and strengths that make the business model work successfully.

This profile was used to describe all business models of companies in different European countries and other major European markets. Furthermore, the CRAVEzero-partners described their own business models. The descriptions of third party business models are based solely on information found on companies' websites rather than insider knowledge. The work therefore does not claim to provide all information about the business models, nor it can be guaranteed that the information given online have been interpreted correctly. However, descriptions aim to provide an overview of different existing business models in various major markets (Germany, France, Italy, Sweden, Austria, Great Britain, Belgium, and Netherlands) and the variety of offers provided.

After collecting information on business models related to various phases along the nZEB life cycle, a comparative analysis was conducted. Repetitive patterns are highlighted and common strengths and key factors are identified. In the end, the key findings of the analysis are described.

3. Analyzed nZEB-Business Models

In a first step, 17 business models, provided by the project partners, have been analyzed in depth (see [3,4]). The business models are mostly performed by the companies directly benefitting from the project and have therefore been described based on first-hand information and experience. In addition to the 17 business models, more nZEB business models of the European markets were collected and described. In total, 60 business models with more than fifteen different stakeholder perspectives and for all stages in a building life-cycle were analyzed. The Business models cover several different stages of a building's lifecycle as shown in Figure 1. Figure 1 also shows that there are stages in the life cycle with many business models available (e.g. Planning, Construction), and stages with only few models (e.g. Political Decision, Monitoring, Recycling/ Dismantling/ Reuse). Detailed descriptions of the analyzed business models can be found in [2].

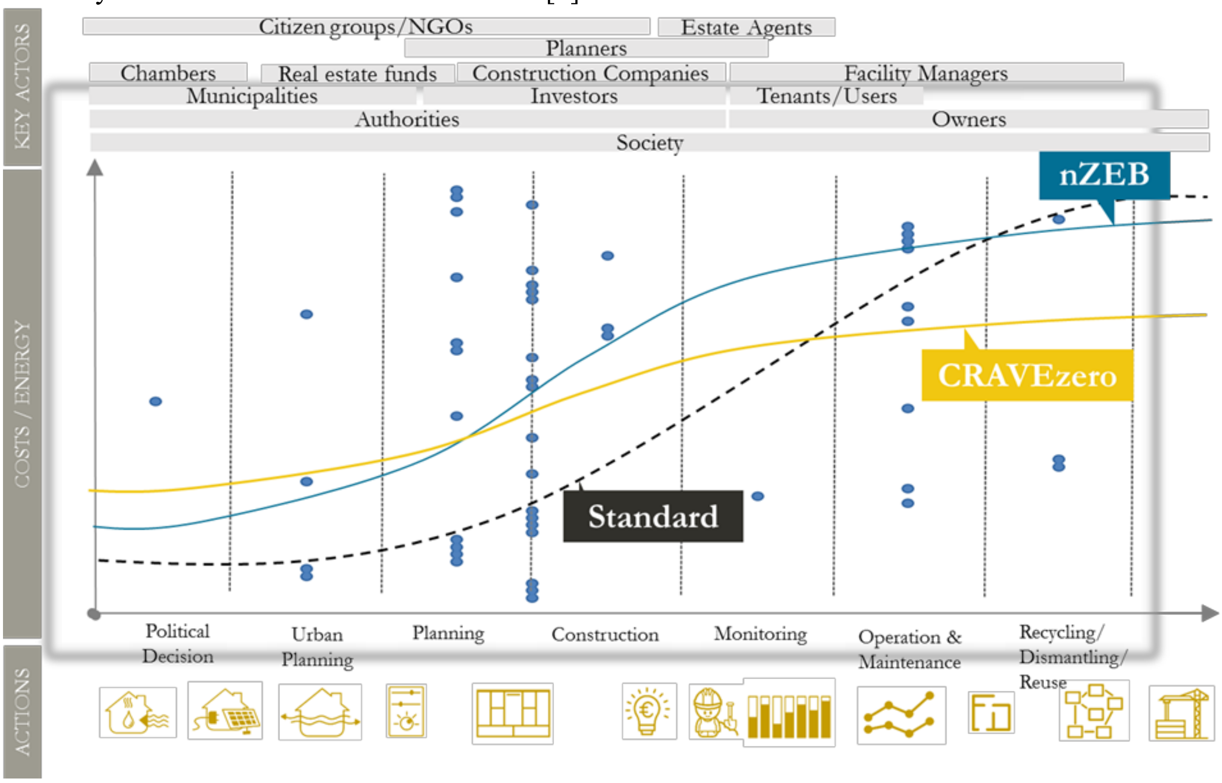

Figure 1: Life cycle phases of nZEBs and Business Model allocation

The business models are categorized according to their stakeholder perspective as follows (the number of analyzed business models is given in brackets):

- Cooperative in Real Estates (1)
- Energy Service Company (6)
- Engineering and Construction (9)
- Facility Management (4)
- Planner (6)
- Real Estate Developer (2)
- User/owner (1)
- Urban Planner (1)
- Certifier (1)
- Consultancy (2)
- Financier (2)
- General Contractor/ Developer (7)
- Political Entity (2)
- Promoter & Information Provider (2)
- Trading Platform (2)
- Vendor (7)
- Research Entity (3)
- Other/ not defined (2)

4. Results of the Business Model Analysis

Results described in the following are based on [2]. The paper presents only the most significant results in detail. However, in the discussion below, also additional results from the cross comparison of the analyzed business models within the CRAVEzero project are shortly summarized.

4.1. Value Proposition

The value proposition describes products and services offered to the market, how benefits for customers are created by relieving pain or creating gains, as well as supporting customers to manage and achieve a certain task. Figure 2 shows the value propositions offered within the collected business models in a comparative analysis. The most common features/ values of the business models are green labels and sustainability; comfort and innovation, (energy) cost reductions and efficient energy performance. Furthermore, the focus on good quality customer services is essential for many analyzed BMs. All these features can be found in BMs of different stakeholder perspectives. Features like customization, the increase of a building's residual value and products' durability, as well as a focus on social responsibility within a company's offer are less common and depend on the stakeholder offering the service/product, often very focused product manufacturers or service provider.

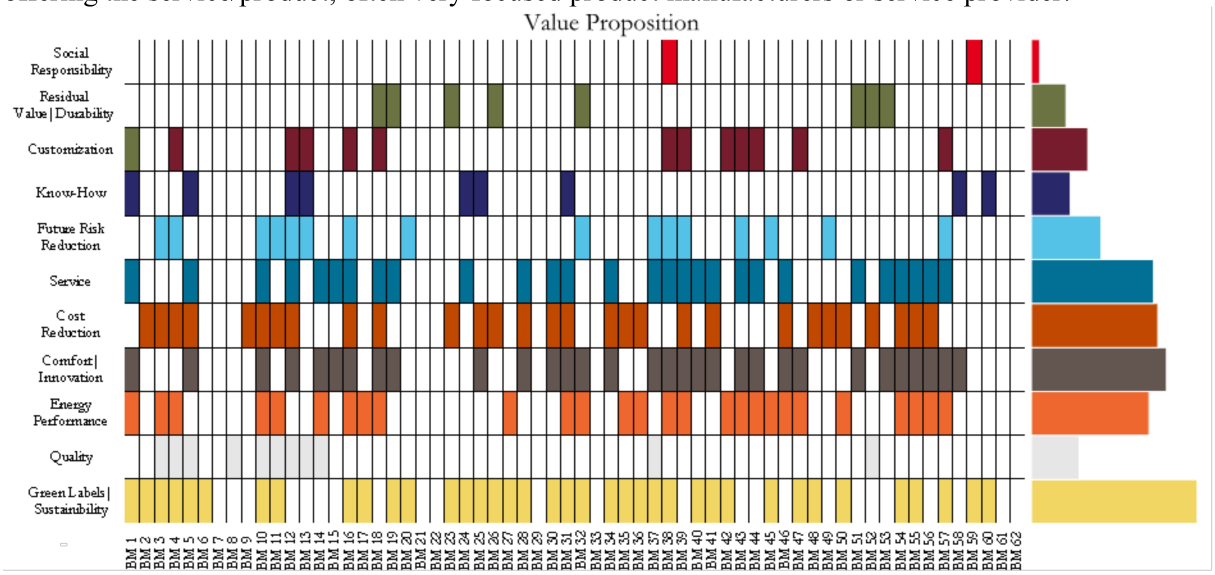

Figure 2: Comparative analysis - Value proposition

4.2. Strengths and Key Factors

The strengths and key factors identified in the analyzed BMs are summarized and compared in Figure 3. These factors contribute to the success of a business. The identification of these factors is important both for the enhancement of existing BMs and for the creation of new innovative ones.

Comparing the collected BM, patterns of common strengths and key factors become apparent. To simplify the analysis the business models are clustered according to different stakeholder perspectives. The most recurring strengths and success factors are: widespread competencies (all services in-house) as well as lock-in, which describes the ability of a company to create and maintain good customer relationships. Thereby the companies are able to convince customers to purchase, win their trust and create long term relationships. Know-how, innovation and sustainability as well as guaranteed prices/ performances are also common strengths and key factors. More specific and less frequently mentioned is the capability of prefabrication, which allows faster building process, and supports the company's image.

For General contractors, scalability (up/down scaling the resources depending on the project size) seems to be important, while real estate developers benefit from having influence on the (political) decision level. Vendors of technical equipment and materials take the whole life cycle of their products into account, take care of waste reduction and stress transparency as well as a strong customer relationship. While developers and general contractors cover the full range of services along the building's life cycle, planners often focus their expertise on a specific and confined planning phase. Innovative planning tools and the capability of using them efficiently are important success factors for planning and design businesses. This includes know-how in the field and experienced and well trained employees. Besides the internal competencies, many nZEB BMs strongly depend on the collaboration of different partners and stakeholders.

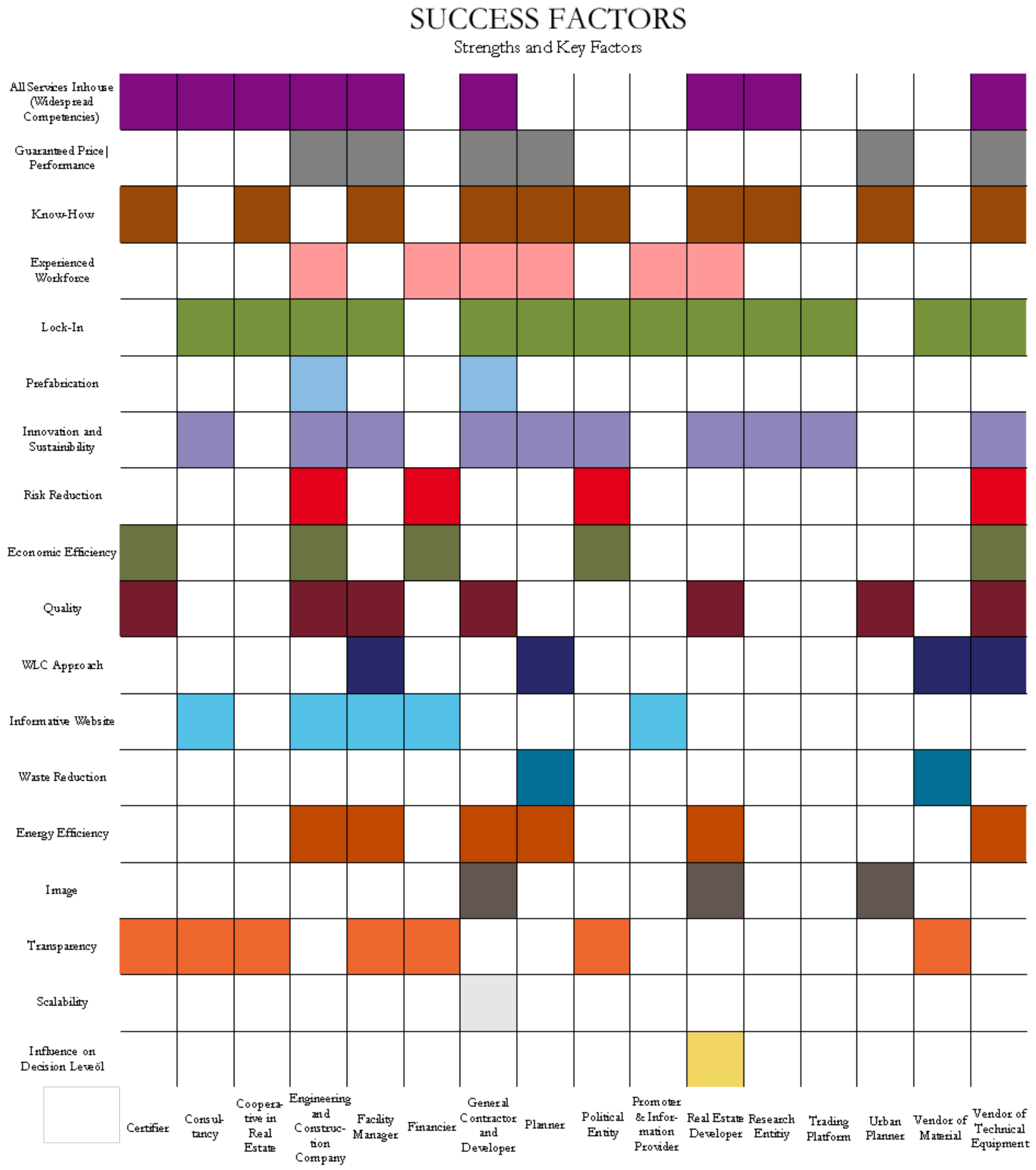

Figure 3: Strengths and Key Factors as factors of success for the Business Models

4.3. Life Cycle Phases

The different nZEB life cycle phases covered by the collected BMs are shown and described in Figure 1. It becomes apparent, which phase still runs behind in terms of business models availability (e.g. Political Decision, Monitoring and Recycling/ Dismantling/ Reuse).

To get an overview of the different business models that evolve around nZEBs, the entire life cycle of a building needs to be analyzed. This includes the phases of political decision-making, urban planning, technical design, construction, operation, maintenance and renovation, as well as dismantling and recycling at life-cycle end. In each of these phases various stakeholders are involved in the buildings life cycle while trying to capture value with their business model. Within CRAVEzero 17 business models of project partners and additional 43 BMs of European markets have been analyzed. Most BMs are in the planning and construction phases. Only one business model has been described for the political decision or monitoring phase. This latter can be a supplement to existing models or be done with partnerships (business model packages). The same could apply for BMs in the recycling/dismantling and reuse phase where only few have been found so far. Here, plenty of room for new business ideas is given.

Comparing the life cycle cost of a Standard building, a nZEB and a CRAVEzero building (see Figure 1), some substantial differences may be observed. At first sight, a standard building seems to be the cheapest solution; in fact, political decision and planning phase have lower costs, however this leads to higher follow up costs. On the other hand, nZEB buildings show greater efforts in the first planning phase, which allows to optimize the following phases. Due to careful study and detailed work during the planning and construction phase, it is possible to have some benefits: monitoring, operation, maintenance and renovation phases involve lower costs. In the CRAVEzero building the goal is to give even more importance to the planning phase leading to higher costs in early stages of the building's life cycle. This additional effort, however, lowers the cost in the following stages. It leads to an improvement of the management of the building and the follow up costs such as energy consumption, operation and maintenance costs in all phases will be lower.

5. Discussion and Conclusion

The results of the comparative analysis are discussed and summarized in the following. Especially noticeable insights, saliences and special learnings are pointed out.

A comparative analysis based on the information of the business model profiles is conducted in order to evaluate whether there are patterns according to different stakeholder perspectives that indicate success potential.

The analysis of the value propositions shows that the most common features have been identified to be green labels, sustainability, energy and cost reductions and efficient energy performance. The usage of renewable energies and sustainable materials is a value that the customer requires to the company in order to increase the efficiency and the value of the building. The customer relationship is a very important point as it is the beginning to build trust. The main way customers get in touch with the company is the website: here it is possible to see references and past projects, with the description of the problem, solution adopted and benefits obtained. Another point that characterizes a business model of a company is the customer segment, described by location, demographic, financial and functional characteristics. Building owners are the most frequently mentioned segment, followed by companies, investors and municipalities. Regarding activities and capabilities, the main tasks are design/engineering and development of projects/buildings; less common are services such as dismantling, reuse and renovation, facility management, certifications, prefabrication of building parts and grid services.

Since the aim of a company is to capture value with their offer, the main sources of revenues are related to asset sales and additional services for administration, management and maintenance. Accordingly, the main costs of a company are represented by personnel expenditures followed by costs for the building and production process and administration/office costs. It could be interesting for future examination how processes can be created or transformed for a better efficiency around personnel related work and to enhance potentials.

The most recurring strengths and key factors identified in the analyzed business models are widespread competencies, know-how, innovation and sustainability and guaranteed prices/ performances. It is important to identify these factors, because they can contribute to a business success or limit the success potential. Finally, the analysis of the maturity stages of business model innovation shows that a company with an established stage has Business Model Innovation as a central topic within the general innovation management of the company.

Acknowledgement

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Energy Flexible Buildings - The impact of building design on energy flexibility

Weiß T[1]

[1]AEE INTEC, Austria

t.weiss@aee.at

Abstract. Thermal load management has substantial theoretical potential for energy flexibility. To use the inherent flexibility in buildings, for example, district heating companies could temporarily control the heating system of buildings to switch-off or preheat dwellings in the morning to avoid using peak load gas boilers. The »thermal flexibility« in this study indicates the tolerance of buildings towards the changes of its heating system operation according to an external signal. The focus of this investigation is to give an overview of »thermal flexibility« of residential buildings in Austria from 1920 – 2020 with different envelope qualities, construction types and heating systems. Existing residential buildings in Austria usually have a high thermal mass within their massive brick or concrete primary structure, and therefore their indoor thermal conditions react slowly to operative changes in the supply of thermal energy. Depending on the buildings ability to retain or store heat **inside** the building envelope, space heating can be used to offer energy flexibility. Among other factors, especially the quality of the thermal envelope, the thermal capacity of the building, the sluggishness of the heat delivery system and passive solar gains are crucial for keeping indoor thermal comfort. Dynamic building simulation in IDA ICE is used to evaluate the potential of selected building typologies to shift heating loads away from peak demand periods. Potentials of various building archetypes according to the EU-Tabula building database to time-shift the operation of the heating system are pointed out respecting occupants' comfort.

1. Background and objectives

Domestic space heating is responsible for about 45% of the total household energy demand in Austria [1]. Especially old buildings before the 1970ies with a high domestic space heating demand have the highest share in the overall heating energy consumption. Still due to their high heat storage capacity, if they have a certain thermal envelope quality, they can stay pleasantly warm for some time after the heating system has been switched off. Austrian buildings before 1970 were often heated by single furnaces as heating systems, and the air-temperature control was depending on how the air supply was adjusted and how the fuel was added to the furnace. Under these conditions, a large heat storage capacity of old buildings was highly desirable and helpful. It reduced the increase in air temperature when there was an excess of thermal heating energy and slowed down the drop in temperature when the furnace was turned off. The heat storage capacity has a »temperature-equalising« or »temperature-stabilising« effect especially useful for uneven or so-called transient-heat-delivery-systems like old furnaces. Under these heating conditions, the heat storage capacity was thus able to compensate for the poor controllability of the heating systems in a certain sense. The larger the storage mass, the better [2]. Most of the old inefficient furnaces and heat delivery systems have been replaced in old buildings in the meantime, often by district heating grid connected heating supply systems or electric heat pumps. With today's low-temperature (compared to furnaces) heating systems and control options, the heat storage capacity has become less important for space heating. Mainly also because the charging of the storage masses by convective heat transfer is incomparably lower than by radiation. With convective heat transfer, the storage mass can at best be charged with the air temperature of the room and not - as in the past - absorb the radiant heat of the furnace. However, with the arising challenge of integrating high shares of renewable energy in energy supply grids, particularly variable wind and solar puts the idea of the heat storage capacity of a building into a new perspective. The concept of flexibility of buildings is to manage their loads based on the requirements of the surrounding grids. In the context of heating flexibility, this means to heat-up the building when there is excess solar, and wind energy available in electricity grids, or renewable heating grids can be operated ideally and reducing heating power at other times. Especially during cold winter periods, control systems in residential buildings can be used to reduce peak demands and take stress from electricity and heating grids [3]. The energy flexibility of heating systems depends on the ability of a building to retain or store the heat inside the building envelope concerning comfort requirements. The amount of insulation, the thermal capacity and the passive solar gains of buildings are crucial for keeping indoor thermal comfort [4] and [5].

The focus is here a quantitative evaluation of the potentials of heating flexibility of residential buildings in Austria from 1920 – 2020 on the level of usable energy. The difference of envelope qualities, construction types and heating systems plays a crucial role in defining the possible heating flexibility of a certain building typology. Dynamic building simulation in IDA ICE is used to evaluate the potential of these building typologies to shift heating loads away from the peak demand periods. Potentials of various building archetypes to time-shift the operation of the heating system will be pointed out, with attention to occupant comfort. With the obtained data, it is possible to offer an estimation of the heating flexibility of prototypical residential buildings in Austria assuming that they are equipped with a grid-connected heating system like electric heat pumps, district heating or direct electric heating. Also, the effect of the insulation level applied to the building envelope as well as the effect of thermal mass on the heating flexibility is analysed.

2. Evaluation Methodology

Heating energy flexibility also referred to as »thermal load shifting« is here defined as the number of hours the energy system can be delayed or forced to operate considering the indoor comfort band as a constraint. For example, when space heating is switched off at the upper excepted limit of the indoor comfort temperature, the indoor temperature remains within the comfort zone for a certain period depending on the level building insulation, ventilation and thermal mass. As the thermal energy inside the building envelope is vanishing, the indoor temperature drops. ΔT denotes the time after which the temperature has fallen from the upper comfort limit to the lower comfort limit, yielding a temperature difference of ΔT [°C]. Other essential definitions are explained in Figure 1.

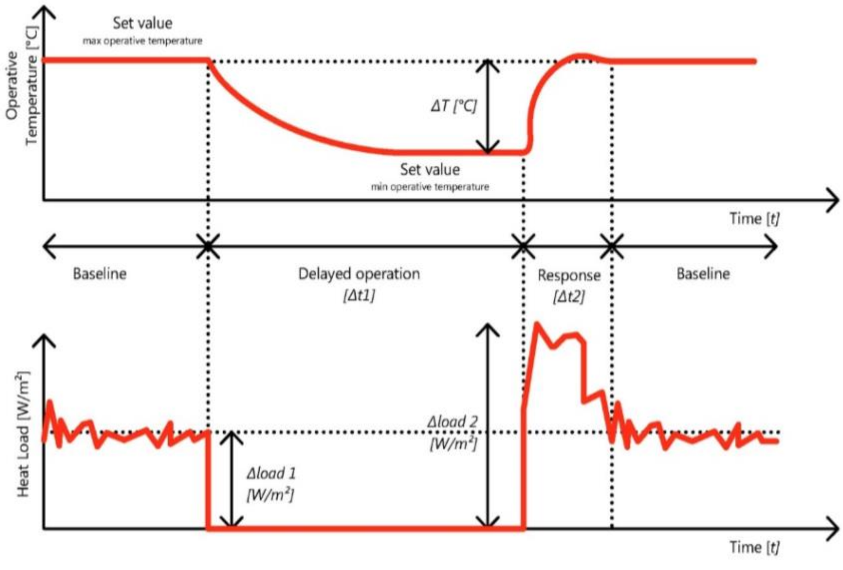


Figure 1 Demand-side control of set temperatures, representation of the cooling-down curve (delayed operation- Δt1) and heating-up time (response - Δt2) (graph based on [9]).

3. Austrian dwellings - Simulation models

The calculation of thermal load management potentials for representative building typologies has been derived from the TABULA/EPISCOPE web database [6]. For the simulation, the weather conditions of the test reference year of Graz, from the 2013 ASHRAE [7] – see figure 2, has been applied. Four different detailed building models with different years of construction and controllable heating systems and defined user behaviour were modelled in IDA ICE. The ventilation and infiltration corresponds to 0,4 air change per hour in order to guarantee sufficient air renewal. All buildings are modelled as a single zone, with the exact physical characteristics derived from the TABULA/EPISCOPE database. Internal heat gains for multifamily buildings according to SIA 2024 [8] have been applied to the building models. The set-point for the indoor operative temperature is 22°C. The allowed temperature band is 22 ± 2°C, and the minimum allowed operative temperature 19°C matches to the PMV-PPD category II of the comfort standard EN 15251 (PPD < 15%, -0.7<PMV<0.7). The influence of different occupancy behaviour on the heat flexibility is not considered here.

4. Results

The resulting load shifting potentials for analysed building typologies defined in Table 1 are presented in the following.

4.1. Delayed operation – cooling down

The simulations were firstly carried out for a characteristic winter week, 16th – 23rd of January, using a simulation time step of 10-minutes. During the working days, the building is non-occupied from 8.00 am. to 17.00 pm. Each occupant emits 80 W due to the metabolism, and the assumed net floor are per person is 30 m². There are also internal gains from appliances during occupied hours resulting in internal heat gains of 13 W/m² as shown in table 1.2. Figure 3 shows the cooling down of the operative temperature after the heating system is switched off. The period it takes for the operative temperature to reach the lower comfort level of 19°C is referred to as the potential »delayed operation« of the heating system. The changes in of operative temperature after switch-off of the heating system on the 16th of January starting at 0:00 is shown in figure 3. When the heating is switched off, the operative room temperature drops rapidly at first and then more slowly. When the room air temperature drops during the first hour after the heat cut-off, the heat stored in the wall returns to the room, and the temperature drops more slowly. Throughout the day, the passive solar gains via the window surfaces lead to an increase in the temperature, which then drops again constantly during the evening and night-time. The positive effect of the passive solar gains during the daytime influences here only the newer better insulated cases (C and D) since the old buildings (A and B) cool down too fast in order to benefit from passive solar gains. If however the switch-off occurred during sunshine, building A and B would also benefit somewhat from the solar radiation.

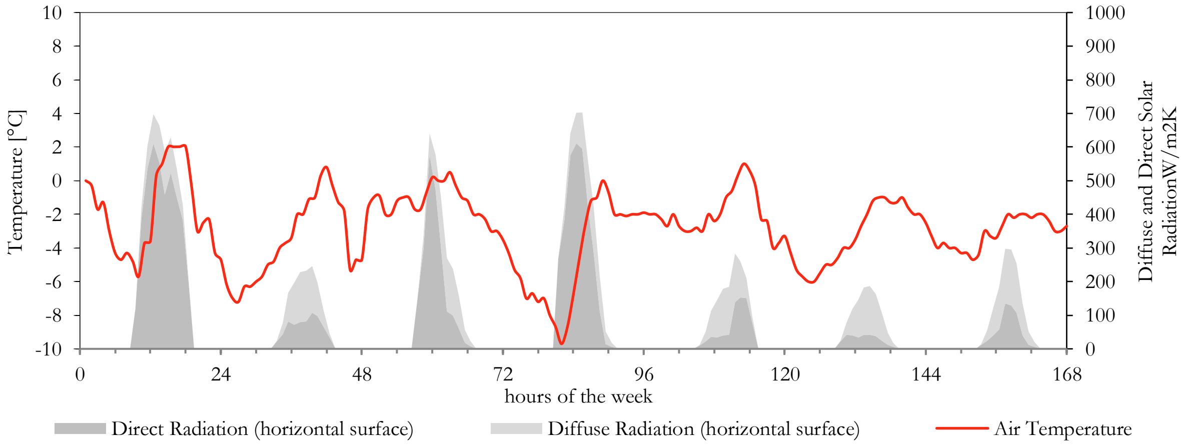
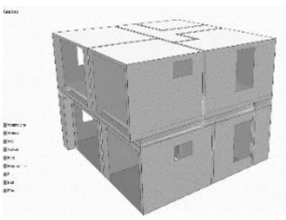


Figure 2 Climate chart of the chosen reference week 16th January to 23rd January, Graz (ASHRAE, Inc.: International Weather for Energy Calculations).

Table 1 Representative building typologies based on TABULA/ EPISCOPE database (retrieved from http://episcope.eu [6]).

[A]		Building Class: Tabula Code: Construction Period: Reference Floor Area: Net /Gross Energy need for heating U-Value exterior Wall U-Value Windows U-Value Roof	Single Family House ATN.SF.3.Gen 1945 – 1960 198m² 134 kWh/m²a 1,40W/m²K 2,30 W/m²K 0,50 W/m²K
[B]		Building Class: Tabula Code: Construction Period: Reference Floor Area: Net /Gross Energy need for heating U-Value exterior Wall U-Value Windows U-Value Roof	Multi-Family House ATN.MFH.5.Gen 1981 – 1990 590m² 90 kWh/m²a 0,60W/m²K 2,50 W/m²K 0,44 W/m²K
[C]		Building Class: Tabula Code: Construction Period: Reference Floor Area: Net /Gross Energy need for heating U-Value exterior Wall U-Value Windows U-Value Roof	Apartment Building ATN.AB.8.Gen 2010 - 906m² 47,8kWh/m²a 0,30W/m²K 1,40 W/m²K 0,40 W/m²K
[D]		Building Class: Tabula Code: Construction Period: Reference Floor Area: Net /Gross Energy need for heating U-Value exterior Wall U-Value Windows U-Value Roof	Single Family House no 2020 - 138m² 12,1 kWh/m²a 0,10W/m²K 0,60 W/m²K 0,10 W/m²K

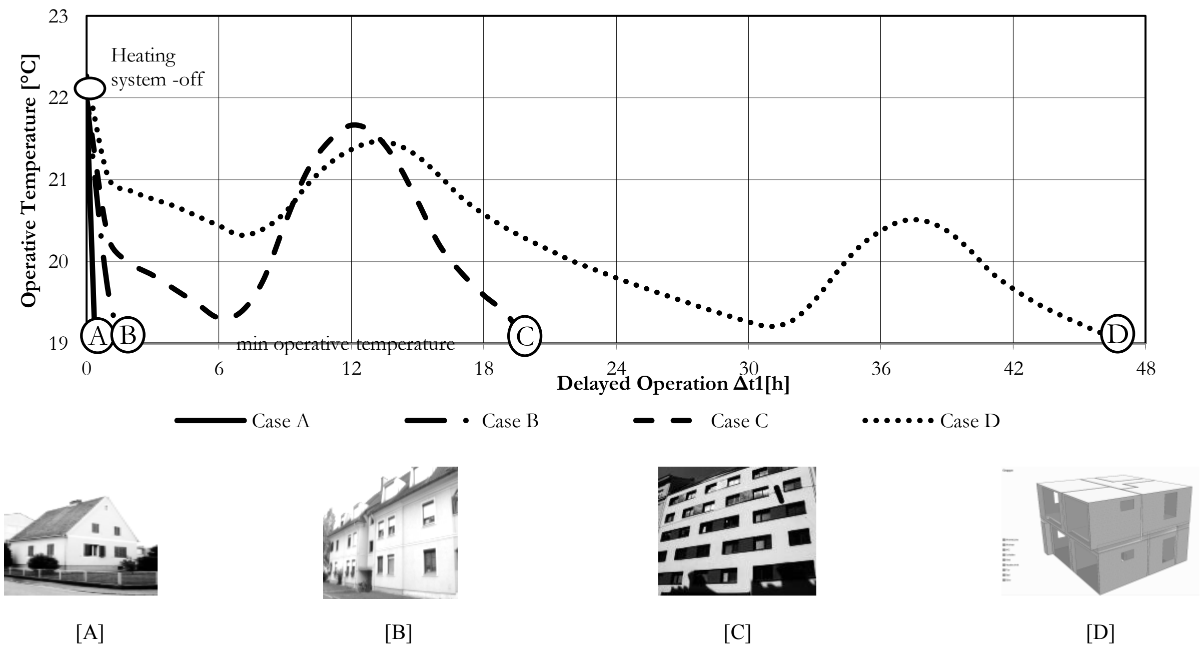


Figure 3 Cooling down time of 4 case studies - delayed operation (Δt1).

It should be noted that the shiftable heating loads are not constant over time as can be seen in figure 4. Further, the average heating power needed to keep the buildings operative temperature at 22°C in this January week ranges from 55 W/m² in case A, 37 W/m² in case B, 18 W/m² in case C to less than 10 W/m² in case D. Buildings with lower heating loads, have longer delayed operation times. Passive solar gains have shown to increase the delayed operation time which is also noticeable in the reduced heating energy power during the daytime These results lead us to the first conclusion: Old buildings, represented in simulation models [A and B], in contrast to new- and highly energy efficient buildings [C and D] have a higher specific performance due to the lower insulation standard. This leads on the one hand to a higher shiftable heating load, but shorter delayed operation periods as seen in figure 3 and figure 4. Figure 5 combines the simulation results of figure 3 and figure 4. The resulting curve displays the delayed operation time (the time that it takes for the room to cool down from 22°C to 19°C) on the x-axis and the shiftable heating power (the average heating power that can be switched off during this period) on the y-axis. The curve shows how long the average specific heating power [W/m²] of the four different building typologies (A to D) can be switched-off while the operative temperature inside the building stays in the specified comfort band of 19°C-22°C operating temperature after the heating system has been switched off.

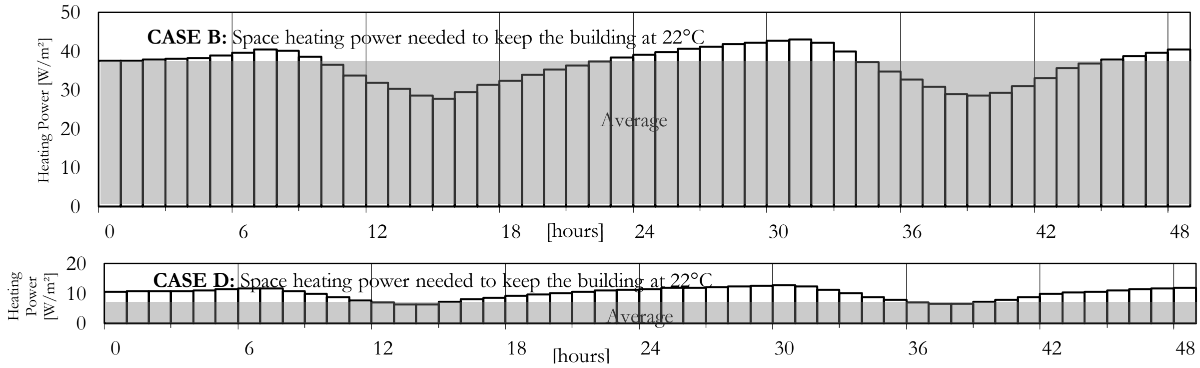


Figure 4 Heating power demand to keep the temperature of the building at a 22°C setpoint temperature (without load shifting) for case B and D.

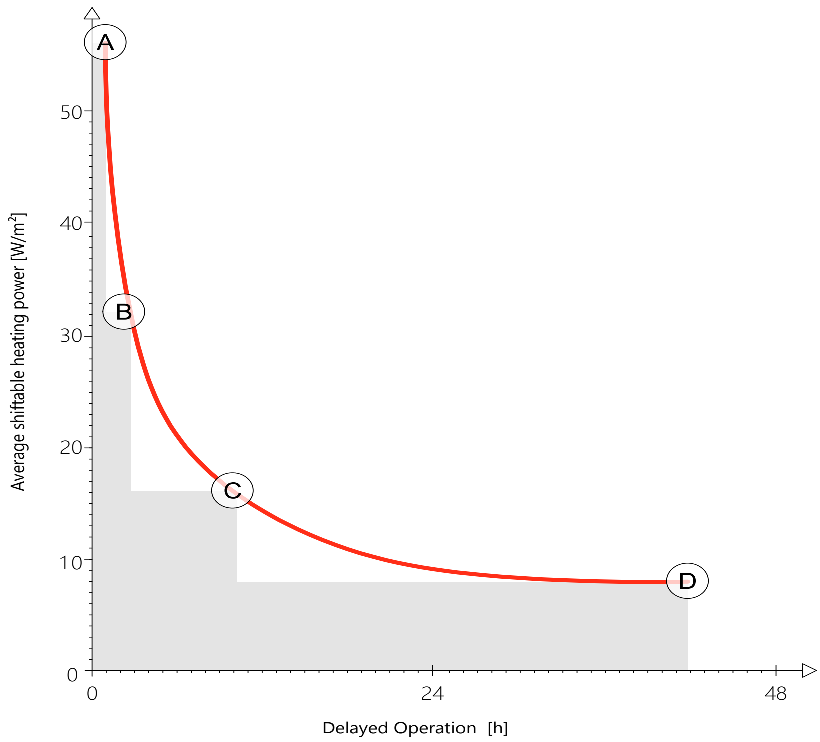


Figure 5 Load duration curves of cases showing the potential of shiftable domestic heating load over time

4.2. Delayed operation – Optimisation

The effect of thermal inertia in relation to energy flexibility has been investigated in detail by (Reynders et al., 2015). Buildings with high thermal mass embedded in the construction, have a huge potential to store heat over long periods. The specific heat storage capacity of the analysed TABULA case studies accounts for approximately 120 Wh/m²K since the buildings all have brick walls and concrete ceilings. Following the primary structure of the case study buildings is changed to a concrete construction (specific heat capacity of construction = 200 Wh/m²K) in the simulation model. Figure 6 shows the effect of increasing the thermal inertia of the building when the heating system is switched off. The larger the storage mass, the slower the building cools down. A heavyweight constructed building in combination with a high insulation standard (case C and D) extends the timespan for thermal load shifting drastically as shown in figure 6. The thermal mass of a concrete constructed building, in comparison to brick buildings, enables it to store more heat.

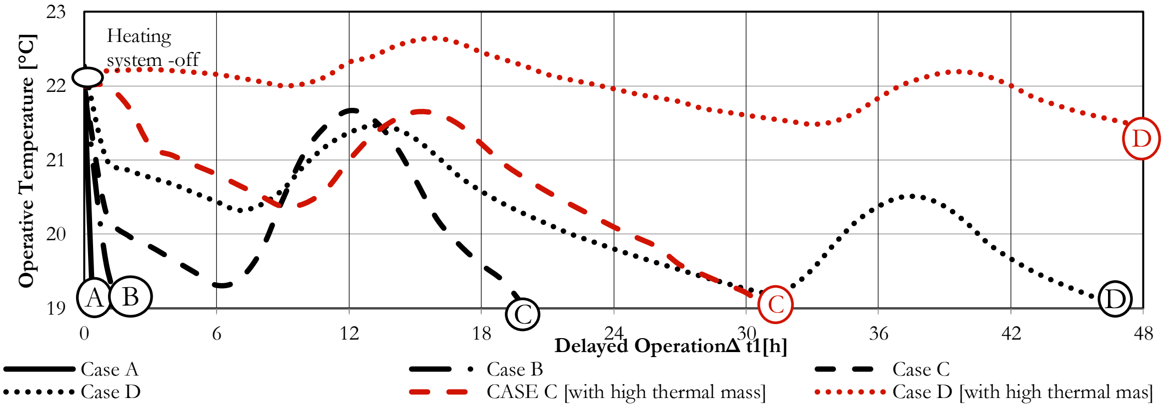


Figure 6 Cooling down time of thecase studies with increased thermal mass for case C and D.

It turns out that the delayed operation time of case study C can be extended from 20 hours up to 32 hours by adding more thermal inertia. This effect becomes even more drastically when adding thermal inertia to the most efficient building, case study D. Here the potential delayed operation time rises by a factor 2.3 from 46 hours up to 102 hours. Figure 7 allows us to explore the influence of shiftable domestic heating loads between heavy and medium-weight constructions, as well as different insulation levels based on the year of construction. The possible off time for case study B, C and C increased considerably, while there is no increase for case A. The latter due to the large losses through the poor thermal envelope.

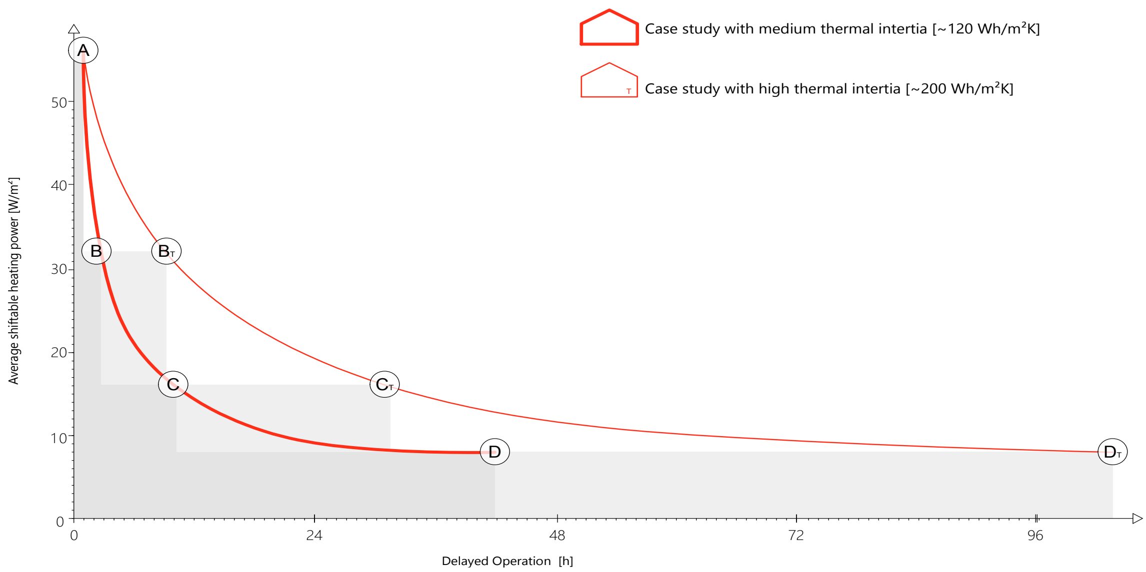


Figure 7 Load duration curves of heavy weight cases - potential of shiftable heating power over time

Even though the load shift period was determined for a typical cold January week, the resulting curve in Figure 7 can theoretically be used for any day/season of the year. If the heating power is known for a certain timespan, the ratio of the average shiftable heating power and the delayed operation time can be estimated depending on the thermal intertia.

In comparison to the investigated load shifting options by modulating the heating system (on/off), state of the art thermal or electrical energy storage systems are a more common way of providing energy flexibility to heating systems. Based on the heating system a state-of-the-art thermal storage water tank of 0.15-0.6 kWh/m² can drastically extend the thermal load shifting potential/ thermal storage potential. These capacities represent a 20-80 kWh thermal storage tank (200-1000 litres) for a typical single-family home in Austria.

The curves in figure 8 show how long a specific thermal power [W/m²] can be provided by different thermal storage system [kWh/m²] after the heat cut-off. It is seen that the load duration curves can be extended drastically by adding thermal storage systems. Figure 9 shows how long a specific electrical power [W/m²] can be provided by three different sized electrical batteries [kWh/m²floor area] after the active power supply has been cut-off. Please notice that this potential seems to rather small because it is assuming a direct electric heating system using each electrical kWh directly as thermal energy for heating the building. If the heating system would be powered by for example, a geothermal heat pump operating at COP 3.5, the load duration curves can be extended drastically. It is essential to notice that batteries can be used all year round for electric energy demand of the building and not specifically only in winter for heating flexibility.

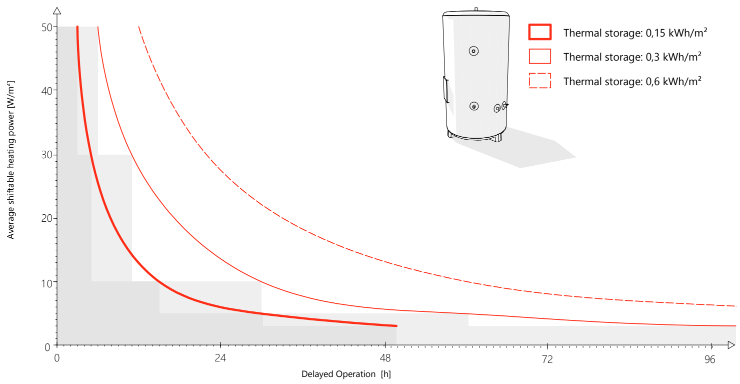


Figure 8 Load duration curves are showing the potential of storeable domestic heating load over time with three thermal storages

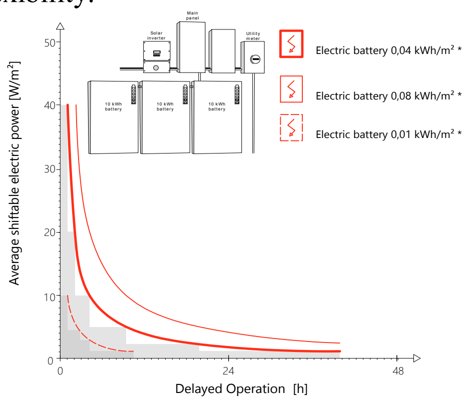


Figure 9 Load duration curves are showing the potential of battery storages to provide for electrical power after power cut-off

4.3. Response - heating-up

Due to the low-temperature heating systems in cases C and D with lower maximum heating capacity, the heating up timespan from the lower temperature setpoint of 19°C up to 22°C usually takes much longer. Also, the sluggishness of low temperature heating systems and modern PI controllers slow down the heating-up timespan. This timespan to reach the original temperature setpoint of 22°C again is referred to as the "response time of the heating system" in figure 10. It is heavily depending on the capacity and the control strategy of the heating system and much more difficult to assume in general than the cooling-down period, which is more related to the physical properties of a building. Figure 10 combines the load duration curves of the case studies showing the potential of shiftable domestic heating load over time for the cooling-down timespan on the right side (delayed operation) with an average predicted heating-up timespan (response) after the thermal load shifting operation on the left side. Also, we can see in figure 10 that from the end of the load shifting period till the heating system reaches the 22°C setpoint temperature again, there is an increase in heating demand since extra power is needed. Old, poorly insulated buildings with slightly oversized heating capacities, can react more quickly and reach the upper setpoint temperature relatively quickly.

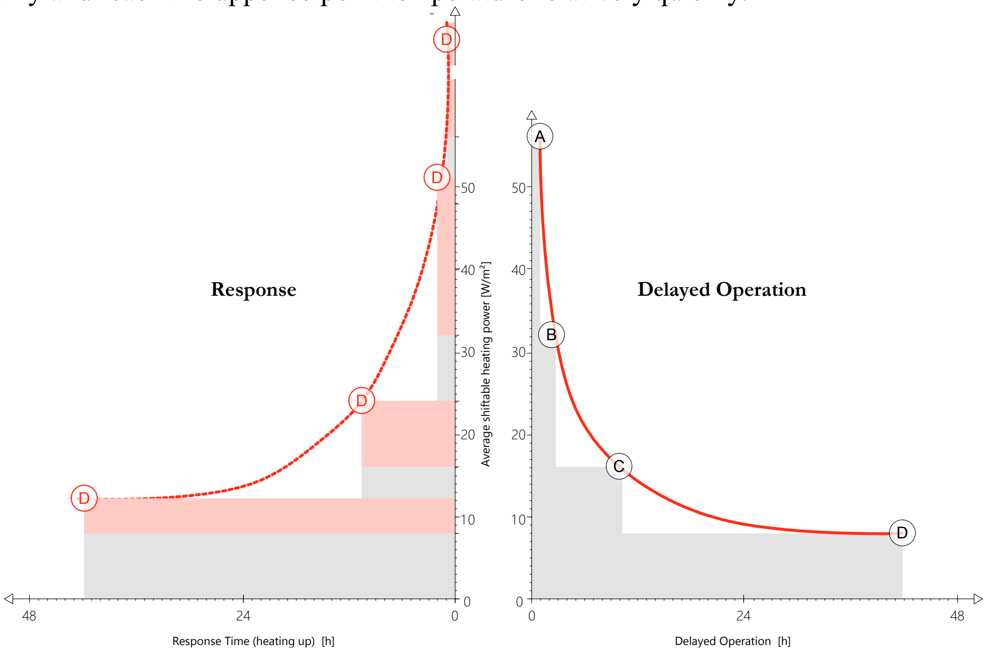


Figure 10 Rebound effect of shiftable domestic heating loads over time delayed operation (Δt1 – right) and response (Δt2 - left).

5. Conclusions

The potential for shifting domestic heat loads from the peak to low demand periods for Austrian building archetypes was investigated, and potentials for optimization were pointed out.

The findings are summarized as follows:

- Old buildings (cases A and B) in contrast to the new (cases C and D) have higher specific loads due to the lower insulation standard. This leads to a higher switchable load, but also a shorter shutdown period. Heat flexibility, therefore, is mainly determined by the buildings' physics-thermal properties. Also, energetic refurbishments of existing buildings can unlock a high load management potential since old buildings usually have high heating loads.
- The total amount of heating energy that can be shifted is beside the thermal quality of the building envelope dependent on the heating set points and acceptable comfort range. Tolerating a larger deviation from the comfort band especially in unoccupied times can significantly extend the load shifting potential of domestic heat loads.
- An increase of thermal mass/heat capacity leads to a damping effect on temperature changes, resulting on average in a 20-30% higher load shifting potential. At least 50% of the domestic heating peak loads can be shifted to off-peak periods during the day for building after 1980 in Austria, also in January, and still reach the comfort band of EN 15251, category II.
- The expansion of electric heating systems on the other side also poses the risk of worsening the seasonal gap of renewables in the grid, leading to higher specific emissions per kWh.
- For all building types, large delayed operation times are possible on days with higher average outside temperatures and high solar irradiation. Also, it is concluded that for four prototypical buildings, it is possible to predict the heating flexibility based on weather conditions – namely outside temperature and solar irradiation. For the older dwellings, the outside temperature has a dominant impact on the heat flexibility, as cooling down times are so fast due to envelope heat losses that these buildings hardly benefit from passive solar gains due to solar irradiance. Especially when the switch-off occurs during periods without solar radiation.

Acknowledgement
The above investigations are part of the Dissertation Project 'EFLEX-NZEB' [FFG 856025] with the support of the Austrian Ministry of Transport, Innovation and Technology by Tobias Weiß within the framework of Annex 67. Parts of this chapter have been published in an article within the scope of this theses [11].

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Mobile Tiny Houses – Sustainable and Affordable?

Leindecker H C[1], Kugfarth D R[2]

[1] Professor of Construction Ecology and Building Optimization, FH OÖ, Wels, Austria
[2] Scientific Assistant, FH OÖ F&E GmbH, Wels, Austria

HerbertClaus.Leindecker@fh-wels.at

Abstract. The topic of „affordable accommodations" has affected the construction industry and the politics for many years, not least due to sharply rising real estate prices. Building plots in good locations are just as prohibitively expensive for young people as larger apartments in urban areas, especially in big cities. This raises the question: How much does a person need to live? Energy efficiency, sustainability and regionality are as equally important as coziness, which decisively defines the quality of life of the residents. As part of the "klimaaktiv" regional partnership, the Upper Austria University of Applied Sciences has carried out several research projects concerning the topic of small sustainable homes. In cooperation with an Upper Austrian prefabricated house company, a building technology concept for an innovative modular construction system was devised. The aim here was the development of an innovative, high-quality and inexpensive modular system that does not exclude increased ecological standards. As part of an interdisciplinary project, a group of students developed an energy self-sufficient cabin for almost every kind of application. Based on extensive research on existing building systems, a variety of topics were examined. The focus here was on mobility, modular assembly, ecological materials, self-sufficiency, energy efficiency and the water cycle. In the end, a single-family house, which considers most of the aforementioned aspects, was built.

1. Background & State of the Art

The statements and findings of this publication are largely based on bachelor and master theses of students at the Upper Austria University of Applied Sciences. The main focus was on the master thesis of Lukas Krainz [1] – Development of a building technology concept for an innovative modular construction system – and an interdisciplinary project from the "Eco-Energy Engineering" bachelor's degree programme [2]. Furthermore, research into the topics of small houses ("Micro homes", "Tiny homes"), modular construction, mobility of buildings and urban development was carried out. The cooperation with Wolfthal Zimmerei GmbH during the completion of a bachelor thesis provided important insights into wood-based module construction [3]. Additionally, alternative building concepts of well-known Austrian module construction companies, like "Wohnwagon" [4] and "Genböck's microHOME" were considered [5].

1.1 Mobility of Buildings

The longing for change, flexibility and freedom often makes people dream of mobile micro homes. This longing presents a variety of challenges for architects, civil engineers and technicians. One of these challenges is the balancing act between cost-effective industrial prefabrication and the mobility of the individual building modules. In Austria, the transport of building modules is regulated in the Special Transport Order (SOTRA - Gesamterlass). Depending on dimensions and weight, these transports are classified into four special transport levels with individual legal requirements (see Table 1). Maximum size and weight of a module are dependent on the existing infrastructure and road conditions e.g. road width, load capacity of bridges or height of underpasses [6].

Table. 1: Special Transport Levels and legal requirements for Federal Highways [6]

	Level 1	Level 2	Level 3	Level 4
Width	3,01 – 3,20m	3,21 – 4,50m	4,51 – 5,00m	from 5,01
Height	-	from 4,31m	-	-
Length	22,01 – 25,00m	25,01 – 40,00m	from 40,01m	-
Weight	individual (depending on weight, axle load and requirements of the expert opinion of the road administration)			from 140,01t
Legal Requirements	self-accompaniment	1 Vehicle incl. 1 sworn road supervisory authority	2 Vehicles incl. 2 sworn road supervisory authorities	min. 3 Vehicles incl. min. 3 sworn road supervisory authorities

The single building modules, which are described in the master thesis of Lukas Krainz have a dimension of 18,00 x 5,50m and a maximum weight of 75t (see Figure 1). According to SOTRA, dimensions of this kind would represent a Level 4 Special Transport which requires a minimum of three vehicles including three road supervisory authorities. By combining the single modules, entire single-family houses can be built effortlessly. Mobile buildings in modular construction are usually mounted on screw foundations, which do not negatively influence the soil of the building ground. This guarantees the preservation of the property value and offers the possibility of removing the modules anytime [1].

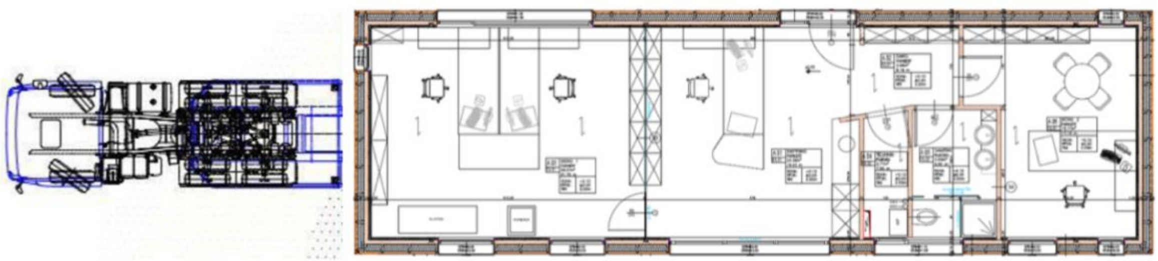

Figure 1. Building in modular design [18,00 x 5,50m] on a truck [1]

1.2 Infrared Heating Systems

For a long period of time, infrared technology was not suitable for use as the main heating system in buildings. This was due to the fact that high-quality energy (electrical energy) is converted into low-quality energy (thermal energy). Due to highly energy-efficient building concepts and the associated low heating requirements, infrared heating systems for buildings can make sense under certain conditions [1].

The most important advantage of this technology lies in the low investment and maintenance costs as well as in the very short heating and cooling phases. These are essential arguments, especially for holiday houses or small rooms that are rarely used. Another advantage is the high proportion of radiant heat, which many people find very pleasant. The high operating costs for buildings with a heating requirement above the passive house standard still represents the most important disadvantage [3].

1.3 klimaaktiv

“klimaaktiv” is the climate protection initiative of the Austrian Federal Ministry for Sustainability and Tourism, which is essentially divided into four main areas - Building & Renovation, Energy Saving, Renewable Energies and Mobility. klimaaktiv Building & Renovation stands for energy efficiency, ecological quality, comfort and execution quality. In order to be able to compare buildings with regard to these criteria, the klimaaktiv building standard was developed. New construction and renovation projects that meet the strict requirements in terms of location & quality assurance, energy & supply, building materials & construction, as well as comfort & indoor air quality are awarded such a designation. A building is assessed for all fulfilled and proven requirements with up to 1000 points, whereby three different quality levels (gold, silver and bronze) can be achieved. In order to ensure a meaningful comparison, a distinction is made between residential buildings and service buildings [3].

2. Implementation & Results

This chapter presents the results of a master thesis and an interdisciplinary project on the topic of "Mobile Micro Homes" written by students of the Upper Austrian University of Applied Sciences. In the end, a single-family house, which considers most of the aforementioned aspects, was built.

2.1 Development of a Building Technology Concept in Modular Design

The construction industry still has high potential in terms of efficiency in the construction of buildings on site. Despite the fact that the average Austrian household size is currently only 2.2 persons, the desire for home ownership is greater than ever. This poses entirely new challenges to the flexibility of the industry. The master thesis entitled “Development of a building technology concept for an innovative modular construction system” was prepared in cooperation with an Upper Austrian prefabricated house company and had the following objectives [1]:

- Preparation of building technology concepts from low to high-tech
- Implementation of a klimaaktiv building declaration for an office building
- Preparation of a building technology document (focus on heating & ventilation)
- Implementation of a photovoltaic simulation

2.1.1 Heating & Ventilation. As already described in the Chapter 1, infrared heating systems only can be economically operated in a building with passive house components. In the context of the master thesis, a modular design based lightweight construction building was considered. The annual heating requirement is 38,1 kWh/m^2a, which is equivalent to a low-energy house.

The annual heating costs with an installed capacity of 70W/m^2 (empirical value) would be € 1993.67 and therefore far above the average heating costs of a water-based heating system. Nevertheless, the implementation of a photovoltaic system (130m^2, 21,6 kWp), which covers nearly 75 percent of the electricity required for infrared heating, significantly reduces the heating costs. By signing a green electricity contract, the ecological aspect is taken into account as well [1].

In accordance with §10 of the "Upper Austrian Air Pollution Control and Energy Technology Law" (From the German "Oö. Luftreinhalte- und Energietechnikgesetzes"), in the state of Upper Austria, electrical resistance heaters may not be used as the main heating system in new buildings, except in justified exceptional cases [3].

Due to the fact that costs and flexibility play an important role in the project, it was decided to concentrate on a decentralized ventilation system. In cooperation with a wholesaler for ventilation units, a suitable concept for the modular building system was developed. The chosen ventilation system comes from a German producer which offers certified passive house ventilation units [1].

2.1.2 klimaaktiv Building Declaration. In order to emphasize the energetic, ecological and economic quality of the building, it was subjected to a klimaaktiv building declaration in the planning phase. The innovative building concept covers a wide range of possible applications. Therefore, two different plans were carried out. In the category Service Building, the (theoretical) bronze award was achieved by satisfying all essential criteria (with a total score of 523). Due to the fact that electrical heating and electrical hot water preparation have a negative effect on the primary energy requirement (PEB_{SK}) and on CO2 emissions factor ($CO2_{SK}$), a klimaaktiv declaration for residential buildings was not possible because these values were too high. The difference between green electricity and mixed electricity also has a very strong effect on the building's primary energy requirement, which should be taken into account when operating infrared heating systems or heat pumps [1].

It must be stated that klimaaktiv recommends infrared heating systems only for true passive houses with heating energy demand lower than 10 kWh/m^2a, including a ventilation system with heat recovery [7]. Further research is necessary to determine whether infrared heating systems in combination with low tech renewable heating systems (e.g. one room pellets stove and intelligent air ventilation management) make sense as a backup heating system for bathrooms and toilets when photovoltaic systems and/or other renewal energy are used.

2.2 Energy Self-Sufficient Cabin

Currently, there is an increased demand for mobile micro homes and module based buildings. An interdisciplinary project offered students from the Upper Austria University of Applied Sciences the opportunity to develop an ecological and economically interesting alternative to standard building solutions. The students had to face a variety of challenges especially in terms of renewable energy, ecological construction materials, energy efficiency and mobility. The project had the following objectives [2]:

- Research into the topic of module construction and mobility
- Substitution of expensive and non-ecological components used in the cabin
- Presentation of a building technology concept including CAD plans
- Optimization of the energy concept
- Economic calculations and comparison with other building concepts
- Construction of an exhibition object (sample wall)

2.2.1 Mobility and Ecological Aspects. The basic construction of the cabin is based on an innovative modular design and can be extended as required, depending on the field of application (see Figure 2). The transportability with a conventional truck (no special transport) had to be considered at every stage of the planning. This requirement means that the floor plan of the individual modules is limited to a maximum floor area of $15m^2$ (length: 5.00m; width: 2.50m). All changes to the interior or exterior wall have a direct effect on the already very limited living space. Therefore, a central problem was the ecological energetic optimization of the exterior walls. The students opted for a lightweight wood construction because it is unrivaled concerning ecology and ensures a healthy indoor climate. The thermal insulation consists of a combination of cellulose and soft-fiber boards. The entire wall construction has a thickness of only 32cm and has a heat transfer coefficient of 0.21 W/m^2K [2].

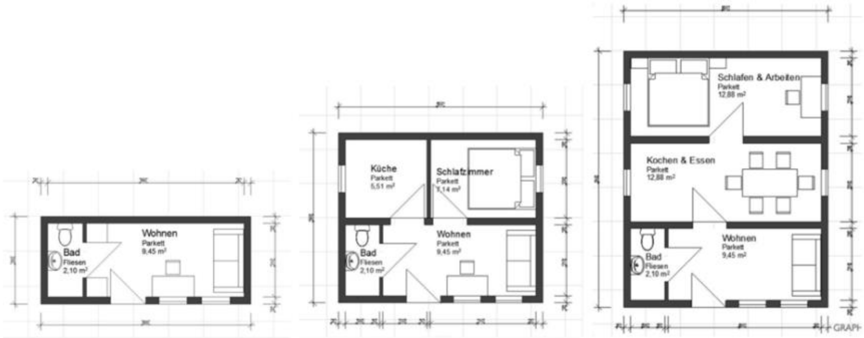

Figure 2. Standard modules for different applications [2]

2.2.2 Building Technology. The self-sufficient cabin contains many innovative ideas, which harmonize in interaction with each other. A well thought out concept that is not only ecological, energy-efficient and practical, but also looks good. Unfortunately, the realization of a 1:1 scale model would have exceeded the time constraints of the project and the budget. A sample wall (see Figure 3) was built, which reflects nearly all aspects of building technology and has already been presented at several internal and public events of the Upper Austria University of Applied Sciences [2].

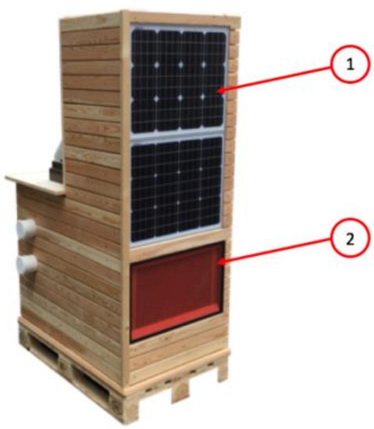

Figure 3. Front view sample wall with PV and cardboard honeycomb insulation [2]

Two integrated 50W monocrystalline PV modules (see Figure 3, No. 1) were installed for the energy supply. In series, they produce 24V direct current, which operates the floor-integrated infrared heating system without conversion loss. If no electrical current is required, the four gel accumulators (34Ah) monitored by the charge controller are charged. To operate household appliances, an inverter (24V DC to 230V AC) and a socket were installed. The cardboard honeycomb insulation (Figure. 3, No. 2) passively uses the sun's rays to generate heat when the sun is low in winter sky and prevents overheating in summer. The single room ventilation unit with an integrated heat recovery system efficiently exchanges the used, low-oxygen air with the fresh air from outside. Compared to manual ventilation systems, 80 to 90 percent of the heat can be recovered. In order to keep heat losses as low as possible, a passive house window was used [2].

2.2.3 Economics of the Cabin. In addition to the two key factors – comfort and sustainability – the cost-effectiveness of mobile tiny homes also plays a decisive role. The total costs for a ready-to-install standard module of the self-sufficient cabin ($15m^2$) amount to € 21,000 (price per m^2: € 1,400). These modules, which are manufactured by a carpenter in the Upper Austrian Ennstal, are also offered turnkey for approx. € 32,400 (price per m^2: € 2,160). At present, the price level is nearly equal to conventional prefabricated houses. In the long term, the price per m^2should fall due to the possibility of industrial production, continuously improved concepts and the increased use of Building Information Modeling [3].

2.3 From tiny homes to modular construction

Fascinated by the concept of mobile micro homes and their modular construction, in addition to the possibility of erecting a house in one day, the first author realized a small single-family home – an extended microHOME [5] with a modular lightweight wooden construction - near the center of a little community, considering most of the aspects of ecological construction (see Figure 4). The main floor of this building consists of 5 modules, which can be replaced later and built up on another site – perhaps introducing a modern way of living in and recycling a building.

Of course it remains to be discussed whether a single family house can be ecological at all. Therefore the concrete foundation level of this building provides space for the next generation. Additionally, this was the only way to fulfill the klimaaktiv essential criteria for heating energy demand because one of the main problems of micro homes is the very bad surface-to-volume ratio.

While redensification in cities is becoming more and more state of the art (e.g. roof extensions), ecological regional planning in rural zones remains the bigger challenge. New approaches are therefore needed, for example the possibility of packing buildings with higher density (e.g. 3-6 tiny homes per 1.000 m^2) in combination with upgrading the public transport systems.

Figure 4. Transport and construction of a module based home [8]

3. Conclusion

Mobility, sustainability and flexibility with regard to private homes are becoming increasingly important. A large number of construction and carpentry companies in Austria already offer mobile living ideas and concepts with a modular construction. More and more start-up companies have also been successfully founded on this basis, which confirms the trend in this direction. One reason for this development is the steady rise in real estate and building land prices, which is forcing both industry and the politics to search for innovative solutions. Mobile homes offer the possibility of renting land for a temporary period of time, allowing them to be adapted to one one's professional and private life changes. Therefore, this living concept can make an important contribution to the sufficiency of real estate.

Due to the continuous development of new housing concepts and work processes - keyword Building Information Modeling - it can be assumed that the costs for modular based buildings will fall in the near future. Nevertheless, a decrease in quality due to series production must be prevented. The flexible use of small residential modules also offers new possibilities for structural redensification in urban areas (see Figure 5). Combined with the consistent use of vacancy (e.g. rooftops, inner courtyards), mobile tiny homes can make a positive contribution to the economic development and the living quality of our cities.

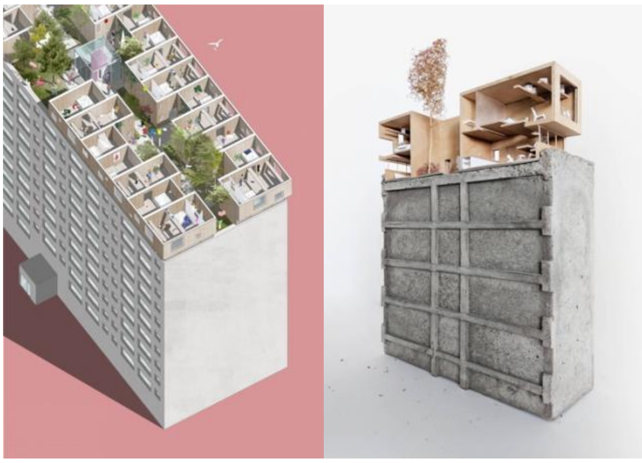

Figure 5. Module based living concept on a rooftop in Berlin, Germany [9]

In terms of ecology and energy efficiency, today's tiny homes are in no way inferior to conventional single-family homes. However, the prerequisites for these are high-quality planning and execution, the use of sustainable construction materials and the use of energy-efficient building technology. The implementation of an infrared heating system in connection with PV and an electrical storage system represent viable alternatives for such building concepts. All of these projects show that modular based building concepts can be produced and operated in an economical and sustainable way. In the end, every person must decide for themselves, whether this living concept contributes to their personal well-being and corresponds to their way of life.

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Challenges of retrofitting affordable housing to net-zero carbon in the United Arab Emirates

Mokhtar A

American University of Sharjah, Sharjah, United Arab Emirates

mokhtar@aus.edu

Abstract. Following the Paris Agreement, several governmental bodies in the United Arab Emirates (UAE) started working on further initiatives to improve the energy efficiency of buildings. Some of these hope to target net-zero carbon for new and existing buildings. As in most countries, the stock of existing buildings represents the bigger challenge for this target. In particular, existing affordable housing is the most challenging segment of the building stock. The limited access to expertise and financial resources makes it more difficult for owners of these buildings to retrofit them. Therefore, there need to be appropriate guidelines on how to achieve net-zero carbon in such building typology. This paper identifies both the technical and the financial challenges when trying to develop such guidelines within the context of the UAE. It also discusses the possible solutions that can be used to overcome some of these challenges. The technical challenges include the variation in construction systems, and the quality of construction for these buildings. It also includes energy modelling challenges such as selecting relevant weather data, and defining the patterns of using electricity for the different functions. The financial challenges include the subsidized price for electricity, the cost estimation for various energy conservation methods, and the payback for installing local renewable energy sources. Finally, the paper suggests a path for research activities to address these challenges and to develop the guidelines.

1. Introduction

The United Arab Emirates (UAE) is committed to reducing its per capita carbon footprint. This is reflected in its signing of the Paris Agreement on Climate Change and in various short and medium term strategies published by the country and many of its emirates. One of these strategies is reducing the demand-side of energy. As the building sector is the largest consumer of energy in the country, many regulations and rating systems that support lowering the energy consumption of newly constructed buildings were developed and are being enforced by the different emirates. An example is the *Estidama* rating system in Abu Dhabi [1], *Al Sa'fat* rating system in Dubai [2], and *Barjeel* regulations in Ras Al Khaimah [3]. The retrofitting of existing buildings is also an important aspect of the strategy. For example, Dubai is targeting the retrofitting of more than 30,000 existing buildings and developing a market for Energy Service Companies (ESCO) to achieve its target.

Housing represents an important section of the stock of existing buildings in the UAE. In Dubai, for example, statistics show that individual villas represent about 77% of the number of buildings [4]. Residential consumption is about 32% of the energy consumed in that Emirate [5]. Affordable housing is a segment of these residential buildings. The term "affordable" housing is a relative term and depends on where it is used. For the purpose of this work, an affordable house is a house that is owned by a UAE citizen through government support. This support can be through providing land and/or finances. Tens of thousands of such houses were built and are being built through some government programs [6], [7]. An affordable house for a UAE citizen is typically a detached or semi-detached villa of one or two floors occupying roughly 30% to 45% of its plot. The area of a villa is roughly between 250 to 500 m^2. The cost is roughly in the range of US$ 300K to 600K. Figure 1 shows a sample of a group of these villas forming a small community. Electricity is also subsidized for the occupants of these houses in most emirates. The subsidized charge is about US$ 0.02 to 0.03 per kWh. In addition, regulations regarding energy efficiency were non-existing for a long period of time resulting in high consumption of electricity in these villas. A study by Al Awadhi et al. for five villas in the UAE, each representing the most common types of villas in each decade starting from the 1970s until the 2010s shows energy use intensity (EUI) from 602 to 371 kWh/m^2/year [8]. The same study showed a potential saving that can reach 30% if these villas were built with a reasonable level required by the green building codes available at the time of the study.

Figure 1 A Google Map for a sample of a residential community in the UAE.
(Image © 2019 DigitalGlobe, Map data © 2019 Google)

The potential for energy saving by retrofitting these buildings is high. However, there are many challenges in trying to realize this potential. This paper discusses these challenges and the possible solutions to overcome some of them. The paper starts with examining the feasibility of achieving different low energy targets for a house in the UAE. It then discusses the technical and financial challenges to achieving a target. Finally, it recommends a line of studies that support developing guidelines to define and achieve the target.

2. Feasibility of Zero Net

It is important to define the terms that are used as targets before studying the feasibility of achieving such target. In this paper, the following terms are defined as:

A Zero Energy (or a Zero Net-Energy) (ZNE) building is an "*ultra-low energy building that consumes only as much power as is generated onsite through renewable energy resources over the course of a year*" [9].

A Zero-Net Carbon (ZNC) is "*a highly energy efficient building that produces on-site, or procures, enough carbon-free renewable energy to meet building operations energy consumption annually*" [10].

A Nearly Zero Energy Building (nZEB) is defined by the Emirates Green Building Council for the case of the UAE as "*a highly energy efficient building with a site EUI less than 90 kWh/m^2/year and covers a significant portion of its annual energy use by renewable energy sources produced on-site or off-site*" [11].

The difference between a ZNE and a ZNC building is that the latter can procure renewable energy from off-site sources while the first cannot. The difference between a ZNC and an nZEB building is that the latter can use energy generated from non-renewable sources while the first cannot. All these buildings are connected to an electric grid and the calculations of net-energy are done on an annual basis. The author starts by examining the feasibility of having a ZNE house in the UAE. This is followed by examining the possibility of having a ZNC house. Finally, it discussed the possibility of having an nZEB.

2.1. Zero Net-Energy

To examine the feasibility of having a ZNE house in the UAE's harsh climate and high standards of living, one needs to find a reasonable number to represent the EUI for an affordable house in the country. Unfortunately, very little information is available on this. However, some studies were done on existing residential villas that can give some guidelines on a possible EUI in the UAE.

Friess et al. studied a villa that was constructed in 2009 from a project that had one thousand villas with the same model [12]. It is a two floor, semi-detached villa with an envelope that followed the municipality requirements at the time. They considered this villa to be representative of villas built in Dubai at the time. They found out that the EUI is 194 kWh/m^2/year from the utility bill. They were able - through simulation - to reduce this EUI by about 23% by just insulating the reinforced concrete elements that represented thermal bridges in the envelope (e.g. R.C. columns). Adding 160mm of external insulation reduced that further to almost 30%.

The author studied the energy bills for 132 attached villas of various sizes. They are all with two floors and located in Sharjah, UAE. They were built in a span of 10 years starting from 1997. The results show that the older villas use an average of 185 kWh/m^2/year while the newest ones that used a bit more insulation use an average of 140 kWh/m^2/year.

The Emirates Green Buildings Council conducted a study using estimated energy consumptions from five villas that were to start being built in 2017 [11]. The range of EUI varied from 44 to 119 with a median of 98.8 kWh/m^2/year. The study also included a survey of professionals about the feasible level of EUI in the UAE. They concluded that 90 kWh/m^2/year is achievable for residential and office buildings.

Another study for the feasibility of achieving ZNE buildings in the UAE climate category concluded that it is feasible to reach 95 kWh/m^2/year for an apartment building (not a villa) [13]. The study used 30 energy efficient measures to minimize energy use without considering their cost implications.

From the mentioned values for EUI in different studies, it seems reasonable to consider the value mentioned by EGBC (90 kWh/m^2/year) as a feasible EUI value for a low-energy villa in the UAE.

From the other side, one needs to estimate the possible energy that can be generated/captured on a site in the UAE. Villas are typically able to do that through solar energy only. This can be in the form of photovoltaic (PV) panels or thermal solar collectors. For simplicity, we will assume the use of PV panels only.

The study by the EGBC mentioned that the five newly built villas in the UAE that voluntarily reported their data showed electricity generations of about 0, 55, 80, 95, 115 kWh/m^2/year. It is not clear how the volunteers calculated these values for their villas. With such large differences, it is expected that this is the electricity each generated divided by the total floor area of the villa. We are interested here in calculating the potential of generating electricity on one square area of a horizontal building roof. To do this, the author uses the PVWatts Calculator tool developed by the National Renewable Energy Laboratory [14]. The weather data of Abu Dhabi (the capital of the UAE) airport is used and horizontally installed fixed standard PV panels are assumed. Default data for system losses and efficiency are used. The result shows that producing about 210 kWh/m^2/year of alternative electric current is expected from the PV panels. This estimation for electricity generation can be used in relation to the considered EUI value of 90 kWh/m^2/year (of total floor area). By dividing 210 by 90, one can conclude that it is possible in the UAE climate for roof-installed PV panels to provide the electricity needs for a villa with two floors. Hence, it is feasible - at least in theory - to operate such a villa as a ZNE villa.

It is worth mentioning that a villa named the "Passive Autonomous House of Mohammed Bin Rashid Space Center" is in operation in Dubai [15]. It is a two-floor villa and fully operational off-grid using the PV panels installed on its roof. It was built for demonstrating the possibility of such operations and the cost did not seem to be an issue.

2.2. Zero-Net Carbon

In their study of existing - and relatively old - affordable villas in the UAE, Al Awadhi et al. reported an EUI of 371 to 602 kWh/m^2/year [8]. These are very different EUI's than the 90 kWh/m^2/year mentioned by the EGBC for newly constructed villas. This is why there is a large potential for energy saving through retrofitting these types of buildings in the UAE. Yet, it may prove to be cost prohibitive for many of the existing buildings to reach the EUI value of 90 kWh/m^2/year and install PV panels to become ZNE buildings.

Therefore, it is expected that many of the retrofitted villas will require procuring renewable energy from outside the building site and hence become ZNC buildings. In the UAE, procuring renewable energy can be done in a variety of ways:

1. Using roads solar panels to generate energy at the community level. This seems to be promising considering that neighborhoods in the UAE tend to have no or very little trees that cast shadows on the street (see Figure 1). This can provide about 50% additional solar energy to those provided by PV panels installed on the roof for a typical arrangement.
2. Using solar panels installed on buildings in the community that have large roofs and seasonal use such as local schools.
3. Using solar panels installed on parking areas of buildings with cyclical use such as local mosques and recreational centers.
4. Making use of a program in Dubai that provides renewable energy credits. The program allows building owners to buy these credits and cover the energy that they cannot generate on their building site [16]. This program should be viewed in relation to the operation and continued construction of a 5000 MW solar park in Dubai. The park will provide many of these credits.

Because of the abundance of solar energy in the UAE, it seems feasible to retrofit many of the existing residential buildings to ZNC. The cost implication certainly needs to be studied.

2.3. Nearly Zero Energy Building

An nZEB can use non-renewable energy to cover its needs. However, according to the definition by the EGBG, such a building in the UAE should not be using more than 90 kWh/m^2/year. It may prove cost prohibitive to retrofit old villas to that level of EUI.

From the above discussions of ZNE, ZNC, and nZEB, the author believes that having ZNC as a target would be the most feasible for retrofitting affordable housing in the UAE. Yet, this needs to be further studied to reach a definite conclusion.

3. The challenges of retrofitting

Many of the affordable houses in the UAE were built at times when energy conservation was not an issue of consideration. Building regulations that aim to conserve energy hardly existed in the UAE before the year 2000 and it took about 10 years after that to reach adequate standards. These regulations are getting better with time. Now with government commitments to reduce countries' carbon footprint and adhere to the Paris Agreement goals, retrofitting of these houses needs to be addressed.

The author suggests an approach where the current stock of affordable housing is classified into categories. Each category includes houses that were built using certain construction materials and building technology. It is common that during a period of time, a limited number of materials and technologies dominate the affordable housing market because of a variety of reasons including the cost. For each of the identified categories, a cost-optimal level should be defined following the example of the European Union [17]. This is combined with a retrofitting strategy that defines a set of energy conservation measures suitable for the category.

The author is investigating the possibility of using this approach for a group of 48 identical villas. These are attached two-floor villas in 8 separate clusters and with four different orientations. They were constructed between the years 1998 and 2000. Energy modeling is used to simulate the energy behavior of a representative villa (reference building). Several energy conservation measures are identified and tested. While this research is still ongoing, there are clear challenges that appear in the process. These challenges will face any efforts to address the retrofitting of housing projects in the UAE. The challenges can be categorized into technical ones and financial ones even though some of these challenges cross both categories.

3.1. The technical challenges

The availability of the technical data is an important challenge. The villas were constructed from very simple drawings with hardly any details or written specifications. The trades' rules-of-thumb were used. Through the author's interviews with contractors working in the country at the time, information on walls and roof layers were collected to a reasonable quality. Properties of glass and window frames are estimated through visual investigation. Air leakage values were roughly estimated through visual appreciation of building components such as gaps in the window frames. Certainly, with more resources, these technical data can be identified more accurately using various technologies. Then, a reference building can be constructed digitally from this data. It would be reasonable to assume that this reference building represents most villas built at the same time. The impact of factors such as building orientation, size, and external shading elements should be studied and some correction factors may be used for a specific villa under study.

The more challenging aspect is estimating occupants' behavior in terms of plug loads, schedules of use, and control of systems (e.g. thermostat setting). Within the 48 villas studied, there are significant differences in electricity bills even with buildings having an identical orientation and similar external shading elements. The difference can be attributed mainly to variations in occupants' behavior. The UAE does not have relevant surveys similar to the "Household Electricity Survey" of the UK [18] or the "Residential Energy Consumption Survey" of the USA [19]. There is also no existing research work to estimate occupants' behavior like that done for Egypt [20]. Collecting this data seems to be a pressing issue for the UAE to support an appropriate retrofitting strategy. The author suggests that this is done first by categorizing affordable housing into groups based on aspects such as the number of occupants, building size, and household income. Then, sub-meters and other measurement tools are used to monitor energy related to users' activities in sample buildings within each category. The data is analyzed and patterns of occupants' behavior are defined for each category.

Sub-meters are also useful to measure the electric consumption of different systems, sub-systems, and specific equipment in sample buildings. This detailed data are very useful in performing the very challenging task of calibrating an energy model. Software are available now to make use of the detailed measurements to adjust various data in the energy model to be as close as possible to the modeled building. A well-calibrated model is necessary to estimate the energy saving impact of any combination of energy conservation measures. The estimated saving is key in determining the cost-optimal level and the retrofitting strategy for each category of housing.

The availability of the hourly weather data - needed for energy model calibrations - is less of a challenge now for the UAE as all major cities has commercially available historical hourly data. However, files with future expected typical weather that reflects the impact of climate change are limited.

3.2. The financial challenges

The major hurdle in retrofitting affordable housing is the heavily subsidized price of electricity. With the exception of Dubai, which has electricity prices comparable to the average price in the USA, all the emirates charge only 20-30% of that price to citizens. The author's initial investigation with different energy conservation measured found that almost no measure would make economic sense with the subsidized prices.

The author suggests that the actual cost of electricity – borne by the government – should be used to investigate the cost-optimal level and hence the retrofitting strategy for each identified category of affordable housing. Following this, the government should initiate programs that gradually shift its subsidy for consumed electric energy to a subsidy for energy conservation measures. The suggestions in the following paragraphs illustrate this approach.

To reduce the consumption of artificial lighting, the government can develop a program to replace existing light bulbs with LED. It can make it a condition to continue the electricity subsidy, remove other light bulb types used in houses from the market, and imbed the replacement cost in the electricity bill for a few years. The number of years should be calculated so the owners of the houses do not see a difference in their bills. The program may also include installing occupancy and daylight sensors for light control.

A similar program can be used for replacing old appliances with high efficiency ones. As an added incentive, the government can buy back old appliances. It can recycle/upgrade them to recover some of the cost.

It also takes a very long time to recover the cost of installing PV panels on villas. To overcome this problem, installing PV panels should also be a condition for continuous electric subsidies. However, the government should allow buying back the electricity generated from them. For a few years, it can pay a price per kWh that is similar to its actual cost to generate electricity. The number of years is calculated to allow the user to recover the cost of the PV installation.

Certainly removing the subsidies on consumed energy will be very beneficial for any retrofitting program. Yet, it does not seem to be happening soon. However, it may be possible to subsidize each housing unit up to a particular EUI. This keeps the government's commitment to its citizens but also encourages them to consume energy more consciously. Spending part of the money allocated to the subsidies on school educational programs and awareness campaigns to encourage energy conservation may also prove to be cost effective.

4. Conclusion and Recommendations

It will be difficult for the UAE to retrofit its existing stock of affordable housing for the purpose of minimizing its energy consumption. This is due to various challenges. Perhaps the biggest challenge is the subsidized energy cost which makes improving any aspect of the energy performance of a house makes no sense for the owner. Yet, it is the quickest challenge to overcome if the government decides to change its pricing strategy. The author would argue that it is better for the government to provide its citizens with current subsidies in the form of cash payments and to raise the electricity price to actual cost. This would generate an incentive to reduce consumption and to invest in retrofitting.

Yet, even with overcoming this challenge, owners need to know where best to invest their retrofitting investments. Individual owners lack the expertise and soliciting such expertise would be too costly. Therefore, the author suggests the following studies to be done for the UAE housing stock:

1. Categorize affordable housing units based on criteria identified through the analysis of the housing stock.
2. For each category, collect the technical data needed to create a quality reference building model. This would be through studying several representative villas and should include:
   a. Identifying the material properties through invasive and/or non-invasive technologies.
   b. Using standard techniques to identify a representative value for air leakage.
   c. Installing sub-meters and other measuring equipment to understand the patterns of users' behavior and the efficiency of the available systems.

   d. Identifying energy conservation measures and the cost of each measure. This should take into account the impact of having a new and large retrofitting market on lowering some prices and increasing others.
   e. Building a reference model, applying the different energy conservation measures, identifying a cost-optimal EUI, and defining a retrofitting strategy.
3. Test the retrofitting strategy on sample buildings for each category and make any necessary corrections.

From the above studies, guidelines can be developed for each category of housing. These guidelines certainly need to reflect the government's intended strategy to price electricity.

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Towards developing a building typology for Sudan

Ismail Ahmed Ali S, Szalay Z

Budapest University of Technology and Economics, Budapest, Hungary

Suha8896@hotmail.com

Abstract. Sudan suffers from hard summers with temperatures approaching 42 0C in the South and 48 0C in the North. In spite of that, the technical solutions in buildings for protection against solar radiation and natural ventilation are generally beyond reach. There isn't sufficient information provided on the characteristics of the building stock, building physics and energy use of buildings in Sudan. The main objective of this research paper is to collect the data from the population and housing census, scientific research papers and different reports, and to use these in preparing a building typology table. The climate in Sudan is divided into three zones: warm desert climate, warm semi-arid climate, and tropical savanna climate zone. The building varies according to the climate zones, geographical feature, and urbanization levels. Building materials range from natural ones like straw, wood, and mud to moderns one like bricks and concrete. Building typology varies from structures to provide temporary shelter to the permanent single or multi-family houses. The main result of this research paper is to identify a building typology in Sudan with reference buildings. This is the first paper that introduced the typology table of Sudan.

1. Introduction

We are living under the mercy of climate. Climate shapes us, it means that our habits, clothing, food, and buildings need to adjust to climate conditions. There are four main climate zones on Earth: cold, temperate, hot-arid and hot- humid zones [1]. Traditional architecture responded to the climatic challenges in every climate zone with locally available solutions.

As the hot-arid climate area where Sudan is located is characterized by excessive heat and glaring sun, there is a focus on designing a shelter to reduce heat impacts and provide shade. Structures in this area were traditionally constructed of massive roofs and walls of adobe. In many developing countries, development efforts often focus on the construction sector to achieve the required level for urban shelter. Sudan as a developing country is still far from providing an adequate level of shelter to its citizens. The harsh environmental and climatic features, worsening economic situation, shortages and the big gap in the scientific data and research prevented the proper adaptation of building materials and technology. On the other hand, there is an incompatibility between the modern building materials and techniques and the country's features and design parameters.

The main purpose of this research paper is to introduce the general features of the Sudanese geodemographic and climate characteristics and to analyze how these features influenced the building stock in the past and in the present. The main goal is to compile relevant information on the building stock of Sudan for establishing a building typology that can be used for further assessment. According to our knowledge, no such building typology existed before in the country, so this can be considered as a first trial effort. A building typology with reference buildings is a useful starting point for energy performance calculations, comfort evaluations, and strategic planning [2].

2. Methodology

The method used in this paper was to collect statistical data from the different authorities and information from the previous research, and using the data to illustrate and analyze the building typology of Sudan according to the different parameters. First geographical, climate and demographic features are introduced, and the relevant information on the housing stock is described.

2.1 Geographical features

Sudan is located in North- East Africa. It is bounded by the Red Sea and Egypt from the North, Ethiopia, and Eritrea from the East, South Sudan from the South, Central African Republic, Chad and Libya from the West. Before 2011, Sudan was the largest country in Africa, but due to the secession of South Sudan, its current area is about 1.886 million km² making it number three in Africa and number 16 in the world. Sudan has many wealth resources of water, livestock, fertile lands, diverse forests, minerals (gold and copper), and oil production. The soils of Sudan are classified into six main categories according to their locations and construction: i) desert; ii) semi-desert; iii) sand; iv) alkaline catena; v) alluvial; and vi) ironstone plateau. There are many local variations due to drainage conditions [3], [4].

2.2 Climate of Sudan

Sudan has a composite climate between hot, cool and rainy seasons. The principal climatic elements which affect the building design and comfort are solar radiation, temperature, humidity, wind speed and direction and precipitation [5].

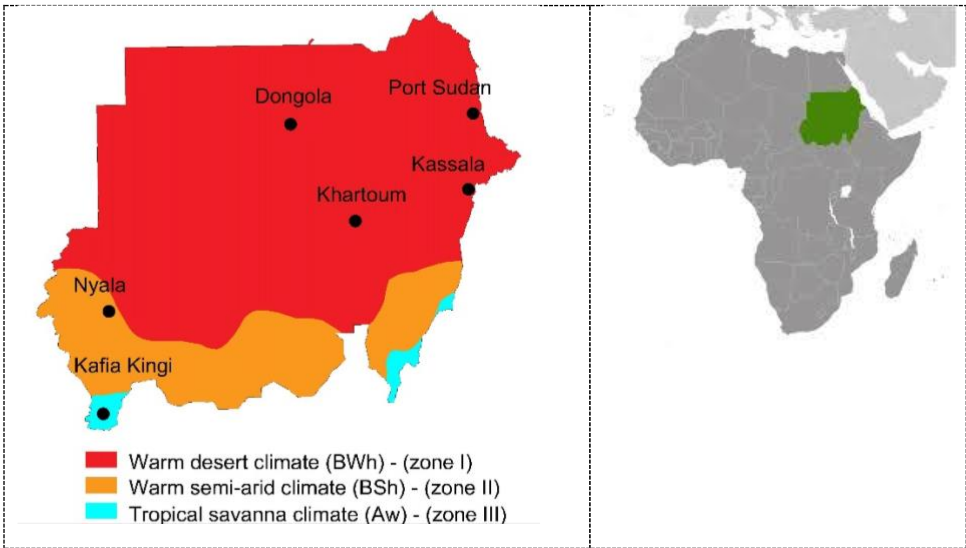


Figure 1. a) Sudan climate zones b) Location of Sudan in Africa,

Source: Based on Koppen [6], and Sudan Meteorological Authority (SMA) [7]

Sudan is classified into three climatic zones (Zone I: warm desert climate, Zone II: warm semi-arid climate and Zone III: tropical savanna climate) as shown in (Figure 1) [6], [7].

In the Northern Part (zone I) warm desert climate zone summer temperatures exceed 43.3 degrees Celsius in the desert zones and rainfall is negligible except in the center, such as the capital Khartoum and Gezira city where rainfall is common between June and September. Dongola, Port Sudan, Kassala, and Khartoum are examples of some cities in this zone (See Figure 1 and 2). The maximum mean temperature registered the highest values in Dongola and Khartoum cities, (Figure 2(a) and Figure 2(b)), while the highest values of humidity are in Port Sudan city because of its coastal location close to the Red Sea (Figure 2(c)). In the capital Khartoum, the average annual temperature is about 26.7 °C;

and the annual rainfall is about 254 mm. The northern part of Sudan has a harsh climate compared to the other parts.

Nyala is located in the South Western warm semi-arid climate zone area (zone II), it has moderate summer and winter temperature and high rainfall and relative humidity values (see Figure 2(c) and Figure 2(d)), this is because its location is close to the tropical savannah region (zone III) [8].

The greatest amount of solar radiation in Sudan is found between 15 and 35 latitude north. Wind speed and direction vary with seasons. In winter, the wind speed ranges between 0.54 m/s to 1.54 m/s in N and NW direction, while in the summer season winds are usually locally supplemented by dust and sand in the direction of NW to SW. Dust storms frequently occur in the desert zone. High temperatures also occur in the southern part, but the humidity is generally high [9].

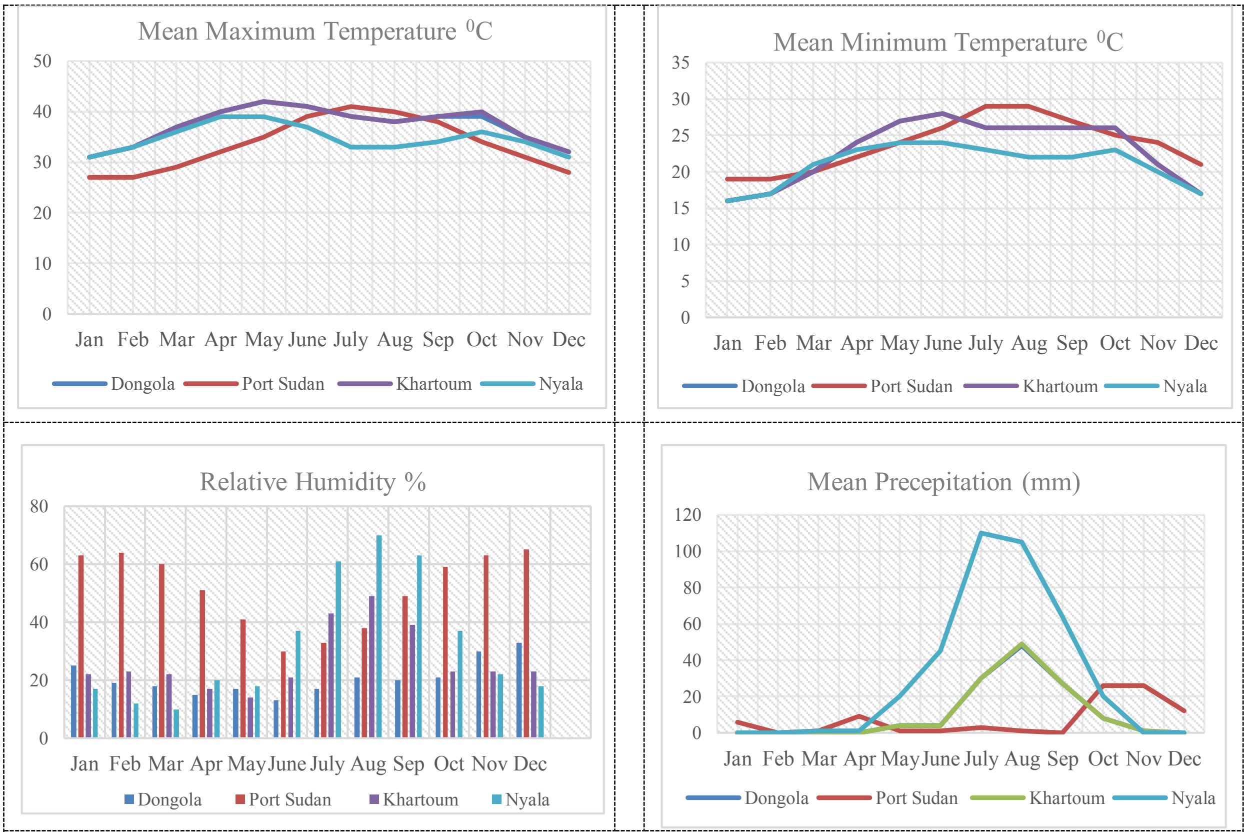


Figure 2. Metrological data of Dongola, Port Sudan, Kassala, Khartoum, Nyala for the: (a) mean maximum temperature for 30 years period (b) mean minimum temperature for 30 years period (c) annual relative humidity in 2009 (CBS) (d) mean precipitation (mm) for 30 years period

Source: World Metrological Organization, Sudan Metrological Authority and Central Bureau of Statistics [8].

2.3 Demographic

The population of Sudan has increased by 49.5% in the past 25 years, reaching 41 511 526 million in 2018, growing at 2.8% rate per annum. The urban population is estimated at about one-third (34.6%) of the total, which indicates that Sudan is still predominantly rural. With this rate of increase, the population could double in about 16 years [10], [11].

Sudan's population pyramid is young and growing, so it belongs to the expansive type (Figure 3). In the population distribution, around 41% of the population is under 15 years, 56% is between 15 to 64 years and 3% of the population is more than 65 years old. Life expectancy is low due to the health and economic system. Most of the population is confined to two climate zones. About 52% of the population lives in the warm desert climate zone and 48% in the warm semi-arid climate zone. Only 0.04% live in the tropical savannah climate (Figure 4 and 1). A conflict region between South and North Sudan in this area (Kafia Kingi City) due to the rich natural resources there [12].

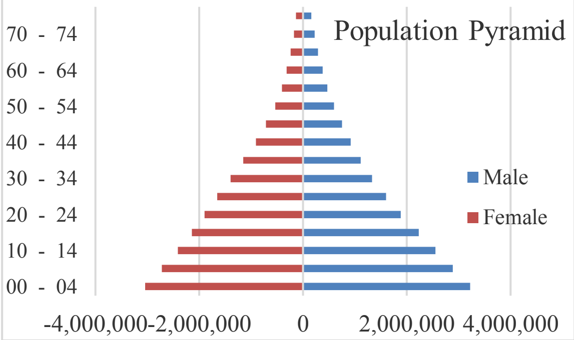


Figure 3. Population pyramid

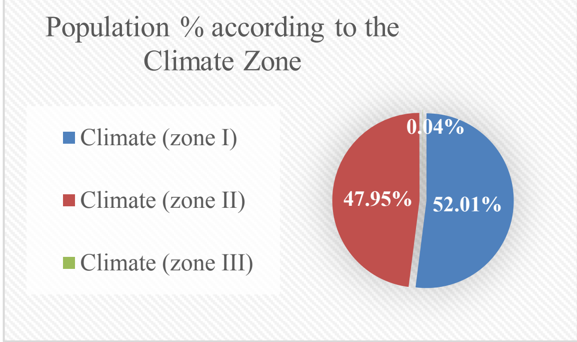


Figure 4. Population percentage according to the climate zone, Source: Annual Health Statistics Report

Source: Annual Health Statistics Report 2017 [12]

2.4 Tenure status of dwellings

Most Sudanese live in simple houses of their own or rent from landlords or agricultural-scheme authorities. Housing can be classified into four types according to tenure status as shown in Figure 5: owned, rented, provided as part of work and free dwelling.

Figure 5 illustrates that most of the dwellings are owned, about 86%, while housing provided as part of work registered the lowest value. The government doesn't play a big enough role in supporting affordable housing [13].

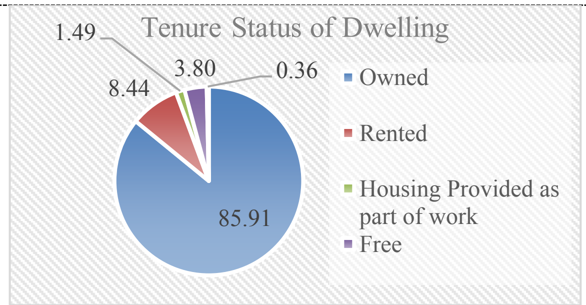


Figure 5. Tenure status of dwelling, Source: Central Bureau of Statistics 2008 [13]

2.5 Building materials in Sudan

The building materials in Sudan are classified into three types: (a) modern materials: i.e., concrete, red brick with cement mortar, cement bricks and corrugated iron sheets; (b) traditional permanent materials: red bricks combined with mud bricks for wall construction, mud construction for walls and roofing made from sticks, thatch and mud; and (c) traditional materials: i.e., thatch used for roofing and for walls. In first class areas (classification according to the residential area level), residential buildings are made of red bricks with clay or cement mortar, reinforced concrete ceilings, and roofs or corrugated iron sheets for roofing [14].

Residential buildings may be classified according to the building materials into straw huts, mud and adobe houses, red bricks houses and apartment houses (Figure 6 (a)). About 65% of the houses are from mud and adobe material, and a very low percent of the houses are apartments. This reflects the low level of urbanization in Sudan.

Another classification is according to the residential area level (Figure 6 (b)). The first and second class residential areas should be durable materials, while the houses in the third class residential areas can be constructed of semi-durable materials. Most of the houses are at the medium level, “the third class housing “and the percentage of the illegal houses are very high. This reflects the slow urban planning process. The top materials that have been used in houses are mud and adobe for wall, straw and palm leaves for roof construction (Figure 7 (a) and figure 7 (b)). Concrete and cement blocks registered the lowest percentage [15].

* Note: the data about the building materials, residential area classes and wall and roof materials of the house are rather old (from 1968). The main reason is to show the classification and the materials that have been used in the past. This survey is used by several authors [16]. According to our knowledge, there is no new data available.

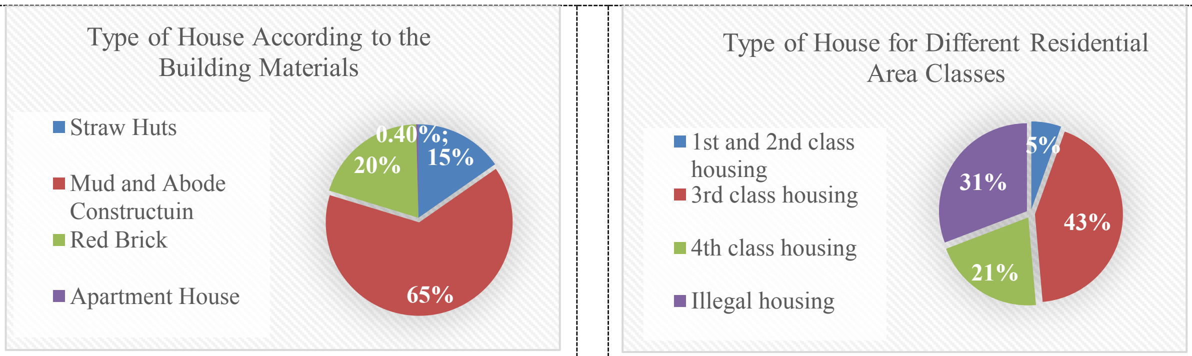


Figure 6. Type of house according to the: (a) building materials. (b) residential area classes Source: Household Sample Survey 1968

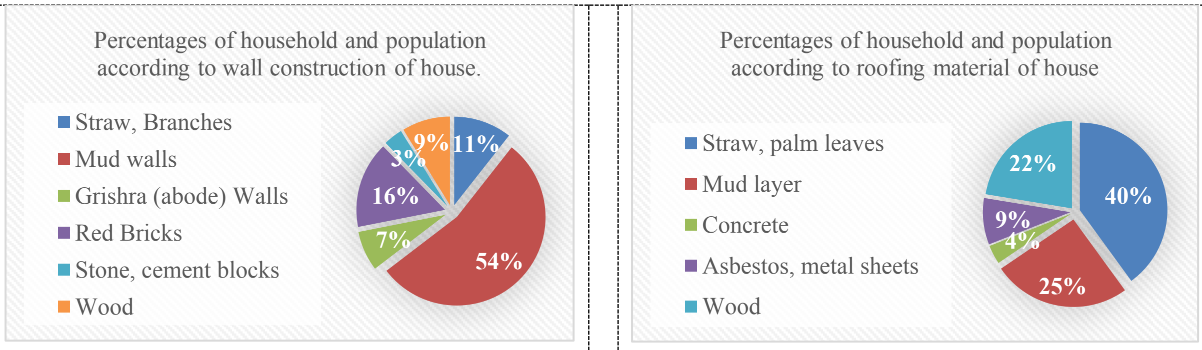


Figure 7. Percentage of household and population according to the (a) wall construction of the house (b) roofing material of the house. Source: Household Sample Survey 1968

2.6 Building construction development in Sudan

There is a big difference in the level of construction activities in Khartoum, the South, and North Darfur. The region of the Southern part and Darfur suffer from the low level of their built environment, due to the war, conflicts and the lack of economic development. There is a shortage of building materials due to draught and the huge need for shelter [17]. The most common houses in the rural part are the so-called Gottiya made of straw or millet stalks covering a wooden skeleton.

At the last census in 2008, over half of all housing units were Gottias (single rooms with round mud walls and a conical straw roof); about one-third were Menzils (multi-room houses with toilet facilities). Almost every house, even in the cities, has a walled courtyard or garden [18].

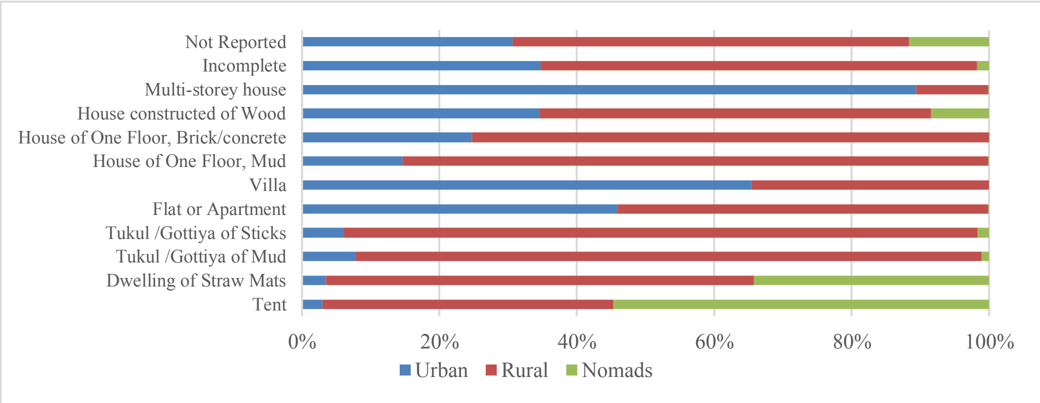
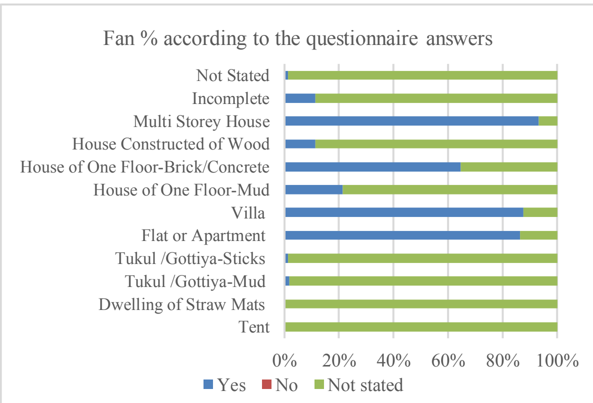


Figure 8. Household and population by type of dwelling
Source: Central Bureau of Statistics Census 2008 [13]

According to the collected data from 2008 census reports, dwellings in Sudan are classified into different types: tent, dwelling of straw mats, Tukul or Gottiya of mud, Tukul or Gottiya of sticks, flat or apartment, villa, single-storey mud house, single-storey brick or concrete, house constructed of wood and multi-story house. Most of the urban population live in a multi-story house and the rest in temporary and traditional houses. In the rural population, one-floor mud houses and Tukul or Gottiya stick houses are the common types, while multi-story houses rarely exist (Figure 8). The nomadic population depends on temporary materials, like straw mats and other temporary materials.

2.7 Heating and cooling devices:

Simple devices like fans and air coolers are used for cooling in Sudan. The data showed that these devices are used by about 18.17% of the total population for fans and 3.94% for air coolers. Most of these devices are used by the urban population rather than the rural population (Figure 9 and Table1). The data in Figure 9 may be unreliable due to a large amount of not stated answers.



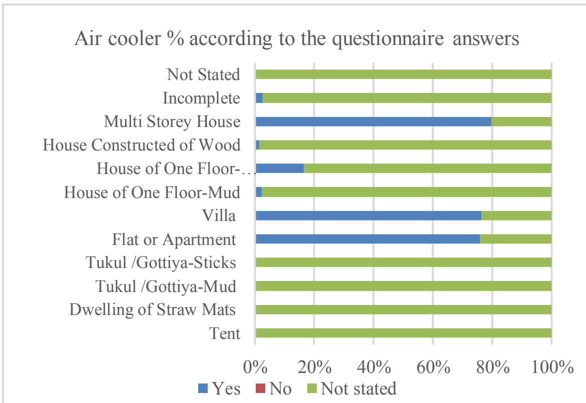


Figure 9. Percentage of fans and air coolers for different dwelling types according to the questionnaire answers, Source: Central Bureau of Statistics Census 2008 [13]

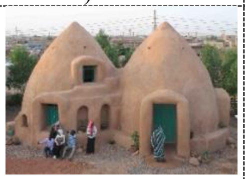
Table 1: Percentage of fans and air coolers of the total population

Item	Households%		
	Total %	Urban %	Rural %
Fan	18,17	40,22	9,3
Air Cooler	3,94	11,05	0,77

Source: Central Bureau of Statistics Census 2008 [13]

In temporary, old and traditional buildings fans and air coolers are rarely used, while they are more common in one-floor brick, concrete dwellings, single or multi-story houses and apartments (Figure 9). Most of the modern houses from reinforced concrete and bricks contain either simple or advanced cooling devices, due to the fact that concrete as a building material is not compatible with the Sudanese environment. Heating devices are not applicable in Sudan, except in a few houses in the northern part where electrical heaters are used for a few days in winter [13].

Table 2. Building typology table.

Construction Time	Temporary	Single Family Dwelling Detached			Multi-family Dwelling
		Climate Zone I (warm desert climate)	Climate Zone II (warm semi – arid climate)	Climate Zone III (tropical savanna climate)	
Very old (1900-1950)[1,2]		 House of One Floor Mud (Adapted)		 Tukul/Gottiya Mud	
Old (1956-2000)[3]	 Tukul /Gottiya Sticks	 Tukul/ Gottiya Mud	 House of One Floor Brick/ Concrete	 Dwelling of Straw Mats  Wooden Dwelling	 Flat or Apartment
Modern (2000- till now)[4]	 Tent  Tukul /Gottiya Sticks	 House of One Floor Mud	 Villa		 Multi Storey House

[1] Early Colonial Architecture (1900–1920)
[2] Late Colonial Architecture (1921–1956)
[3] The Post-Independence Era (1956–2000)
[4] Architecture from 2000 onwards [19]

3. Results

The aim of the research was to present an overview and create the building typology of Sudan based on the data collected according to the different parameters: construction time, climate zone, construction materials, durability, tenant status of the dwelling and the building capacity.

From the collected data we could arrange the building typology table (Table 2) according to construction time, different climate zones, the durability of the material and the family size. A short description of each type is as follows:

The Tent is a very old, temporary and easy to move dwelling, which is used by nomads. It is made from the local materials. ***Dwelling of Straw Mats*****:** a traditional dwelling which is made from pieces of mats connected together to form a room shape which is used as a shelter, it could be as a hut or a rectangle shape. ***Tukul/ Gottiya of Mud:*** a mud hut or house which is made essentially from the mud. (Tukul is a simple room made from traditional materials, some people use it as a place for cooking, while Gottiya is a single room with round walls and a conical roof.). ***Tukul/ Gottiya of Sticks:*** it's a temporary stick room, which is made essentially from sticks as supporters for the dwelling. ***Flat or apartment:*** made of modern buildings materials, such as bricks and reinforced concrete. ***Villa:*** includes a large amount of land and often barns, garages, or other outbuildings as well. ***House of one floor, mud:*** a traditional house with one or many rooms. It is made from mud as an essential material. ***House of one floor, brick/ concrete:*** a one family house with many rooms which is made from bricks and concrete. ***House constructed of wood:*** a single family house which is made from wooden elements. ***Multi- Storey House:*** a multi-family dwelling which is made from modern materials such as red bricks, reinforced concrete, cement block, and others.

4. Conclusions

The collected data from the country censuses, surveys, reports, and research papers had a lot of information about the climate, topography, building materials, and building technology of Sudan. A building typology table was prepared from the different collected data and with different parameters, such as construction time, the durability of the dwelling, and building capacity.

From the analysis the following points could be concluded:

- Climate change has a deep effect everywhere. In Sudan, the hot-arid areas have advanced southward, especially in the vulnerable areas surrounding Al Fashir and Nyala. This climate change caused a strong food scarcity, draught and affect the thermal comfort of buildings.
- The means of cooling and heating devices, such as air-conditioning is rarely used in Sudan because of the high cost of the operation, the price of the equipment and the low income of the majority of the urban population.
- The research on building typology was a starting point to better understand the features of Sudan's climate and to study and organize the building typology. These typology results should be improved and transferred into practical results.
- Data from Sudan's fifth population and housing census in 2008 were used, because it was the most recent, although there was some shortage of information on housing and building materials in the data. Due to this reason, some of the information applied in this paper is rather old but at least it was helpful in the classification and analysis procedure. Future research and updating the information will be much easier in the future.

5. Acknowledgment

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Life cycle environmental impact of refurbishment of social housing

Van de moortel E[1], Allacker K[1], De Troyer F[1], Stijnen L[2], Schoofs E[3]

[1]KU Leuven Faculty of Engineering Science – Department of Architecture, Leuven, Belgium
[2]Zonnige Kempen, Westerlo, Belgium
[3]Molse Bouwmaatschappij, Mol, Belgium

els.vandemoortel@kuleuven.be

Abstract. The current focus on climate change mitigation is reflected in policy goals to reduce the energy use of buildings. However, buildings are not only responsible for a large share of energy use and corresponding GHG emissions, they moreover require a lot of resources, produce a lot of waste, and emit harmful substances. In this paper, an approach is developed to investigate the most preferred renovation strategies for social housing, considering various parameters such as efficiency of the current and future heating system, service life of the heating system and insulation level of the building envelope. Moreover the reduction in life cycle environmental impact due to the replacement of heating systems by systems with increased efficiency is studied. The results show that for non-insulated buildings an increase of the thermal resistance of the building envelope is more effective than replacing the heating system while for, even poorly, insulated buildings the efficiency of the heating system is more important. A holistic Life Cycle Assessment approach is preferred to assess renovation scenarios as focussing on energy reduction might lead to an increase of the life cycle environmental impact of the building. Although this paper focuses on social housing, the approach is broadly applicable.

1. Introduction

Buildings are responsible for a large share of energy use and GHG emissions in Flanders [1] [2], require a lot of resources, produce a lot of waste and emit harmful substances [2] [3]. Despite these insights policy currently focusses merely on the reduction of energy use in buildings. The current draft climate policy plan for Flanders aims for a compliance of all residential buildings with an Energy Performance Certificate (EPC) level A by 2050 [4], [5]. An EPC shows the energy score of the building compared to other buildings [6] and is calculated using a standardized method [7]. To reach this goal the energy use in residential buildings should decrease 76% compared to 2012 by 2050 [5] and therefore Nearly Zero Energy Building (NZEB) renovations are put forward [8] [4]. Social housing companies face an important challenge in renovating their existing housing stock to a level compliant with these policy goals [1] [4] [8] as they have limited budgets. Although operational energy use is causing an important impact on climate change [9], a narrow focus on energy reduction should be avoided. This paper therefore evaluates renovation scenarios using a Life Cycle Assessment (LCA) approach, considering multiple environmental impacts. The most preferred refurbishment strategies for social housing are investigated, considering various parameters such as efficiency of the current heating system, service life of the heating system and (increased) insulation level of the building envelope. Typically, LCA studies are static studies, meaning that the impact of the interventions of to date are included in the assessment, but that future improvements during the service life of the building are not considered. In this paper, a dynamic approach is developed that takes into account future improvements such as expected improvements of heating system efficiency for every future replacement.

2. Description of the method

2.1. Estimation of the energy use

In a first step the energy use for spatial heating of the building is estimated based on the equivalent degree day method [10] [11](1). Ventilation losses and solar and internal gains are assumed to be constant for the various refurbishment strategies as data collection on these aspects is not yet finalised.

$$Q_t = \left(0{,}024\ \sum_{q=1}^{w} \frac{S_q\, a_q}{R_q}\right) Eq°d\ \frac{1}{\eta} * L \tag{1}$$

Table 1. Parameters to estimate the energy use to compensate transmission losses over the service life of the building.

Q_t	Heating energy over the building service life (kWh)	
Sq	Surface of each element (m²)	Input
a_q	Correction factor heat losses	Input [12]
Rq	Thermal resistance of each element (m²K/W)	Input [12]
Eq°d	Equivalent degree days (K d)	1200 [13], [14]
η	Global system efficiency (%)	Input [15]
L	Building service life (years)	60

For the energy calculation (and related environmental impact assessment), a dynamic approach is used whereby a more efficient heating system is assumed each time the system is replaced. As future efficiencies are unknown, estimates are made based on the analysis of historic data. The estimated efficiency of the heating system installed in the year of the replacement ($\acute{\eta}_t$) is based on the efficiency in year 0 ($\acute{\eta}_0$) and the annual growth rate for efficiency ($g_{\acute{\eta}}$) (2). The latter is assumed to be 0,5%. Sensitivity analysis on this parameter is foreseen in a future step of the research.

$$\acute{\eta}_t = \acute{\eta}_0 * \left(1 + g_{\acute{\eta}}\right)^t \tag{2}$$

2.2. Assessment of the environmental impact

The environmental impact of the materials used for the renovation measures and of the energy use for heating is assessed through a Life Cycle Assessment (LCA) [16] [17]. The Belgian LCA method for buildings and building elements [13] is used. This method considers seven impact categories in line with the European standard EN15804+A1:2013 [18] and ten additional impact categories in line with the Belgian legislation [19].

For the inventory of the data, the Ecoinvent database version 3.3 [20] is used. Scenarios for transport to the building site and installation, as well as scenarios for cleaning, maintenance, sorting, transport to the End Of Life (EOL) treatment and the EOL treatment itself are based on the Belgian LCA method [13]. The dismantling of materials is assumed to be manual and therefore no impact is included. In case the elements are still in a good condition, the existing element is maintained. In case the element is renovated, both the impact of the new element and the impact for the EOL treatment of the existing element (E_0) are taken into account. It is furthermore assumed that the service life of some components is lower than the service life of the building and hence require replacements during the building service life. More specifically, it is assumed that 10% the roof tiles and the entire internal roof finishing are replaced each 30 years. These are assumed to be replaced by identical materials (with the same environmental impact as to date). The estimated service life of the windows is assumed to be 30 years and these are replaced by better insulating windows. The service lives of elements are based on literature [21]. At the end of the service life of the building, here 60 years, the impact of the EOL treatment of all elements is included. The assumptions for the EOL treatment of the elements and systems are presented in Table 2.

Table 2. Overview of EOL treatment **[13]**.

	On site Sorting on site	Fractions landfill	allocated to incineration	specific EoL recycling
Waste glass sheet (window)	70%	5%		95%
Wooden products (window)	40%		85%	15%
Ceramic roof tiles	75%	95%		5%
Fibre cement slabs	75%	100%		
Gypsum plasterboard	50%	80%		20%
System (metals)	100%	5%		95%

2.3. Assessment of the Environmental Life Cycle Cost

The national LCA method in Belgium includes the option to aggregate all impact categories in a single score by calculating an external environmental cost in euro, the E-LCC, presented in Table 3 [22]. This represents the costs to avoid or compensate the environmental impacts caused. To make straightforward decisions in case of contradictory indicators, the E-LCC is used to compare the renovation strategies.

Table 3. Overview central monetary values [22, table 3 and 4, p 12]

Environmental indicator	Unit	Monetary value (€/unit)	Environmental indicator	Unit	Monetary value (€/unit)
Global warming	kg CO2 eqv.	0.100	Ecotoxicity: freshwater	CTUe	3.70E-05
Depletion of the stratospheric ozone layer	kg CFC-11 eqv.	49.10	Water scarcity	m3 water eqv.	0.067
Acidification of land and water sources	kg SO2 eqv.	0.43	Land use: occupation: a. soil organic matter	kg C deficit	2.7E-06
Eutrophication kg	(PO4)3- eqv.	20	Land use: occupation:		
Formation of tropospheric ozone photochemical oxidants	kg etheen eqv.	0.48	b. biodiversity		
			- urban: loss ES	m2.a	0.30
			- agricultural	m2.a	6.0E-03
Abiotic depletion of nonfossil resources	kg Sb eqv.	1.56	- forest: biodiversity	m2.a	2.2E-04
Abiotic depletion of fossil resources	MJ, net caloric value	0	Land use: transformation: a. soil organic matter	kg C deficit	2.7E-06
Human toxicity			Land use: transformation:		
a. cancer effects	CTUh	665109			
b. non-cancer effects	CTUh	144081	b. biodiversity		
Particulate matter	kg PM2,5 eqv.	34	- urban:	m2	n.a.
Ionising radiation,			- agricultural	m2	n.a.
a. human health	kg U235 eqv.	9.7E-04	- forest, excl. tropical	m2	n.a.
b. ecosystems	CTUe (per kBq)	3.70E-05	- tropical rainforest	m2	n.a.

3. Results and discussion

3.1. Description of the case study building

The case study building is a terraced family house of two floors with three bedrooms for four people. The building is constructed in 1983. The external walls and roof are insulated with 6 cm of mineral wool insulation. Currently no ventilation system is installed. The present heat production system is a gas boiler with a production efficiency of 85%. The default values of the Flemish EPB standard [15] are assumed for the efficiency of the other system components (emission, regulation and distribution) which results in a total system efficiency of 69%. The surface area and composition of the building elements being renovated are presented in Table 4.

Table 4. Composition of building elements being renovated.

Element	Construction	U value (W/m²K)
Floor on grade 86,85 m²	- Concrete slab - Support layer - cement based screed - Ceramic tiles	2,89
External walls 83,20 m²	- Gypsum plaster - Loadbearing brickwork - Mineral wool insulation (6 cm) - Brick veneer	0,45
Pitched roof 83,70 m²	- Roof tiles - Wind and water barrier - Mineral wool between wooden beams (6 cm) - Gypsum board	0,55
Windows (27,88 m²) and roof windows (3,15 m²)	Wooden frame with double glazing	3,30

3.2. Description of the renovation scenarios

The renovation scenarios for the building envelope are presented in Table 5. For each scenario several thicknesses of the insulation material are considered. For the external walls the first scenarios is adding external mineral wool insulation with a finishing of façade tiles on a wooden frame. In a second scenario external EPS insulation is added to the walls, finished with a mineral rendering. It is assumed that the service life of the external rendering is 30 years and that it is then replaced by an identical one.

Table 5. Description of renovation scenarios.

External wall					
Scenario stone wool (λ0,04 W/mK)			Scenario EPS (λ0,03 W/mK)		
Thickness (m)	U value (W/m²K)	Environmental investment cost (euro/m²)	Thickness (m)	U value (W/m²K)	Environmental investment cost (euro/m²)
0,06	0,67	2,04	0,06	0,50	1,83
0,07	0,57	2,09	0,08	0,38	1,94
0,085	0,47	2,14	0,10	0,30	2,05
0,09	0,44	2,20	0,12	0,25	2,17
0,10	0,40	2,25	0,14	0,21	2,28
0,12	0,33	2,35	0,16	0,19	2,39
0,18	0,22	2,67	0,18	0,17	2,51
Pitched roof					
Scenario stone wool (λ0,036 W/mK)			Scenario PUR (λ0,024 W/mK)		
Thickness (m)	U value (W/m²K)	Environmental investment cost (euro/m²)	Thickness (m)	U value (W/m²K)	Environmental investment cost (euro/m²)
0,06	0,60	2,69	0,06	0,40	3,17
0,08	0,45	2,77	0,08	0,30	3,65
0,10	0,36	2,85	0,10	0,24	4,13
0,12	0,30	2,94	0,12	0,20	4,61
0,18	0,20	3,19	0,16	0,15	5,56
Windows					
High efficiency double glazing - wooden frames U 1,5 W/m²K		Environmental investment cost (euro/m²) 12,46	Triple glazing - insulated wood-cork frames U 0,9 W/m²K		Environmental investment cost (euro/m²) 14,95
Roof windows					
High efficiency double glazing - wooden frames U 2,45 W/m²K		Environmental investment cost (euro/m²) 12,46	Triple glazing - insulated wood-cork frames U 1,47 W/m²K		Environmental investment cost (euro/m²) 14,95

For the renovation of the pitched roof, again two scenarios are considered: (1) insulating with mineral wool between the existing wooden structure and (2) adding PUR insulation boards on top of the existing structure. The finishing for both roof scenarios is assumed to be with new ceramic roof tiles. For the heating boilers three options are considered: (1) the existing boiler was recently replaced and hence can be used for another 10 years, (2) the boiler is replaced by a new one with a service life of 30 years and (3) the boiler is replaced by a new one with a service life of 20 years. After 10, 20 or 30 years the boiler is replaced by a new system with a better efficiency and the EOL treatment of the previous system is included. For the scenarios where the heating boiler is replaced in year 0. The efficiency of the new heating boiler (in year 0), is assumed 97% or 104%, resulting in a heating system efficiency of 78% or 84% respectively. As mentioned in section 2.1, the efficiency of the replaced boilers at year 10, 20 or 30 is assumed to be higher than to date according to formula (2).

3.3. Analysis of the influence of the insulation level of the base case

As the housing stock of social housing companies in Flanders is divers and consists of buildings with different construction periods, it would be interesting to see whether this would affect the selection of the renovation scenarios. To provide this insight, the assessments are done for the case study building as described in section 3.1 and for a hypothetical case assuming the building is not insulated.

3.4. E-LCC and energy demand for several renovation scenarios

3.4.1. The effect of including the efficiency increase for future replacements of the heating system. To gain insight in the importance of using a dynamic LCA approach, the results of the dynamic approach are compared with ones using a static approach (i.e. efficiency of the heating system is kept constant during the whole service life of the building). For this comparison it is assumed that the existing boiler was recently replaced and will be replaced in 10 years by one with a higher efficiency and a service life of 30 years. The results for both the case study and the hypothetical uninsulated house are presented in Figure 1 per building element and in Figure 2 per impact category. A decrease of the total E-LCC of 5,47% for the poorly insulated building and 8,99% for the non-insulated building is noticed when the dynamic approach is used. This is due to the decrease of the energy use needed for heating the building and a corresponding decrease of the impact on global warming. This confirms that a dynamic approach is important.

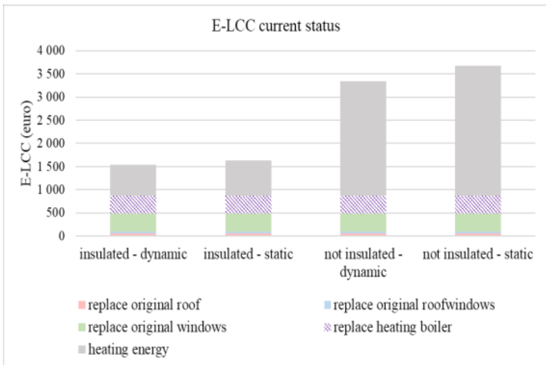

Figure 1. E-LCC per element of the case study building and hypothetical uninsulated building using a dynamic and static LCA approach

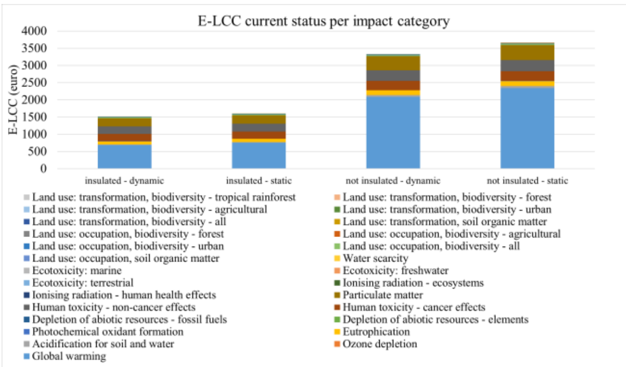

Figure 2. E-LCC per impact category of the case study building and hypothetical uninsulated building using a dynamic and static LCA approach

3.4.2. E-LCC results of the renovation scenarios. The E-LCC of several renovation scenarios for the poorly insulated case study building and the non-insulated hypothetical situation are presented in Figure 3. Table 6 shows a description of the renovation scenarios studied in Figure 3.

Table 6. Description of the renovation scenarios studied in Figure 3

	Insulated	Not insulated
Current status	6 cm mineral wool wall insulation 6 cm mineral wool roof insulation Roof windows U 3,30 W/m²K Windows U 3,30 W/m²K Heating 69% efficiency, 30 year service life	No wall insulation No roof insulation Roof windows U 3,30 W/m²K Windows U 3,30 W/m²K Heating 69% efficiency, 30 year service life
Minimal investment	6 cm mineral wool wall insulation 6 cm mineral wool roof insulation Roof windows U 3,30 W/m²K Windows U 3,30 W/m²K Heating 78% efficiency, 30 year service life	No wall insulation No roof insulation Roof windows U 3,30 W/m²K Windows U 3,30 W/m²K Heating 78% efficiency, 30 year service life
Minimal energy use	18 cm EPS wall insulation 16 cm PUR roof insulation Roof windows U 1,47 W/m²K Windows U 0,90 W/m²K Heating 104% efficiency, 20 year service life	
Minimal E-LCC	6 cm mineral wool wall insulation 6 cm mineral wool roof insulation Roof windows U 3,30 W/m²K Windows U 3,30 W/m²K Heating 84% efficiency, 30 year service life	10 cm stone wool wall insulation 12 cm stone wool roof insulation Roof windows U 3,30 W/m²K Windows U 3,30 W/m²K Heating 84% efficiency, 30 year service life
NZEB 1	18 cm stone wool wall insulation 18 cm stone wool roof insulation roof windows U 2,45 W/m²K windows U 1,50 W/m²K Heating 84% efficiency, 30year service life	
NZEB 2	12 cm EPS wall insulation 10 cm PUR roof insulation Roof windows U 2,45 W/m²K windows U 1,50 W/m²K Heating 84% efficiency, 30year service life	

One of the current renovation measures in social housing is replacing the existing heating system by a better one, represented in Figure 3 as the scenario “min investment”. For the case study building this results in an E-LCC decrease of 4%, while for the non-insulated building the effect is higher, namely 7%, due to the higher original heating demand. The results show that (1) the effect of improving the heating system is lower when the building is better insulated and (2) that it is more interesting to improve the insulation level of non-insulated buildings than replacing the heating boiler.

The renovation scenario minimal energy use in Figure 3 leads to the lowest heating demand for the poorly insulated building. For this renovation scenario a reduction of the energy use of 64% is obtained, however, the E-LCC for this scenarios increases with 88% compared to the current status. Apparently the reduction of the impact for heating the building due to the extra insulation and more efficient heating boiler cannot compensate the additional impact for the new materials and the new boiler. On the other hand, for the non-insulated building a reduction of the energy use of 89% is shown for the scenario leading to the lowest energy use, which results in a reduction of the E-LCC with 19%. Striving for a minimal energy use is hence not the best approach for all buildings to reduce the environmental impact.

The renovation scenario resulting in the lowest E-LCC for the poorly insulated case study building results in a reduction of 7% of the E-LCC and a reduction of 15% of the energy use. This scenario only includes a replacement of the heating system. Further increasing the insulation of the building envelope does not result in a sufficient reduction of the heating demand to compensate for the additional impact of the new materials. For the non-insulated building a much higher (44%) reduction of the E-LCC is achieved for the scenario leading to the lowest E-LCC. The further energy reduction due to additional replacement of the windows is insufficient to compensate for the additional environmental investment costs.

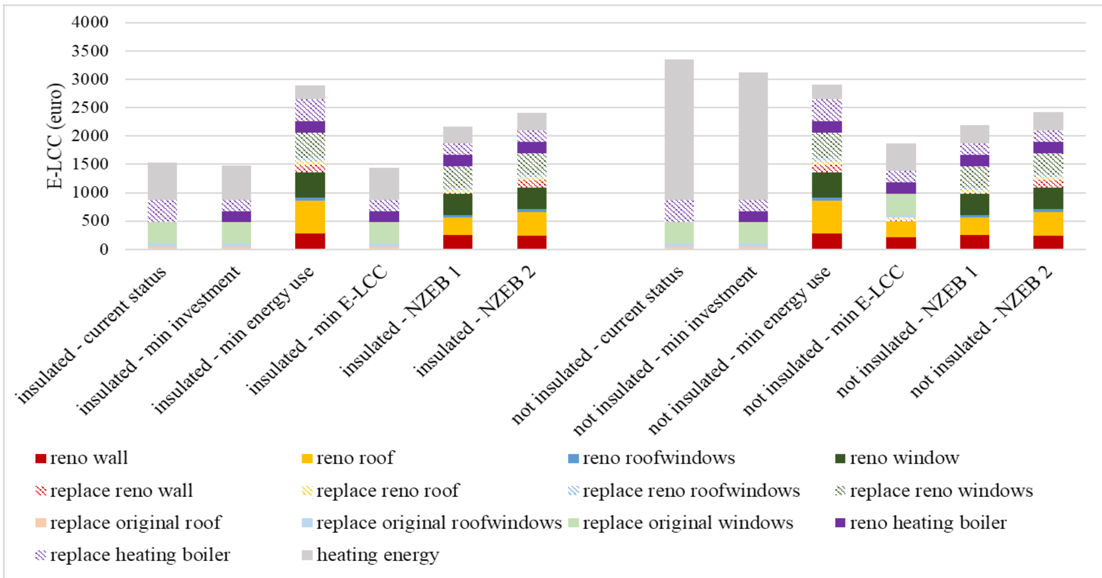

Figure 3. E-LCC for several renovation scenarios for the poorly insulated case study building and the hypothetical non insulated situation

3.4.3. E-LCC results of two NZEB scenarios. The requirements for NZEB renovation are based on U values for the building elements *[8]*. However, the environmental impact of buildings is not merely related to the impact of the energy use, but moreover the impact of the materials can be important. To gain insight in the E-LCC of NZEB buildings compared to the analysed renovation scenarios, two scenarios for NZEBs, with different materials, were defined. The results are presented in Figure 3 for both the poorly insulated case study and the hypothetical uninsulated building.

For the poorly insulated building the reduction in energy use of the two NZEB scenarios is similar, 54% and 53%. Although the E-LCC is increased for both scenarios the magnitude of the increase is slightly different due to the different impact of the insulation and finishing materials used in each scenario. For the scenario with mineral wool insulation the E-LCC has increased with 41%, while for the scenario with EPS and PUR insulation the E-LCC has increased with 56%. This can be explained by the difference in the impact of the production process of both the insulation and the finishing materials and in the difference in service life of the chosen finishing [21]: the rendering needs to be replaced once entirely during the service life of the building while the façade tiles need only one partial replacement. For the non-insulated building the NZEB renovation scenarios lead to a decrease in energy use of 87% and 86% and a decrease in the E-LCC of 35% and 27% respectively.

For the case study building, the NZEB renovation scenario leads to an increase of the E-LCC of the building compared to the current status, while for the non-insulated building the NZEB renovation scenarios lead to a decrease in the E-LCC, although other scenarios lead to an even further decrease.

Table 7. Overview of the effect on energy use and E-LCC of the various renovation scenarios.

	Insulated building		Non-insulated building	
Scenario	Energy use (kWh)	E-LCC (euro)	Energy use (kWh)	E-LCC (euro)
Current	100%	100%	100%	100%
Min. investment	-9%	-4%	-9%	-7%
Min. energy use	-64%	+88%	-89%	-19%
Min. E-LCC	-15%	-7%	-80%	-44%
NZEB 1	-54%	+41%	-87%	-35%
NZEB 2	-53%	+56%	-86%	-27%

The effect on the energy use and E-LCC of the various renovation scenarios is presented in Table 7. The policy goal to reduce the energy use with 76% seems not possible for the case study building. However as the case study building is already insulated, this goal is possibly to strict. Based on the current EPC score (241) for the case study building [23], only a reduction of 42% is needed to reduce the EPC score to 100. Based on the results presented in Table 7, a 42% reduction can be achieved although resulting in a higher E-LCC and thus leading to a higher environmental impact. If the case study building would not have been insulated, all energy renovation scenarios would lead to a lower E-LCC, however important differences in the magnitude of the reduction of the E-LCC are noticed.

4. Conclusions and further outlook

This paper studied whether a future increase of the efficiency of heating systems has an important impact on the estimation of the life cycle environmental impact of a building. Furthermore the most preferred renovation strategies for social housing are investigated.

Considering that replacements of heating boilers during the service life of a building will include a higher efficiency at each replacement, results in a decrease in the Environmental Life Cycle Cost (E-LCC) of 5,47% for a poorly insulated building and 8,99% for a non-insulated building. As improvements in the emission and distribution components of heating systems as well as coupling with other systems, such as for example heat pumps can be expected, it seems interesting to further study possible improvements in technology for heating in detail. Besides the effect of efficiency increase of heating systems, the effect of the service life of the system on the E-LCC of the building is studied. As a shorter service life of the heating boiler results in more replacements and the corresponding increase in E-LCC linked to the investment in new systems, it is preferred not to replace the heating system before the end of its technical life.

The most preferred renovation strategy for a non-insulated building proved to consist of improving the thermal resistance of the building envelope rather than replacing the boiler by a more efficient one. For poorly insulated buildings, the opposite was found: for these buildings it is more interesting to replace the heating boiler by a more efficient one.

The analysis of NZEB renovation scenarios as proposed by policy revealed that these lead to an increase in the E-LCC for the poorly insulated building, whereas for the non-insulated building this scenario leads to a reduction of the E-LCC compared to the current status of the building. However renovation scenarios with a lower insulation level lead to an even lower E-LCC. Striving for a minimal energy use results in a higher E-LCC for the poorly insulated building because the E-LCC of the additional materials to insulate the building envelope cannot be compensated by the reduction of the E-LCC for energy. It seems therefore more efficient to focus in the E-LCC of renovation scenarios rather than on the reduction of the energy use.

As the impact on global warming is linked to the amount of energy from natural gas needed for heating the building it seems interesting to study the effects of a shift to renewable energy. Therefore estimations on the energy use needed to prepare sanitary hot water and the electricity use should be included in future research to assess the effect of renewable technologies such as solar collectors or PV panels.

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Improving Construction Efficiency with Digital Fabrication. An Environmental Insight

Kuzmenko K[1,2], Féraille A[1], Baverel O[1]

[1]Laboratoire Navier, UMR 8205, Ecole des Ponts ParisTech, IFSTTAR, CNRS, 6-8 Av. B. Pascal, 77455 MLV Cedex 2

[2]Kardham C&H Architecture, 10 rue du Débarcadère 75017 Paris

kateryna.kuzmenko@enpc.fr

Abstract. This paper presents a case study of environmental evaluation of innovative shell-nexorade hybrid timber construction system designed within fabrication-aware technic and fabricated using robotic construction technology. The life cycle assessment of construction phase of the system has been performed; a sensitivity study of the robotic system's outlay has been effectuated. The results show that the contribution of robotic construction system to the overall result is fairly significant and, in some figures, can even exceed the material's one.

1. Introduction

The ongoing development of digital design and fabrication techniques has explicitly changed the way architecture is thought, designed and produced. The emergence of the non-standard movement in the early 2000 was explicitly arguing for the beginning of the new era based of mass-customization paradigm, that was supposed to bring some spectacular changes to construction industry by releasing its production from the curse of standardization [1],[2].

Therefore, empowered by computation, a whole generation of highly optimized forms appeared, spreading a belief into the sustainable character of those as well as the potential of digital technologies in the field of environmental performance of the sector.

Nevertheless, most of optimization and rationalization technics are principally focused on a single phase of life cycle of a product or a single impact indicator. Today's most of energy-efficiency policies are focused on the operational phase of a building, e.g. heating, cooling, etc [3]. And a recent slight progression towards life cycle performance generated a hot discussion amongst practitioners on ecological character of different construction materials, with a succeeding popularity of timber high-rise buildings.

Regarding the academic trends, multiple lightweight construction systems were developed within digital design-to-production workflow [4], [5]. A significant reduction of construction materials in various building elements was achieved, strengthening the credence into the sustainable potential of digital fabrication.

In this paper we question the environmental performance of morphologically optimized and numerically produced construction system. The use of life-cycle assessment method is proposed to evaluate the question. An innovative timber construction system - shell-nexorade hybrid is taken as a case-study.

The purpose of the study is twofold: in the first place, the environmental impact of the construction system is assessed, secondly the impact transfer of the system is investigated. In other terms, the fundamental question of this work is the possible trade-off between efficiency of the structure and environmental load of robotic construction system.

2. Description of the structure

2.1. Design

The structure was built for the occasion of 20 years of the new site of Ecole des Ponts ParisTech, by the team of Navier Laboratory. Also known as R2 pavilion, the structure incorporates manifold researches on structural morphology and architectural geometry conducted in laboratory.

Figure 1. *R2 Pavilion* built with shell-nexorade hybrid structural system

The structural type of the pavilion was baptized as shell-nexorade hybrid, due to the elegant blend of both principles. Nexorades, are largely known as reciprocal frames. They are constituted of load bearing members which support each other in a cyclic manner along their sides [6]. This specific arrangement of members makes them connect by pairs, creating a significant simplification of assembly, which is a general problem of classical space structures and gridshells. However, the simplification of assembly technics comes along with an increase of geometrical complexity, which is usually solved by a form-finding method as far as design part is concerned [7].

The membrane behaviour was achieved by introducing the flat panels that act like bracing elements and transform the grid of beams into the shell structure. Therefore, with an additional 30% of material mass the structural stiffness was multiplied by 10.

The planarity of the bracing quad panels was held within marionette method [8] in order to ensure their fabrication flair as well as to avoid the coupling between bending and axial forces. Therefore, the initial surface was meshed with planar quads, then using translation method [9] the T-joints were generated, preserving the planarity of the quads.

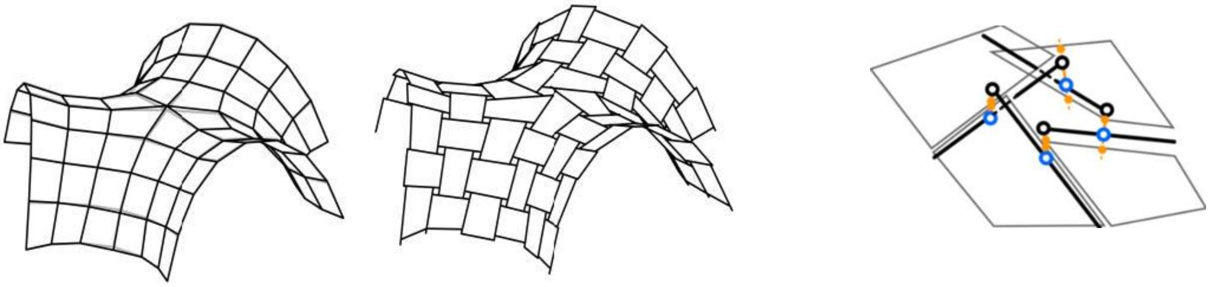

Figure 2. PQ-mesh transformation to Reciprocal Frame(left); Marionette technic for planarity of quads (right) **[10]**

2.2. Fabrication

Most of design choices of the project were made within the fabrication-aware strategy [11] , which could be briefly described as the geometry rationalization principle focused on manufacture constraints. Thus, the final structure is composed of 102 straight glulam beams and 48 flat plywood panels, each of which is non-standard. The totality of formal and manufacturing complexity was brought into beam's geometry (Figure 3), to be held with 6 axes robotic milling. As follows, the panel fabrication was abridged to a mere CNC cut.

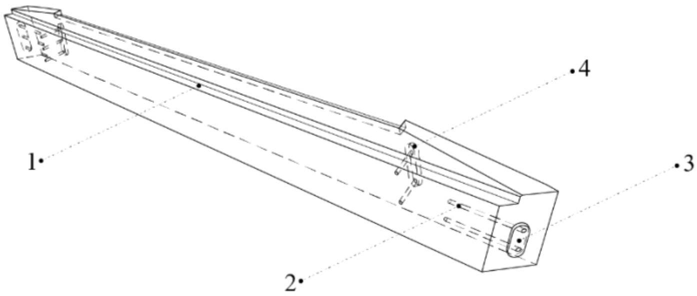

Figure 3. Example of beam element:

1. Reservations for panels
2. Screws to set place
3. Tenon
4. Mortise

The layout scheme of the robotic platform of Ecole des Ponts ParisTech is shown in Figure 4. It is composed of two collaborating 6 axes robotic arms (1): one is mounted on a 9 m track (2) and referred as gripper robot (1a), the other is fixed and referred as fixed robot (1b). The milling head (3) is mounted on fixed robot and the pneumatic gripper (4) is fixed on gripper robot. Next, eight independent operations were effectuated with stationary fixed tools dispatched around the track (cf.[12]).

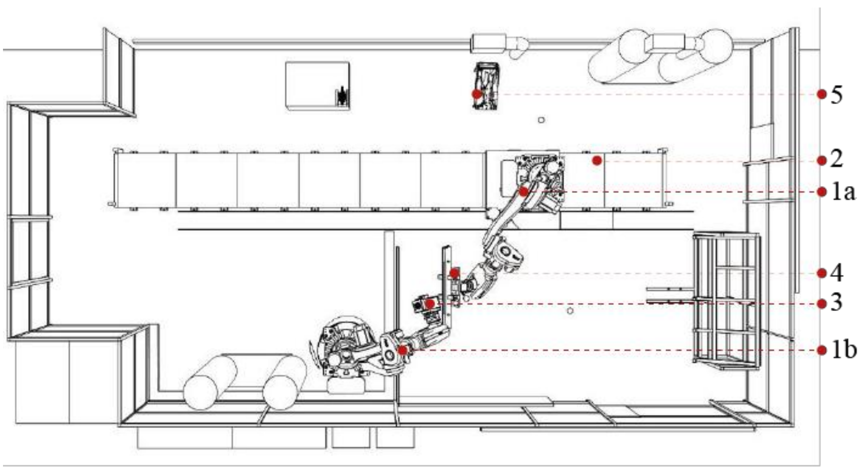

Figure 4. Top view of layout of robotic fabrication platform: 1a _Gripped Robot; 1b _Fixed Robot; 2_Track; 3_Milling head; 4_Pneumatic gripper; 5_Circular saw [10]

2.3. Assembly

The assembly technic of the structure represents the most low-tech part of the construction process. It basically demands some drilling skills and some specific crews, that can be set against the wood fibres [13] (Figure 5).

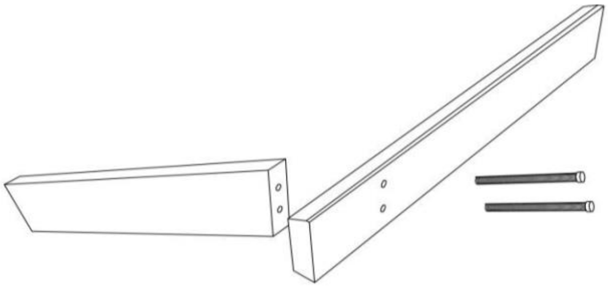

Figure 5. Scheme of T-connections assembly of Beams [12]

All the construction elements of a structure were prefabricated off-site and assembled in-situ, which demands an approximately zero tolerances of fabrication and assembly processes. The assembly sequence starts from the construction of a hexapod from the central node and then progresses to the boards. Geometric control of connections was ensured through the tenon/mortise system milled on the beam's extremities (Figure 3) and the adjustment of the bracing panels (cut with a tolerance of 2 mm on each side). Authors claim that the assemblage part can be handled by 2 persons [12], back in time though the human resources needed to figure one were 6 PhD students, 2 Academic Researchers and 1 Professor.

3. Methodology

In order to evaluate the environmental character of the structure, the Life Cycle Analysis method is used [14], [15].

A few academic works have already explored a similar problem. Agusti-Huan et al. have effectuated a foremost work in the field, comparing digitally fabricated elements with ones fabricated conventionally [16], [17], concluding that digital fabrication processes do not really count in total results, comparing to the potential in terms of material reduction they bring. The system boundaries of the analysis were cradle-to-gate, without consideration of end of life phase.

Krieg et al. have also performed an LCA study of an innovative timber structure [18]. The constructive system was compared with its alternatives, differentiating materials and fabrication technics. The stiffness of the structure was referred as functional unit and only the GWP indicator was considered. The results show that even if the embodied carbon of materials is still more important than the one of robotic construction system, the second does contribute to global result. It seems that only energy consumption of the robot was taken into account.

In present case study we focus on the methodology for taking into account robotic construction system. Therefore, a detailed life cycle model of robotic fabrication system was assembled, taking into account the maintenance and the replacement of components during service period that was set for 12 years. Then, a sensitivity study of the outlay of the construction system to the referenced process was effectuated, ranging a working period of machines within three scenarios (Table 1) in order to investigate the difference it will bring to global result. The outlay calculation follows the expression below:

$$\frac{\text{Working Period of Machine}}{\text{Lifespan of Machine}}\ 100\%$$

The first one considers uniquely the fabrication time which is around 20 minutes by beam and one hour for panels. The second one reflects an idealistic scenario of the entire production process: one week by machine, which still is greatly optimist for the research project. The third scenario accounts an actual duration of parametrisation and set up period needed at the time: two months for robotic cell and two weeks for CNC cell. It is important to note that the energy consumption remains the same in all three scenarios.

Table 1. Three scenarios of machines' outlay

	1st Scenario	2nd Scenario	3rd Scenario
Robotic Cell's Outlay	**37.62 H** / 105120 H = 0,04%	**120 H** / 105120 H = 0,1%	**1440 H** / 105120 H = 1.4%
CNC Cell's Outlay	**1 H** / 175200 H = 0.0006%	**120 H** / 175200 H = 0,07 %	**576 H** / 175200 H = 0,3 %

In order to have comparable results regarding other construction technics, the cradle-to-gate stages were set as system boundaries (A1-A3 cf. EN 15804).
Recipe Midpoint (H) method of impact calculation was chose, following to the ILCD Handbook recommendations [19]. The EcoInvent 3.2 cut-off database was used for inventory within OpenLCA software. Finally, the life cycle model of the system is depicted in Figure 6.

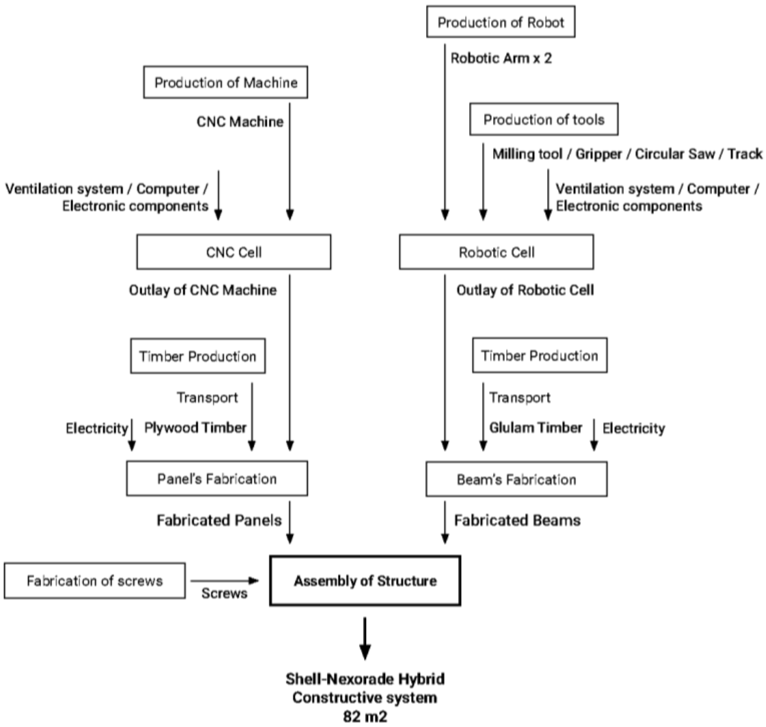

Figure 6. Life-Cycle Model of Shell-Nexorade Hybrid Construction System

4. Results and Discussion

The environmental impact of the shell-nexorade hybrid construction system is presented on the Figures 7 and 8. The variation in results is related to different outlay calculation of robotic and CNC cells to the process of reference. In other terms different working time of machines were considered in order to investigate the sensitivity of the parameter.

The present study illustrates that digital fabrication processes contribute significantly to the overall environmental impact of the system, which means that optimisation design strategies based on robotics technology for the production part should take into account the environmental load of the last.

The same hypothesis needs to be verified for the structure of larger scale containing more elements. Considering the important amount of time needed for the parametrization of production sequence versus the rapid execution, the environmental load of digital fabrication may be insignificant for larger production series. Finally, the present results need to be compared with an alternative construction system fabricated without robotic technology, in order to have the complete vision.

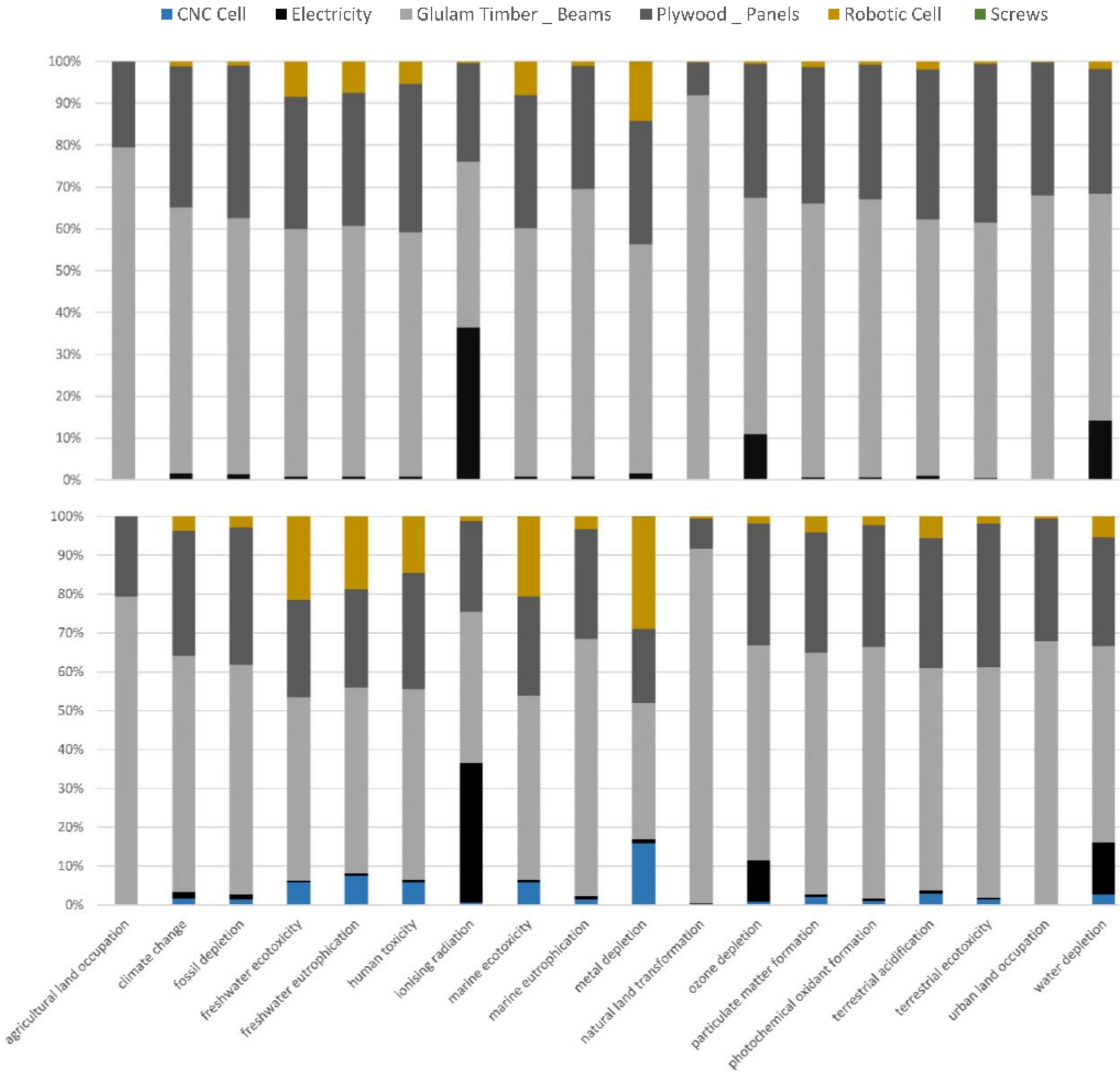

Figure 7. Environmental Impact of Shell-Nexorade Hybrid _ 1st Scenario (above), 2nd Scenario (below)

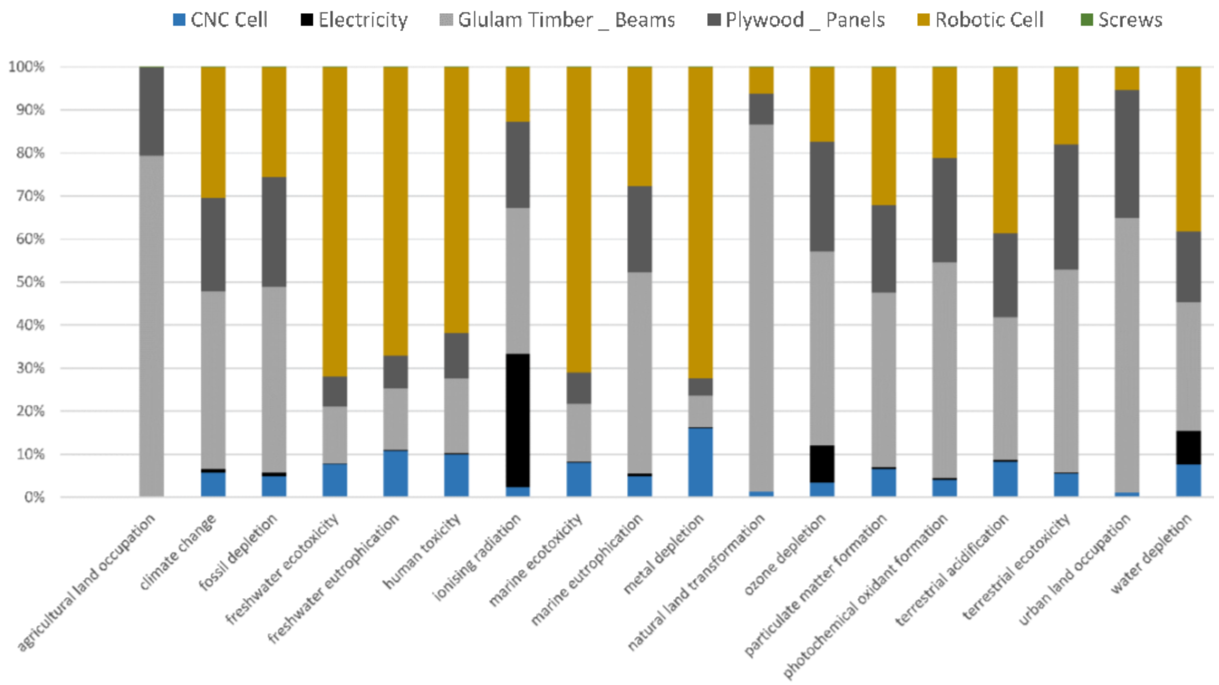

Figure 7. Environmental Impact of Shell-Nexorade Hybrid _ 3rd Scenario

5. Conclusion

This LCA study of innovative timber construction system designed within the fabrication-aware strategy and produced using digital fabrication technics demonstrates the occurring of an important impact transfer in the life cycle of the system caused by robotic fabrication technology. The sensitivity analysis of the outlay of machine's working time has confirmed the significance of this parameter in the overall result. Consequently, depending on the accountment method the contribution of digital fabrication system can be almost as important as the one of the materials, which answers the fundamental question of this work on the possible compromise between those two.

In closing, automation in construction is today's one of the most major research topic in building sector. In early 2000, numerical controlled machines were theorised as the solution for the differentiated mass production, in middle 2010, robotics begun to be seen as the solution to the environmental problem of the sector. Yet, for multiple reasons of legal and technological inertia of the industry, the mass-customisation is barely ready to advent, and the environmental performance of automation remains to be developed within the appropriated theoretical agenda.

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A holistic approach for industrializing timber construction

Santana-Sosa A[1], Fadai A[1]

[1] Vienna University of Technology, Department of Structural Design and Timber Engineering, Karlsplatz 13 / 259-2, A-1040 Vienna, Austria

a.santana-sosa@iti.tuwien.ac.at

Abstract. Many strategies have been investigated seeking for efficiency in construction sector, since it has been pointed out as the largest consumer of raw materials worldwide and responsible of about 1/3 of the global CO_2 emissions. While operational carbon has been strongly reduced due to building regulations, embodied carbon is becoming dominating. Resources and processes involved from material extraction to building erection should be carefully optimized aiming to reduce the emissions from the cradle to service. New advancements in timber engineering have shown the capabilities of this renewable and CO_2 neutral material in multi-storey buildings. Since their erection is based on prefabrication, an accurate construction management is eased where variations and waste are sensible to be minimized. Through this paper, the factors constraining the use of wood as main material for multi-storey buildings will be explored and the potential benefits of using Lean Construction principles in the timber industry are highlighted aiming to achieve a standardized workflow from design to execution. Hence, a holistic approach towards industrialization is proposed from an integrated BIM model, through an optimized supply chain of off-site production, and to a precise aligned scheduled on-site assembly.

1. Introduction

For the first time in over 20 years of United Nations (UN) negotiations, a global agreement on climate dealing with the reduction of greenhouse-gas (GHG) was established in Paris in 2015 within the 21st Conference of the Parties (COP 21) of United Nations Framework Convention on Climate Change (UNFCCC) and the 11th session of the Meeting of the Parties (CMP) to the 1997 Kyoto Protocol.

The main long-term goal of the so-called Paris Agreement is to maintain the global temperature increase bellow 2°C related to pre-industrial levels through reducing GHG emissions [1], what would substantially help to mitigate the irreversible effects of a climate change. However, a report from the United Nations Environment Programme (UNEP) has concluded that such a goal is not achievable under current circumstances. According to the report from the UNEP, the energy intensity per square meter of the global buildings sector needs to improve on average by 30% by 2030 compared to 2015 to meet the ambitions from the Paris Agreement [2].

Building sector has here a decisive role since accounts for 36% of global final energy use and 39% of energy-related carbon dioxide CO_2 emissions [2]. Obviously there is an environmental need to reformulate construction implementing a better use of resources and avoiding wasteful practices.

2. Why timber?

Since building regulations have become more restrictive in terms of energy consumption in use stage, operational carbon has been considerably reduced. Consequently, the CO_2 emissions produced by building product manufacturing and construction phases (A1-A5), called embodied carbon, have assumed a main role when reducing global emissions. By using low-carbon materials and employing more-efficient design and construction processes, the CO_2 emissions could be reduced up to 30% [3].

Lifecycle Assessment (LCA) is a standardized method to quantify environmental impacts of buildings throughout the whole life cycle stages, from material extraction and product manufacturing (A1-A3) through construction (A4-A5), use and maintenance (B1-B7), and end of life (C1-C4). Even supplementary information beyond the building life cycle can be quantified meaning the benefits and loads beyond the system boundary (D) [4]. Following this discourse, for the life cycle assessment of two variations of concrete and two types of construction timber, the Global Warning Potential GWP [kg CO2 –eq] over a time horizon of 100 years was analyzed (s. Table 1) according to the European standard EN 15978 [5]. The system boundaries for the calculation is based on the general LCA framework [5] and following stages are included:

A1-A2-A3	Product stage: Raw material supply – transport – manufacturing
C2	End-of-life stage: Transport
D	Benefits and loads beyond the system boundary stage: Reuse, recovery, and recycling potential

Table 1. LCA indicators of building materials Global warming potential GWP [kg CO2 –eq] per m³

	A1-A3	C2	D
Concrete C25/30	211.1	12	-21.4
Concrete C35/45	265.1	12	-21.4
Glued laminated timber	-652.6	0.46	-372.6
Cross Laminated Timber	-633.4	0.44	-357.6

The life cycle assessment (LCA) is based on the data coming from EPD (Environmental Product Declarations), containing transportation, set to truck, during extraction/production (module A2) which is included in the EPD module A1-A3 and transportation to waste disposal (C2).

Attending to the environmental impact of the selected materials, the ecological advantages of timber compared to conventional concrete is highlighted underlining the potential for further developments, since its production is less carbon intensive, it is renewable and stores carbon for the long term contributing positively to the global warming control. Its strength-to-weight ratio makes timber an attractive material to build with since transport emissions are reduced, as so is the size of the foundations, while the workability increases.

Besides material selection, a leaner approach needs to be implemented to avoid the wasteful practices, which have put construction sector as the largest consumer of raw materials and responsible for about 1/3 of the global waste annually. Since the focus of the so-called Lean Management relies on eliminating waste, minimizing material use, avoiding errors and increasing accuracy and efficiency, a low-emission building site is therefore achievable through its implementation.

3. Methodology of research

Off-site construction may be the most positive factor when building with timber. Though prefabrication exists since decades, it is at present when it is not anymore linked to mass production, where all elements look alike with no customization, but to a systematic working methodology where sub-pieces, when combined, form an end-product with bare constrictions. Implementing off-site timber construction, overall time can be reduced by 25% [6] since the erection on site is based on an assembly process within an in-time project delivery. Besides, the production of the elements takes place in a factory away from weather detriments while parallel work on-site is allowed. Hence, strategies focused on industrializing and professionalizing the sector, based on prefabricated elements, are needed to be investigated in order to take the lead in the market of urban multi-storey buildings, taking into account that already from the design phase, different procedures as in traditional planning are needed in order to achieve an Integrated Planning (IP) with a high definition grade, buildable and divided into aligned work packages.

With the purpose to explore the weaknesses and potential improvements of the timber industry towards industrialization, expert surveys and extended literature review was conducted, where two main topics were explored: the constraints and possibilities of implementing timber or timber-based materials in multi-story buildings and the potential benefits of using some Lean Construction principles and methods throughout the entire process from design to execution. Through a crossed information exchange and case studies, a holistic approach about how to efficiently behave when planning and constructing multi-storey buildings with timber or timber-based materials is proposed. As an ongoing project, the conclusions drawn served as basis to develop running systematic semi-structured interviews with selected experts on both themes with the purpose to deep into the underperformance of timber in multi-story buildings.

3.1. Expert surveys and literature review on multi-storey timber buildings

In the field of this research, a round of workshops under the umbrella of the project Holz.System.Bau were conducted and organized by MAGK-Architektur together with Eco.Plus (Bau.Energie.Umwelt Cluster Niederösterreich) and accounting 41 professionals taking part. Within two months different stakeholders from the timber industry actively highlighted weaknesses, potential improvements and possible strategies to investigate aiming to implement the use of timber as main material for multi-storey buildings. Planners, researchers, contractors, constructors, timber specialists and timber engineers, among others, in a brainstorming oriented round table, discussed an amount of decisive factors regarding to use resources more efficiently along the whole process from design to erection.

The first workshop was focused on highlighting the main goals and the boundary conditions of the approach, and the second was established as a follow up to deep into the proposed strategies and precisely establish work packages for a tentative project. A third workshop is expected to be arranged in upcoming months. The results of the sessions are organized in the following table (s. Table 2) with the purpose of simplifying the objectives, goals and strategies discussed.

Table 2. Summary of the main topics discussed within the workshops series

<table>
<tr><th></th><th>Urgent value-adding goals</th><th>Strategies</th></tr>
<tr><td>Design</td><td>- Extended knowledge in architectural design
- Know-how exchange platform
- Specific academic training
- Energy and material efficient concepts
- Less constructive elements, joints and details</td><td rowspan="5">- Define a reactive and adaptive modular system with standard assemblies from already existing components
- Develop an integral catalog with all load-bearing and not load-bearing modular system elements
- Spread the solutions through a BIM library as an open source
- Advance a collective value-adding actions catalog throughout the whole process
- Implement a crossed specific training
- Improve efficiency through Lean Management
- Promote reliable cost and time plans by implementing Lean Construction</td></tr>
<tr><td>Production</td><td>- Optimized logistic and coordination
- Competent handcraft
- Shorter production time in factory</td></tr>
<tr><td>Erection</td><td>- Faster assembly through higher prefabrication grade (plug-and-play)
- Use rainproof constructive elements
- Optimized logistic and coordination
- Null-error performance</td></tr>
<tr><td>Cost-time</td><td>- Refinement of planning costs
- Reliable cost and time plans
- Faster offers and lighter comparability</td></tr>
<tr><td>End-product</td><td>- Cradle-to-cradle
- Improved end-product quality</td></tr>
</table>

Planning a contemporary timber building implies more expertise, since factors such as support structure, fire resistance, sound isolation, energy concepts and prefabrication need to be taken into account in an early stage of the project. Hence, important decisions must be taken sooner than in conventional constructions such as element size, joints, timber system and degree of prefabrication. Also technical building equipment must be integrated and their interfaces identified and defined [7]. According to the specialists, around 80% of the projects are already defined when the decision to build it with timber comes, implying a re-design process wasting time, effort and resources. If the decision of building with timber were earlier taken and therefore, specific know-how from timber specialists or timber engineers were implemented in an early stage of the project, a significant amount of unneeded rework could be avoided. This lack of explicit knowledge in the design phase was highlighted by the specialists as one of the main factors constraining a fluent workflow. A collaborative design approach is needed to be implemented within an IP where all disciplines and aspects above mentioned are coordinated avoiding collisions, misunderstandings and errors among others. Some strategies regarding this procedure and cooperation models for planning and execution were proposed at the Technical University of Munich through the research project LeanWOOD showing how far is this ideal picture of a fluent workflow to reality [8].

Beside the lack of expertise in early stages, the overwhelming variety of materials and elements available on the market was also underlined as constraint, since the wide range of construction options eased often varies between construction companies. To simplify planning and construction, a standardization of available timber solutions should be implemented and construction sets should be implemented, which allows not only flexible solutions with fixed price, but technical details, work packages and coordinated production and erection. Within the research project Bauen mit WEITBLICK, a system building set was proposed based on parametric building blocks and a building assembly systematic to enable industrialized social housing in a high quality. All elements were digital defined in a BIM model including every relevant data to produce the building assemblies and the production planning. This optimization in planning and production shown a significant saving potential within a number of process analysis and optimization cycles [9].

According to the experts, an optimized construction management based on industrialized building methods using system components is still missing in the sector and should be implemented, for timber to take the lead as main material on multi-storey buildings. Main topics to be considered to reach such a goal are modularity and high prefabrication grade with standards elements and joints, and implementing reliable and transparent planning including work scheduling, tasks, logistics and construction techniques, what implies close collaboration within regular meetings, and fluent communication between architects, structural engineer and construction companies to coordinate the assembly sequence and connections. As a promising suitable work methodology, Lean Construction was proposed since the implementation of Lean Management in other industries such as automobile and manufacturing has brought relevant benefits in terms of productivity and resource and flow efficiency.

3.2. Literature review on Lean construction

Lean Construction (LC) is an adaptation of the Toyota Production System (TPS) applied to construction sector. The so-called Lean Management is a work philosophy whereas waste and errors (called *muda* in Japanese) are seen as opportunities to improvement, as quoted by his initiator Taiichi Ohno, “having no problems is the biggest problem of all” [10]. Its goal is to track and eliminate every task with no value to the end product. One of its main basis is the pull planning, instead of push planning, common on mass production like in the Ford Production System, where a large quantity of similar products are pushed forward along the production line. Contrary, pull planning delivers only the specific products and components asked, wherein a tight involvement and trust-based relationship between producers and sub-producers are needed. Throughout a Just in Time (JIT) delivery is allowed, coming the elements and products directly on site with no unnecessary stock space, no waiting time nor movements, also considered as *muda*. Another key concept related to lean is the so-called *Kaizen* or continuous improvement, where workers at every stage are able to stop the production process if a mistake is detected, being involved more actively in the process, assuming more responsibilities and avoiding unnecessary hierarchal climbing. Their implication is decisive since they know exactly how the tasks should be done. Such a statement was sentenced by Taiichi Ohno saying: “Standards should not be forced down from above but rather set by the production workers themselves” [10]. The source of the problem is then tracked and removed, becoming the process more efficient.

The term Lean Construction was first formulated by L. Koskela in 1992 [11] who highlighted the main and chronic problems of construction sector and suggested to learn from another industries which have managed to increase their productivity while in construction sector has stood still [12]. LC was then defined as a production system to minimize material use, time, and effort in order to generate the highest value possible, as it is made in a factory. Its principles follow transparence, quality and stability based on collaborative and reliable plans, with no constraints nor deviations. Such an approach is under the umbrella of LC within three main methods that trigger a cooperative and efficient way of construction management. These methods are Integrated Planning (IP), following the line of Last Planner System® (LPS), and the Takt Time Planning (TTP).

LPS is a pull planning system developed by Glenn Ballard, whereas regular meetings are handled between workers*, last planners*, aligning the tasks of every trade in a trust-based collaboration achieving a reliable planning and a continuous workflow [13]. It consists on defining which tasks *can* be done, which *should* be done and which *will* be done in different periods of time, providing besides the order and the requirements and preconditions for the tasks to be performed. This work methodology can be applied during the design phase by integrating the different departments and stakeholders in one planning process, and throughout achieve an IP [14].

TTP is another significant strategy inherent from LC, which aims to increase productivity by fitting and optimizing work packages and workers to suit a balanced and desired frequency of production, so-called *takt*, where non value-adding time is reduced and a continuous flow of production at a steady rate is achieved [15]. TTP was developed by Porsche Consulting and its suitability to improve project-based production systems has been highlighted since a better use of available resources is achieved. Although theories have explained how to apply TTP and its potential benefits, there is a lack of documentation about practical approaches and analyzed empirical data [16].

3.3. Case Studies: Timber goes Lean

Both the utilization of timber on multi-storey buildings, and the application of lean construction strategies have been barely implemented together in the sector, even though it is expected to bring a lot of positive aspects. Through this paper two case studies were selected whereas IP, LPS and TTP were implemented in high-rise timber buildings and analyzed through extended literature review, being suitable examples of the implementation of some principles described within this paper.

3.3.1.Moholt 50|50

A complex system was developed specifically to build the five passive house tower blocks made from timber elements which comprehend the Moholt 50|50 in Trondheim. At the time of construction, the project designed by Masu planning and MDH Arkitekter SA, was the largest massive timber building in Norway, with 632 student apartments [17]. The erection of this nein stories high student housing was based on prefabricated Cross Laminated Timber (CLT) elements industrially produced coming on site JIT and scheduled through TTP and an adaptation of LPS and IP to “Nordic Model of Work”, named “Involved Planning”, what was especially developed for this project by the construction company Vaidekke AS and the researcher Lars Andersen [18].

Builders were strongly involved throughout the whole process within the Involved Planning holding multiple roles and employing actively their skills in planning and problem solving. Because of their implication in early stages, the project was buildable and the technical plans detailed with a description of the building process. Planning meetings were regularly conducted, where builders, leaders and engineers planed work packages in terms of “look ahead”, as in LPS, for different periods of time, two months, two weeks or one week. Thus, the information was always up to date and the tasks for next week accurately updated, adapted and planned. Consequently, a smooth building process with few errors was achieved. The work on site involved an intense participation through daily planning meetings between on-site crew leaders and office foremen about what was done and how, being the Key Performance Indicators of the running status of on-site work. Works on-site started in February 2016 and in November 2016 the first three towers were completely finished and students moved into, while the last two were under final inspection [19].

The interior building process was structured under the TTP principle, since the deadline was extremely close and no delay was possible. The TTP was developed and managed by the site manager from the main contractor, who had been trained in Porsche *Takt*. The right method to correctly define a TTP according to his experience, consists on identifying trade order while minimizing the times each trade enters the same zone and reducing the time wasted on non-productive work [20]. It was the third project of the company and site manager where TTP was implemented. Within the first project was not able to maintain the path, and the second, though becoming better results and being smoother, could have been further optimized [21]. However and based on *kaizen*, the workers got more experience and achieved for this project a harmonized workflow. Despite the high reliability of the schedule planned, unpredictable errors and unforeseen issues occurred during the building process but were flexibly handled and adjusted by the builders since there was a shared holistic understanding of how the system works and a mutual interdependency [19]. However, there were suppliers who depended on third parties which resulted to be the most common source of problems since were not correctly involved in the shared agreement.

There were totally 23 assembly lines with two to four workers, called wagons, who moved along work stations of the tower blocks executing specific operations. The speed of construction was one floor per week and per wagon, moving the first wagon after finishing the first floor to the second floor and coming the second wagon inside the first floor. Following this path and once the first wagon finished the last floor of the first tower, moved to the first floor of the second tower to keep on working. Hence, the 23 wagons-train moved through the entire complex in 23 weeks [20]. Along this period, with a fixed train speed, builders became more efficient and the productivity increased, being the wagons occupancy reduced, while other tasks were parallel performed by builders within weekly meetings.

Based on this collaborative working model, builders were able to finish Moholt on time, below budget and without serious errors nor injuries. Furthermore, leaders stated they would continue to perform down this path [19]. However, an important factor to be mentioned is that the project was selected through an architectural competition, wherein its construction was planned within a conventional steel and concrete structure. It was after winning when the decision to build it with CLT came in order to meet better energy and climate standards [22]. Consequently, the whole process could have been optimized, as highlighted also within the expert survey, if the decision of using timber as main material would have been earlier taken, and thereafter specific know-how sooner implemented.

3.3.2. Suurstoffi 22, Baufeld A + Arbo, Baufeld 1 – Areal in Risch Rotkreuz

The first high-rise timber building in Switzerland, designed by Burkard Meyer Architekten, is a pioneer project where BIM and Lean Construction Management (LCM) were together successfully implemented. The ten stories high office building located in “Baufeld A”, in Risch Rotkreuz is part of a renowned innovative project with nine areal in Luzern promoted by Zug Estates Holding AG. The whole project, which has been widely praised because of its innovation and sustainability, was defined through a BIM model as a digital twin within all processes were defined and optimized through LCM in an iterative way linked to the architectural model. The 36 meters high building received the silver price from Prix Lignum, where the best accomplishment of timber use in Switzerland is recognized in an every three years event. The final CAM (Computer Aided Manufacturing) plans needed for the industrialized prefabrication of the timber elements within CNC (Computer Numeric Control) machines succeeded directly from the architectural BIM model by the company Erne AG Holzbau. The BIM model was based on a catalogue from the construction company where all building elements were defined and identified. Hence, a JIT delivery was allowed from ordering along production and delivery to on-site execution. LPS and TTP were implemented within the project, where one day was defined as the *Takt* Time and one floor was finished in ten days [23].

Following the discourse by S22, another 60 meters high timber building with 15 stories was designed by Manetsch Meyer Architekten and Büro Konstrukt AG in “Baufeld 1”. This new high timber-based building named Arbo (Tree in Latin) will host the Hochschule Luzern (HSLU) and is, since December 2018 [24], erected and therefore the highest timber-based building in Switzerland. Besides, two more buildings conform the area, whereas one is also a wood-based construction. The first phase is expected to be completely finished by August 2019 with two institutes from HSLU moving inside, and the second one by spring 2020 [25].

Drees&Sommer (DS Consulting Process & Organization GmbH), together with Schockguyan, are the responsible of the LCM of the project in “Baufeld 1”, which was praised with the Arc-Award BIM 2018 in the category “Innovation”. Besides, Kaulquappe AG and Archobau AG as BIM and LC

Managers, made possible the coordination of the information exchange between all stakeholder through an Open-BIM system, and the digital management of on-site performances through a permanent monitoring linked to the BIM model. For the development of the required IP, an Open-BIM system served for the coordination of around 260 stakeholders from 40 different companies using each office different software for their specific purpose. J. Amann from Kaulquappe AG assumed the role of BIM Manager together with M. Giera, and assisted, together with A. Eisenhardt, as BIM Support within architecture, engineer, building equipment and construction site management. Besides, there were BIM Coordinators also taking part from different offices [25].

Like in S22, the IP was conformed of construction elements from a catalogue what allowed a high definition and, as above exposed, the possibility of getting the CAM plans directly from the BIM model. Each activity was linked to its element on the model with an ID and subdivided into daily tasks [26].

The alignment of those tasks started with an overall process analysis with the definition of work areas and process steps enhancing transparency and identifying problems. Then the *Takt* and *Takt* zones were defined with the amount of work per area, size of crews and duration with the purpose to uncover optimization potentials. After that the TTP is leveled and visually draw with the identification of trades and workflows optimizing its duration and identifying parallel processes. Throughout, an overall schedule was planned with the milestones and checked upfront processes making sure all requirements are available and preconditions are solved, following the philosophy of LPS. At the end, a detailed planning board was developed with specific information for daily activities, where was possible to identify obstacles, increase the stability and reliability and consequently optimize the *Takt* [26]. Within the on-site daily meetings, the BIM model served as a basis to define the tasks to be done with information about work steps, resources needed and their ID's. Those tasks, were printed on so-called *Kanban* cards, like in manufacturing, and posted on the planning wall on-site. At the end of the day, for the controlling, the cards whose tasks were accomplished were turned green and scanned through a bare code and updated into the BIM model [25].

Consequently within the digital twin it was possible to know what had been done, how, when and with which amount of resources in a short period of time. Thanks to the Open BIM approach, a steady up-to-date Single Source of Truth (SSOT) was achieved, and throughout the loss of information and possible misunderstandings were minimized, while the transparence increased. According to Brigitta Schock, from Schockguyan, the application of lean construction principles came after the development of the BIM Execution Plan (BEP), what brought re-adjustments and changes. Consequently the whole process could have been further optimized if those principles would had been earlier implemented [27].

4. The holistic approach: potential of industrialized timber construction.

A systematic approach, where a project is subdivided in similar elements being produced in a factory, brings several positive aspects like higher productivity, speed of execution, fewer errors, higher quality and reliable cost and time plans. Since it is based on standardized elements and details, the planning and production of fewer elements is eased, while the errors are minimized. Timber appears to be predestined to success with such a systematic approach since solid timber products have been for decades made in industries and customized for specific projects, firstly being represented within 3D software with a high grade of detail and information, through CAM files, and then sent to CNC machines. Besides, collaboration and an engaged commitment with material use and resources are main pillars of the work systematic of the timber industry, what have been found as synergies between BIM and Lean philosophy.

Based on the research conducted throughout this paper, a holistic approach is proposed, where the whole process, from design to construction, is optimized and automated based on standardize products and processes with the purpose to highlight the potential of timber towards industrialization applied on multi-storey urban buildings.

Considering that on-site changes are not an adequate procedure when building with timber, the collaboration between all disciplines in the design phase is crucial. Technology, especially BIM, enables a continuous know-how exchange and a permanent up-to-date information access, and through the integration of detailed components, elements and systems in a BIM model, an IP is achieved, being fundamental for an off-site construction implementation. Based on the IP and within the Pull Planning, the off-site production is allowed, being the elements produced after being called, in the right amount, in the right sequence and delivered to the right place in the right time. Thanks to this JIT delivery, no stock space is needed, nor waiting time, minimizing the time spent on-site and consequently costs, accidents, noise and dust, and achieving a pulled smooth production line from factory to field.

Within regular collaborative meetings under the framework of LPS and its backwards working philosophy, the milestones and "look ahead" plans are visually settled down, where work packages, areas and steps are defined and aligned, identifying restrictions and unlocking constraints. Combined with TTP [15], the amount of work is leveled, synchronized, stabilized and sensible to be optimized through the definition and analysis of daily activities. Although it has been proven that TTP can be applied in non-repetitive projects [28], its application in projects sensible to be divided into zones with similar work packages appears to be the most suitable scenario [29]. Consequently it can be stated that a systematic approach, such as the one proposed within this paper, seems to be the most suitable procedure for an efficient TTP. Through the construction phase and thanks to these detailed tasks planning and based on regular collaborative meetings, an earlier detection of deviations and constraints is allowed, providing a proactive approach which brings the possibility to modify and adapt the procedure and stay in plan, while potential improvements are uncovered and sensible to be implemented.

Supported with specific software, the daily planned activities, are digital defined and shared with all participants. Within an ID, those defined activities are linked to the particular construction elements in the BIM model, including valuable data such as location, work stage, resources needed and trades among others. Printing those activities on so-called *Kanbas* cards, the daily tasks and their accomplishment are permanently monitored on-site and through the scan of their bare code, the real state of the construction site is up-to-date in its digital twin serving as a real SSOT.

5. Conclusions

BIM is the tool that allows a lean management along the whole process, from design along production to execution [30], starting with a Lean Design based on IP, following with a Lean Production on a factory within JIT and getting to LCM through LPS and TTP. All in a backwards planned smooth process which implements not only the resource efficiency, but the flow efficiency. Although their application is not specific for timber constructions and can and should be implemented also in massive construction, timber seems to be predestinated to optimally perform under such an approach, considering that the industry has been working since decades within 3D models with lots of information, off-site construction within a responsible material use and close collaboration. Nevertheless, there is a need of empirical applications regarding the use of lean principles linked to a BIM model in timber sector, in order to state and document some proven principles, strategies or methodologies and quantify benefits, deficits and potential improvements.

While traditional construction culture is strong based on the so-called "golden triangle" of "quality + schedule + budget", both BIM as a supporting tool and Lean as a work methodology are strongly based on collaboration and communication seeking for efficiency, higher productivity and continuous improvement, so is the timber industry, being those more focused on "people + process + technology". All in all, several synergies and enormous potential exist between Lean, BIM and timber, aiming to be explored and exploded, being the timber industry in an optimal position to take the lead in the multi-storey urban buildings market.

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Massive timber building vs. conventional masonry building. A comparative life cycle assessment of an Italian case study

Pittau F[1], Dotelli G[2], Arrigoni A[3], Habert G[1], Iannaccone G[4]

[1] ETH Zürich, Institut für Bau- und Infrastrukturmanagement, Chair of Sustainable Construction, Stefano-Franscini-Platz 5, 8093 Zürich.

[2] Politecnico di Milano, Department of Chemistry, Materials and Chemical Engineering "Giulio Natta", P.zza Leonardo da Vinci 32, 20133 Milano.

[3] University of Toronto, Department of Civil Engineering, 35 St. George Street, Toronto, Ontario, M5S 1A4, Canada

[4] Politecnico di Milano, Department of Architecture, Built Environment and Construction engineering (ABC), Via G. Ponzio 31, 20133 Milano.

pittau@ibi.baug.ethz.ch

Abstract. This work aims to investigate the environmental friendliness of building materials, and in particular the benefit of using biogenic products as replacement of conventional materials. The sustainability of wood as a construction material is a complex issue since the environmental impacts are strongly related to forest management, service life and, finally, to end-of-life scenarios and waste treatment processes. In this study, a Life Cycle Assessment (LCA) comparison was carried out between a semi-detached house out of cross-laminated timber (CLT) and a conventional building with similar geometric characteristics and equal thermal performance (U-value), out of light-clay bricks with a reinforced concrete structure. Particularly, the environmental impacts from raw materials supply, transportation and product processing (cradle to gate) were investigated and the Recipe mid-point method was adopted for the impact assessment to compare the environmental burdens of the two equivalent buildings. The positive environmental values resulted in the massive timber building are mainly connected to the replacement of the reinforced concrete mass used in the structure. The outcome, in terms of global warming potential, show that the use of wood as a building material instead of conventional materials results in a reduction of greenhouse gas emissions of roughly 25%. This material replacement, if extended on a large scale, could give a valid contribution on achieving the community goals of reducing emissions from the construction sector.

1. Introduction

The construction sector plays a decisive role in the achievement of the European targets for the reduction of energy consumption and carbon emissions. With this aim, European and, consequently, Italian standards mainly addressed the decrease of the environmental impact during the use phase through reducing the demand for operating energy [1]. As a consequence, the energy performance of buildings has been improved, mitigating the environmental impact of the operation phase. However, the importance of the other life cycle stages has increased due to higher material inputs [2]. As a matter of fact, the (fossil) carbon emitted when manufacturing the materials and during the construction stage might significantly affect the carbon savings from operational energy [3]. Building materials selection strongly affects the overall environmental impact of a building; in particular, the choice of the materials for the structural frame and the building envelope (foundation, exterior wall and roof) has a major influence [4].

This work presents the results of a study conducted with the aim of assessing the benefits, in terms of environmental impact, deriving from the use of construction technologies based on wood instead of traditional materials for the construction of residential buildings. Specifically, a Life Cycle Assessment (LCA) comparison was carried out between a semi-detached residential building with a load bearing structure made of Cross Laminated Timber (CLT) panels and a building of the same size and similar architectural and performance characteristics composed of a reinforced concrete load bearing structure and light-clay bricks. More precisely, the environmental impact deriving from the production cycle of the materials and products used for the construction of the two buildings has been assessed.

2. Methodology

The assessment of the environmental impacts of the two buildings was carried out according to the European standard EN 15978:2011 [5], which divides the life cycle of a building into different stages: the product phase (A1-A3), the construction process phase (A4-A5), the use phase (B1-B7), and the end of life phase (C1-C4).

The LCA analysis presented in this study was limited to the product phase (A1-A3) and it is used, specifically, to assess the environmental impact of materials and products used for the construction of the body of the two buildings. This phase includes the following activities: extraction of raw materials (A1), transport of the materials to the production company (A2), and production of the finished packed product up to the factory gates (A3).

For the comparative study of the two buildings, the construction technologies described in the technical documentation provided by the construction company were analyzed. Specifically, a list of all the materials necessary for the construction of the main structural and envelope elements was drawn up and the environmental impacts of these materials were calculated using the datasets available in the Ecoinvent 3 database [6]. Finally, the results for the two buildings were compared.

The methodology of LCA analysis is uniquely defined by the international standards ISO 14040:2006 and ISO 14044:2006 [7]. These standards provide the general principles, requirements and guidelines to properly conduct the analysis and define a scientific framework to assess the environmental load of products and processes allowing a comparison between them.

3. Case study analysis

The two case studies considered in the analysis are two residential buildings built in the same year in the same area in northern Italy with similar features and dimensions, but built with different construction technologies. The first, Building A, was built using a structural system of load-bearing walls made of cross laminated timber, while the second, Building B, was built using traditional construction technologies (i.e. a load-bearing frame of reinforced concrete and walls made of light clay bricks).

The objective of the analysis was to compare the environmental impacts of the two buildings, broken down with respect to the materials and components used for the construction of the two buildings.

Figure 1. Building A, built with a load-bearing structural system of cross laminated timber.

Figure 2. Building B, built with a reinforced concrete load-bearing frame and brick walls.

Table 1. Dimensional characteristics of the two buildings

	Year of construction	Gross floor area *(m²)*	Number of floors	Number of apartments
Building A	2016	820	3	8
Building B	2016	814	3	8

3.1 Preliminary assumptions and limitations of the analysis

The Functional Unit (FU) used for the comparison of the two buildings is 1 m^2 of heated floor area. An LCA analysis of materials was carried out from a "cradle-to-gate" perspective (i.e. from the extraction of the raw materials to the factory gate).

The following assumptions were made for the analysis:

- Only elements of the buildings that differ between the two scenarios were included in the analysis. For above ground elements, vertical and horizontal external structures and closures were considered, while installations, finishes (coatings, paints) and fixtures, which are assumed to be the same for both buildings, were excluded. For the same reason, all underground structures were excluded, including the lower horizontal closure (ground floor);
- Non-load-bearing internal partitions (partitions and doors) inside the apartments were excluded since they may vary according to the needs of space distribution;
- 10 kg/m^3 of steelwork and hardware were considered for the wooden building;
- 150 kg of steel bars were assumed to be used per cubic meter of reinforced concrete.

For each building an inventory of all the materials and components was compiled according to the documentation provided by the contractor, which included graphs of the executive project, technical reports, and tender specifications.

3.2 Inventory analysis and impact assessment

Secondary data from the Ecoinvent database were used for the inventory analysis. On the other hand, the characterization factors and the impact categories considered by the ReCiPe Midpoint method were considered to assess the potential environmental impacts of the two buildings [8]. Finally, the SimaPro software (www.simapro.com) was used for the analysis. In the results, only the most meaningful impact categories for the present case study are presented.

4. Results

4.1 Impact assessment of the whole buildings

'Figure 3' compares the potential environmental impacts of the two building scenarios assessed with the ReCiPe method. Figures are expressed in percentage terms, where the worst case for each impact category is set to 100% in order to simplify the comparison.

The wooden building proves to have a lower potential impact for many environmental categories, while it results comparable to a building with a reinforced concrete frame and masonry infill panels in the others. Only in one environmental impact category (i.e. marine eutrophication), the wooden house shows larger potential impacts.

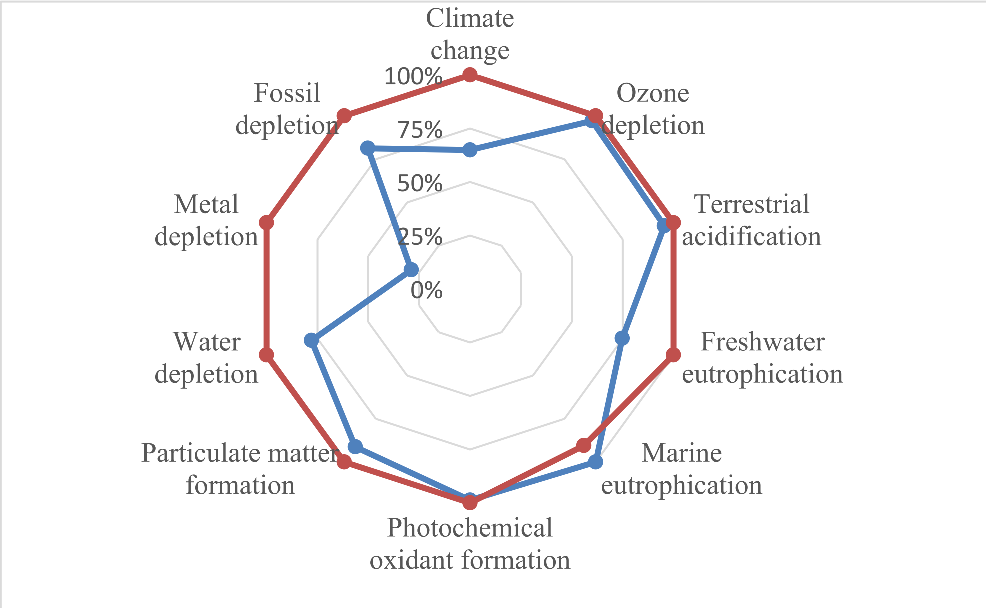

Figure 3. Comparison of results calculated using the ReCiPe method and the ecoinvent database. Blu line states for Building A (CLT), red line states for Building B (reinforced concrete).

Climate change results to be one of the categories where the timber building shows the highest impact reductions. In fact, more than 25% of the greenhouse gas emissions could be spared if timber was used instead of reinforced concrete and masonry. This difference could be even higher if the additional benefits related to the storage of biogenic CO_2 in construction products was included. In fact, wood can absorb carbon dioxide from the atmosphere and store it in the construction products. If the forest is properly managed, the carbon cycle can be defined as "neutral" since the biogenic CO_2 withdrawn is totally reabsorbed by the regrowth of the forest during the useful life of the building (i.e. 90 to 100 years). Nevertheless, these emissions were not included in the assessment since they are outside the scope of the study, given that they belong to the use phase of the life cycle of a building (i.e. B1-B7 modules in the EN 15978:2011 standard).

Moreover, the wooden building ensures a significant reduction in the consumption of non-renewable natural resources such as water, metals and fossils. Although it uses hardware to connect the various pre-shaped parts, the wooden building requires much less metal elements than the reinforced concrete counterpart, which uses large quantities of metal for the reinforcing structural elements. This results in a significant reduction in the impacts associated to energy usage as well, considering the high energy-intensity of metals production processes.

The use of wood, on the other hand, shows higher marine eutrophication impacts. The higher impacts are related to the management of the forest and the emissions of nitrates from fertilization.

For the remaining environmental impact categories, the two buildings do not exhibit significant differences.

4.2 Impact assessment of the buildings per FU

According to the design documentation, Building A (timber structure) has a gross floor area of 820 m^2, while Building B (reinforced concrete structure) 814 m^2. Total impacts were divided by the respective gross surfaces of heated floor to obtain the environmental impacts per functional unit. As the two overall surfaces are almost identical, results do not significantly differ from the results shown for the entire buildings. Results per FU are reported in 'table 2'.

Table 2. Results calculated using the ReCiPe method and the Ecoinvent database per functional unit (i.e. 1 m^2 of heated floor area).

	Climate change *(kg CO_2eq)*	Ozone depletion *(kg CFC-11eq)*	Terrestrial acidification *(kg SO_2 eq)*	Freshwater eutrophication *(kg Peq)*	Marine eutrophication *(kg N eq)*
Building A	2,24E+02	2,29E-05	1,29E+00	7,98E-02	7,01E-02
Building B	3,46E+02	2,35E-05	1,35E+00	1,07E-01	6,35E-02

	Photochemical oxidant formation *(kg NMVOC)*	Particulate matter formation *(kg PM_{10} eq)*	Water depletion *(m^3)*	Metal depletion *(kg Fe eq)*	Fossil depletion *(kg oil eq)*
Building A	1,39E+00	7,78E-01	2,65E+00	2,86E+01	6,80E+01
Building B	1,40E+00	8,53E-01	3,40E+00	9,91E+01	8,36E+01

4.3 Environmental impacts of each technical building component

In this section, the environmental impacts were divided into classes of technical elements (walls, roof, structure) and the results are presented in 'fig 4, 5'. For both buildings, "walls" and "roof" include all the materials and components that are part of the vertical and horizontal envelope that do not have a load-bearing function. On the other hand, the "structure" category include all the structural components with load-bearing functions. For Building A, all the materials used for the structure were considered: the internal load-bearing walls in XLAM, the beams and the joists, the slabs, the OSB panels in the internal floors, the stairs, the EPDM gaskets, and the metal joints. Conversely, for Building B, the "structure" includes the columns, the beams, the slabs and the stairs.

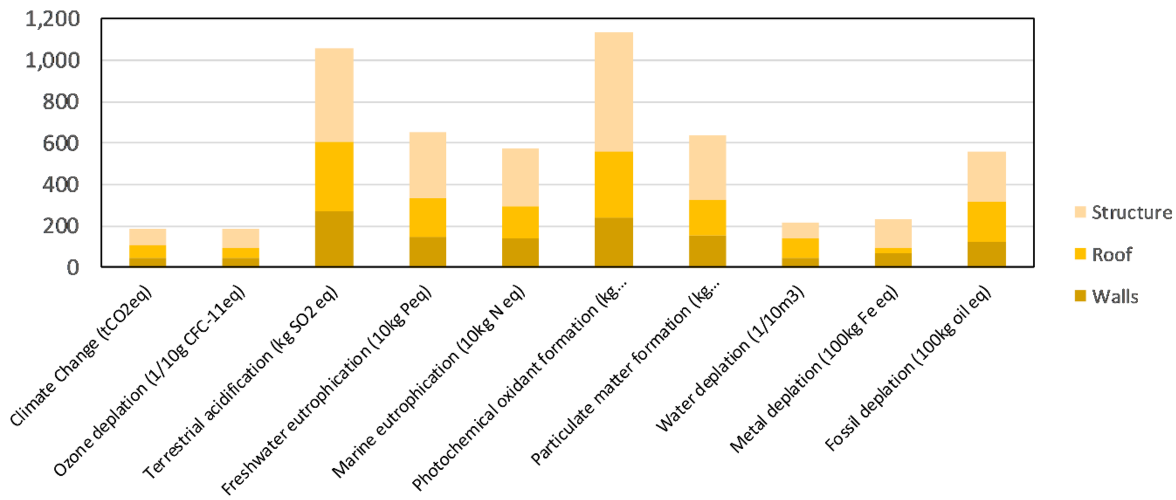

Figure 4. Results calculated using the ReCiPe method and the Ecoinvent database – Building A (timber structure)

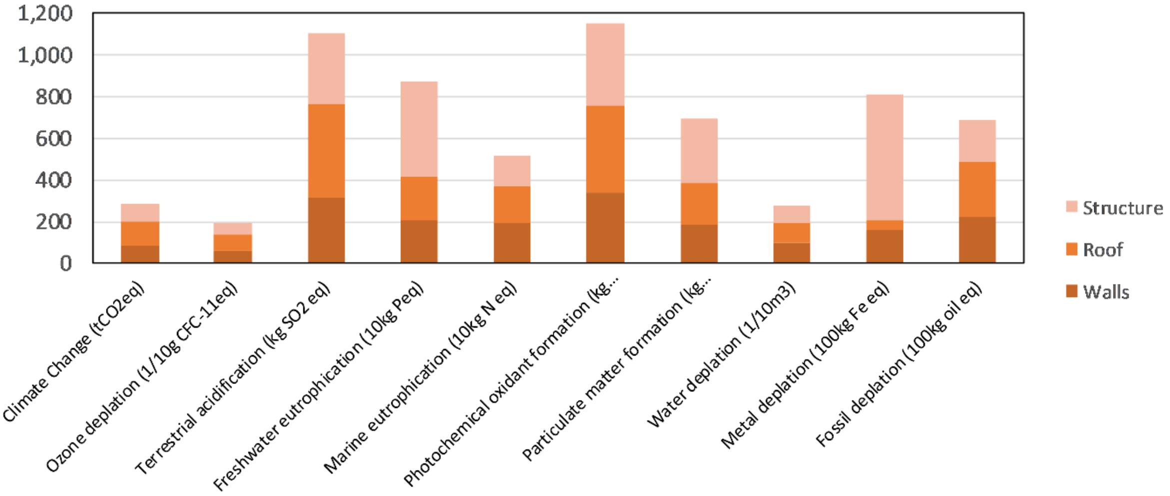

Figure 5. Results calculated using the ReCiPe method and the Ecoinvent database – Building B (reinforced concrete structure)

5. Discussion

The present analyses allowed to characterize the environmental impacts of the two houses both at the materials and the building level. As highlighted in other studies, the significant contribution of the structural elements to the total impacts was confirmed for both buildings, with a contribution of more than 50% compared to all the other technical elements for all the categories considered. Wooden building requires a lower amount of metal elements, and this results in a significant reduction of the potential impacts associated with the use of metals, which are particularly severe due to energy-intensive processes and typically long transports. The nearly total elimination of cement, used in the wooden building exclusively for the subfloors, also ensures a net reduction in the impacts. The production of cement, in fact, is one of the most impactful activities in the building industry, accounting alone in Europe for 55% of the CO_2 emissions of the entire construction industry. These impacts are particularly severe due to the clinker production process, which requires particularly high temperatures (around 1450 °C). In addition, large amounts of CO_2 are released as a result of the calcination reaction during the lime production process, which is also used in the preparation mixture of substrates and mortars. Nevertheless, it should be noted that part of the carbon dioxide emissions released during the production process can be reabsorbed during the useful life and end of life of the building due to the carbonation of the lime-based products. This process, however, is outside the boundaries of the analyzed system and it is not included in the assessment.

The use of wood is particularly beneficial for the Climate Change impact category compared to the use of reinforced concrete and masonry, thanks to the lower energy consumption during the extraction and production phases.

Moreover, the variation in insulation thickness can guarantee energy savings during the use phase of the building, but it is not so decisive in generating a significant environmental weight when compared to the contribution generated by the elements characterizing the entire building. This is partly due to the relatively modest masses of the insulating elements, which are typically rather light, and to the production impacts, which are not particularly heavy. Significant differences could be found in the use of alternative insulation materials, since moving from plant-mineral to synthetic materials can amplify the impact of some key indicators, such as Climate Change and Fossil Depletion.

6. Conclusions

Although life cycle assessment is becoming increasingly popular at the design level of buildings, there are still some methodological gaps due to the variability of the transformations involved in the building process. One of the main problems encountered is linked to the numerous uncertainties, at various levels, that characterise the several processes necessary for the production and assembly of the various building materials used in a building.

The sustainability of wood as a building material is a complex issue because from the point of view of the life cycle, the environmental impact is strongly linked to the management of the forest where the wood is sourced, to the durability of the building material, and, above all, to the end-of-life scenario. This study uses a standardised calculation methodology, based on EN-15978:2011, which allows comparison of the results of other works achieved with the same assumptions.

During the study it was necessary to establish some hypotheses and assumptions in order to clearly define the limits of validity of the results on the basis of the data currently available and provided by the contractor. In this context, the quantified contributions with purely economic values, the energy needed for the construction of the machinery, the energy provided by the workers and the energy spent on their transport to the workplace were neglected.

The positive environmental value measured in the wooden building is mainly linked to the replacement of the reinforced concrete masses used in the load-bearing structures. For instance, the use of wood as a building material instead of traditional materials leads to a reduction in greenhouse gas emissions of about 25%. The mere replacement of reinforced concrete and brick walls and floors with wooden panels guarantees a significant reduction in greenhouse gas emissions into the atmosphere, which, if extended on a large scale, could contribute on its own to the achievement of the EU Community objectives of reducing emissions from the construction sector.

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Comparative LCA of a concrete and steel apartment building and a cross laminated timber apartment building

Eliassen A R[a], Faanes S[b], Bohne R A[a]

[a]Department of Civil and Environmental Engineering, NTNU, Høgskoleringen 7A, 7491 Trondheim, Norway
[b]Veidekke Entreprenør AS, Postbox 506 Skøyen, 0214 Oslo, Norway

alexander.roy.eliassen@gmail.com

Abstract. In this paper an LCA is carried out on a concrete and steel apartment building and a cross laminated timber apartment building to compare the greenhouse gas (GHG) emissions from the two buildings. The buildings are built by Veidekke Entreprenør AS and they are almost identical except for the structural system and the number of floors. They are connected by an underground car park of reinforced concrete. The product stage (A1-A3), transport to the building site (A4) and operational energy use (B6) is examined. Results show that the cross laminated timber building has 25% lower GHG emission compared to the concrete and steel building when looking at the production stage, and 13% lower emissions when looking at all stages. The results also show that the material that contributes to the most GHG emissions is reinforced concrete, and that the underground car park has a high GHG emission because it consists of a lot of concrete. What is new in this paper is that there are two real buildings close together that can be compared to find out which has the lowest environmental impact. The paper is valuable for people designing environmentally friendly buildings with a low carbon footprint.

1. Introduction

Climate change is an enormous problem for the world today, and if global warming is not limited it will have huge negative consequences. Therefore, it is urgent to reduce the greenhouse gas emissions to reach the 1,5° C goal stated in the Paris agreement [1]. The building sector is responsible for a large share of the world's total greenhouse gas emissions. In 2010, buildings stood for 32% of the total global energy use, and 19% of energy related greenhouse gas emissions [2]. Therefore, reducing the greenhouse gas emissions from the building sector can be an important measure to reach the goals of reducing global warming as much as possible.

Concrete is one of the most widely used construction materials in the world today, but one problem with using concrete as a building material is that it contributes to a huge amount of greenhouse gas emissions globally. It is especially cement, which is an important ingredient in concrete, that contributes to a large amount of greenhouse gas emissions. In 2017 cement clinker production stood for around 4% of the global CO_2-emissions [3].

One way to reduce the greenhouse gas emissions from buildings can be to use cross laminated timber-elements (CLT) as a construction material instead of concrete. More and more large buildings are constructed with CLT-elements today instead of more traditional materials like concrete and steel.

Mjøstårnet in Brummunddal is an 85,4 m tall apartment- and hotel building which was completed in March 2019, and is an example of a new building that uses CLT and glulam for the structure [4].

In this paper it will be investigated whether or not it is possible to save greenhouse gas emissions by using CLT elements to construct apartment buildings instead of concrete. The case which will be examined is Maskinparken 2 and TRE, which are two new apartment buildings constructed by Veidekke AS in Trondheim, Norway. Maskinparken 2 is a five-story apartment building which is constructed in concrete and steel, while Maskinparken TRE is an eight-story apartment building constructed using CLT-elements. What makes the two buildings comparable is that they are constructed side by side and they are almost identical except for the number of floors and the structural system. An LCA of the two buildings looking at the impact category climate change will be carried out to compare the greenhouse gas emissions from the buildings.

1.1. Previous research on greenhouse gas emissions of concrete and wood buildings

Skullestad et al. [5] investigated the climate change impact of reinforced concrete structures and timber structures in buildings with heights between 3 and 21 storeys. The study only examined materials in the load bearing structures and foundations. When attributional LCA was applied, the timber structures caused a climate change impact that was 34-84% lower than the reinforced concrete structures. The results of the study showed that the timber structures had a lower climate change impact than the reinforced concrete structures for all scenarios. Kaspersen et al. [6] looked at greenhouse gas emissions from technical systems for buildings of different heights. The scope of the study was cradle-to-gate. The results showed that the change in GHG emissions from the technical systems for increased building height was small.

Dodoo et al. [7] looked at carbon emissions from the entire life cycle of three different building systems in wood. The building systems that were investigated were CLT elements, beam and column system and prefabricated modules. They looked at both conventional and low-energy versions of the building. The results from the study showed that the low-energy version of the CLT building had the lowest carbon emissions, while the conventional version of the beam-and-column building gave the highest emission. The reason for this was because the beam-and-column system used more concrete and steel in the foundations and elevator shaft compared to the CLT building.

Dodoo et al. [8] also examined the effects of management of materials after use on the life cycle carbon balance of buildings. They found that carbonation of crushed concrete gave a significant uptake of CO_2, but that the emissions of CO_2 from fossil fuels that are used to crush the concrete reduced the CO_2 benefit of the carbonation. They also found that recycling of rebar and energy recovery of wood was more important and gave larger CO_2 benefit compared to the carbonation of concrete.

In a Swedish report from 2018 [9] an LCA of five different construction systems (cast-in-place concrete frame, cast-in-place concrete frame with light wooden and steel walls, prefabricated concrete frame, volume elements of wood and CLT frame) was carried out. The reference building is a 6-story apartment building in Stockholm which was completed in 2010. In this study the CLT frame building had a 40% lower greenhouse gas emission compared to the concrete frame building in the product stage. The CLT frame building had a higher emission in transport than the concrete frame building.

1.2. LCA of buildings

Life Cycle Assessment (LCA) is a method to assess the environmental effects of a product through the whole life cycle of the product, from extraction of resources to disposal. LCA is used to evaluate all types of products and product systems. NS-EN-ISO 14040 is a standard that describes principles and framework of an LCA, while NS-EN-ISO 14044 gives detailed requirements for the implementation of an LCA [10, 11].

NS-EN 15978 gives calculation principles to assess the environmental performance of new and existing buildings [12]. In this standard, system boundaries are defined for LCA of buildings. The system boundaries defined in NS-EN 15978 are A1-A3 (product stage), A4-A5 (construction process stage), B1-B7 (use stage), C1-C4 (end of life stage) and D (benefits and loads beyond the system boundary).

Environmental product declarations (EPDs) are built on an LCA of a product, and gives verifiable, accurate, non-misleading environmental information for products. NS-EN 15804 gives core product category rules for all construction products and services [13].

2. Method

2.1. System boundaries and functional unit

The goal of this study is to compare greenhouse gas emissions from a concrete and steel apartment building and a CLT apartment building. Therefore, the impact category which is investigated is climate change.

In this study the product stage (A1-A3), transportation to the building site (A4) and the operational energy use (B6) is examined. It is chosen to look at these stages because it is assumed that these are the stages with the highest greenhouse gas emissions [9], and because there is a lack of data on the other stages. The end of life phase (C1-C4) is not included in this study because there is a lack of data in many EPDs when it comes to end of life. There is also a large amount of uncertainty with respect to how the materials will be treated when the building is demolished in 60-100 years.

The functional unit that is used is kg CO_2-eq per m^2 gross internal area. The lifetime of the building is set to 60 years in this study. All the materials that are in the actual buildings, and that are assumed to contribute to the greenhouse gas emissions, are included in the calculations. The materials that are not included are assumed to be less than 1% of the total mass as stated in NS-EN 15804 [13]. Any materials used outside the buildings or foundation are not included in the calculation.

A detailed calculation of the technical systems has not been done in this study, because the main goal of the study is not to look at the technical systems, but rather to compare the two building structures. The technical systems are assumed to be very similar in the two buildings, and therefore it will not have any effect on the results that the technical systems are omitted from this study. [6] showed that there was not a large increase in GHG emissions from technical systems for increased building height.

Biogenic carbon is not included in the greenhouse gas emission calculations because the end of life phase is not included. The approach within the ZEB Research Centre is to exclude biogenic carbon if the end of life phase is not included [14]. This is because the biogenic carbon that is absorbed in the trees in the product phase will be released in the end of life phase when the wood is burned, or it decomposes.

2.2. Calculation of quantities

The quantities of the building materials are extracted from the BIM-models of Maskinparken 2 and TRE. The program Solibri model checker v9.8 is used to extract the quantities, and the quantities are afterwards exported to Excel where they are organized. Drawings of the buildings have also been used to get information about quantities and to understand the structure of the building.

2.3. Calculation of emissions

Environmental product declarations (EPDs) for the different building materials have been used in this paper to calculate the emissions of greenhouse gases. For most products EPDs for the actual product used in the buildings are used, but for the products without EPD available, EPDs for similar products that could have been used in the building were used. The EPDs are obtained from the Norwegian EPD Foundation [15], the German Ökobaudat [16], the International EPD system [17], IBU [18] and manufacturers' websites.

Energy calculations performed by Ramboll [19, 20] are used in this study. The dynamic calculation program Simien 6.007 is used to calculate the energy use of the buildings.

The emission factor for district heating is 51,1 g CO_2-eq/kWh taken from Statkraft [21] which is based on data for Trondheim. For electricity an emission factor of 132 g CO_2-eq/kWh is used. This is the CO_2-factor used in the ZEB Research Centre, and it is the simulated average carbon intensity of the European electricity grid for the next 60 years [22].

The bathrooms used in the project are prefabricated bathroom cabins which are fabricated in Finland and transported to the building site. No EPD was available for the bathroom cabins, and to calculate the GHG emissions, the bathroom cabins are assumed to be made of concrete, reinforcement, steel and ceramic tiles. This is based on drawings of the bathroom cabins and the SINTEF certification [23]. EPDs of the different products have been used to calculate the GHG emissions of the bathroom cabins.

The GHG emissions from the concrete underground car park are allocated between the buildings by using the gross internal area of the buildings as a factor.

2.4. Calculation of emissions from transport

The emissions from the transportation to the building site (A4) is taken from the information in the EPDs for the different products. This means that the greenhouse gas emissions from transport is not accurate for this construction site, but it gives an indication of how large the greenhouse gas emissions from the transportation of materials could be for a typical building site.

For the materials that did not have any transport information (A4) in the EPD, a transport calculator developed by Østfoldforskning has been used [24]. This transport calculator is based on data from Ecoinvent version 3.1. In the calculator information about the weight of the material, distance and the means of transport is entered. Both direct and indirect environmental impacts are included in the total environmental impacts from the calculator.

3. Case buildings

Maskinparken 2 and TRE are two apartment buildings in an area called Lilleby in Trondheim, Norway. Maskinparken 2 was completed in August 2018 and Maskinparken TRE was completed in December 2018. The buildings are connected by an underground carpark made of reinforced concrete.

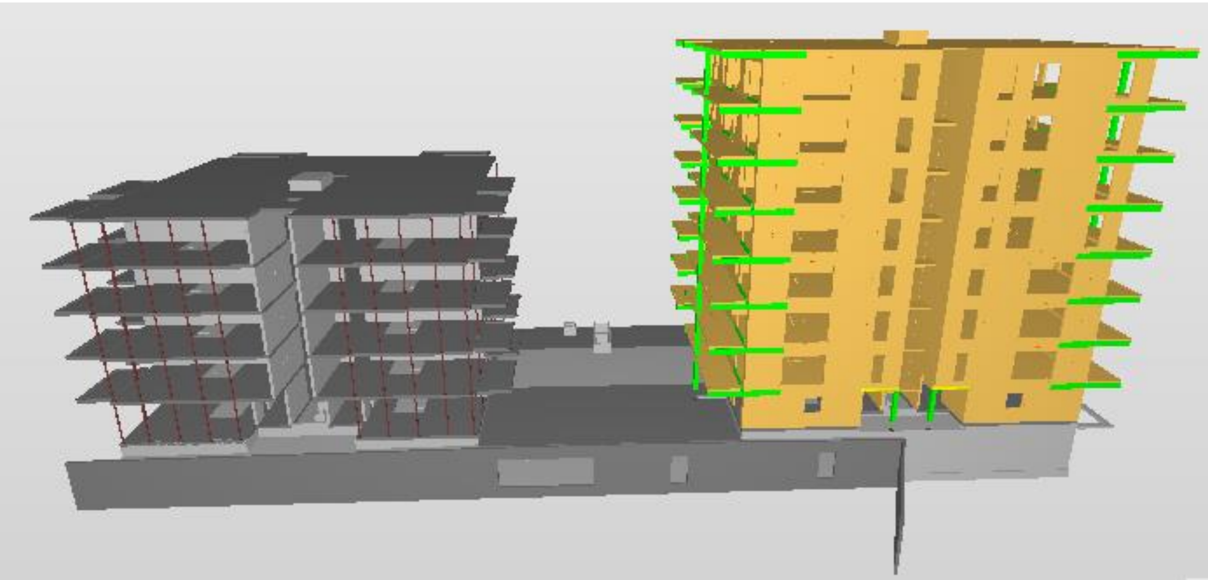

Figure 1. Maskinparken TRE to the right and Maskinparken 2 to the left with the concrete underground car park underneath. The picture is taken from the Solibri model of the buildings.

3.1. Maskinparken 2

Maskinparken 2 is a 5-story concrete and steel building with 31 apartments. It is built according to the Norwegian TEK10 standard energy demands. Slabs and walls in the building are made of reinforced concrete, with steel columns around the edges of the slabs. The slabs are reinforced with prestressing steel. The main staircase in the building is made of prefabricated concrete elements, and the elevator shaft is cast-in-place concrete. There is a technical room on the roof of the building. The outer walls are built as isolated timber frames with outer wind barrier and inner vapour barrier with gypsum board, and the façade of Maskinparken 2 is an aired plaster system. The concrete quality used in the slabs and walls of Maskinparken 2 and the underground car park is C35.

3.2. Maskinparken TRE

Maskinparken TRE is an 8-story wooden apartment building with a total of 47 apartments. The building is built to meet the passive house standard NS 3700 [25]. The walls, slabs, main staircase and the elevator shaft are made of CLT-elements. Outer and inner load bearing walls and the ceilings are lined and covered with gypsum board. The façade cladding is wooden panels. Maskinparken TRE has a technical room underneath the building in the underground car park.

Table 1: Differences between the two buildings

	Maskinparken 2	Maskinparken TRE
Gross internal area	2376,1 m^2	3784,8 m^2
Number of stories	5	8
Number of apartments	31	47
Construction system	Reinforced concrete and steel	CLT
Foundation	Concrete underground car park	Concrete underground car park
Façade	Aired plaster	Wood panelling
Balconies	Prefabricated concrete	CLT
Outer walls	Insulated stud work	Lined CLT walls

Table 2: Delivered energy

	Maskinparken 2 [kWh/m^2]	Maskinparken TRE [kWh/m^2]
Direct electricity	34,0	36,4
District heating	63,9	49,9

Table 3: Material quantities of the two buildings

	Maskinparken 2 [ton]	[%]	Maskinparken TRE [ton]	[%]
Cast-in-place concrete	3874	82,8	3185	65,6
Prefabricated concrete	227	4,9	66	1,4
Steel	20	0,4	23	0,5
Screed	196	4,2	417	8,6
Reinforcement	151	3,2	125	2,6
Cross laminated timber	4	0,1	540	11,1
Wood	34	0,7	51	1,1
EPS	2	0,1	0	0,0
Bathroom cabins	62	1,3	102	2,1
Façade panel and plaster	13	0,3	0	0,0
Gypsum board	51	1,1	207	4,3
Stone wool insulation	8	0,2	71	1,5
Windows and balcony doors	16	0,3	25	0,5
Doors	11	0,2	16	0,3
Glass railing	0	0,0	17	0,3
Other materials	10	0,2	10	0,2

4. Results

The results from the LCA are shown in figure 2 below. The total GHG emissions for the production stage (A1-A3), transport (A4) and operational energy use (B6) is 801,5 kg CO_2-eq/m^2 for Maskinparken 2 and 696,6 kg CO_2-eq/m^2 for Maskinparken TRE for a building lifetime of 60 years. When looking at the production stage alone, Maskinparken 2 has a greenhouse gas emission of 312,9 kg CO_2-eq/m^2, while Maskinparken TRE has an emission of 233,9 kg CO_2-eq/m^2.

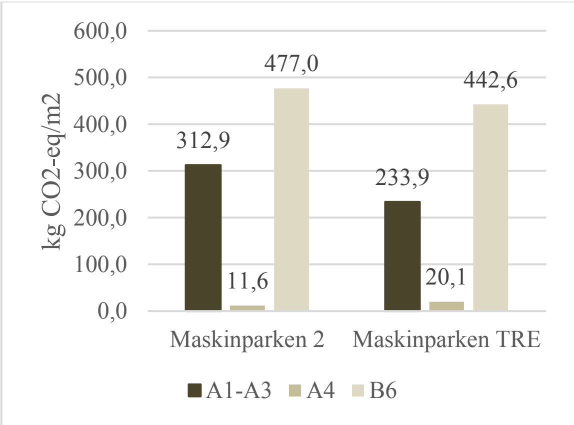

Figure 2: GHG emissions from Maskinparken 2 and TRE for the production stage (A1-A3), transport (A4) and operational energy use (B6).

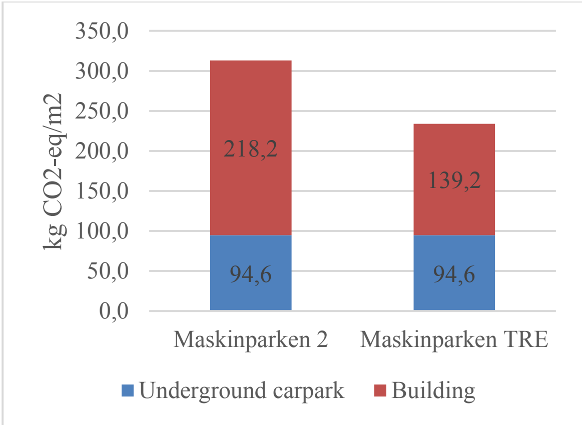

Figure 3: GHG emissions from the underground car park and the building (A1-A3).

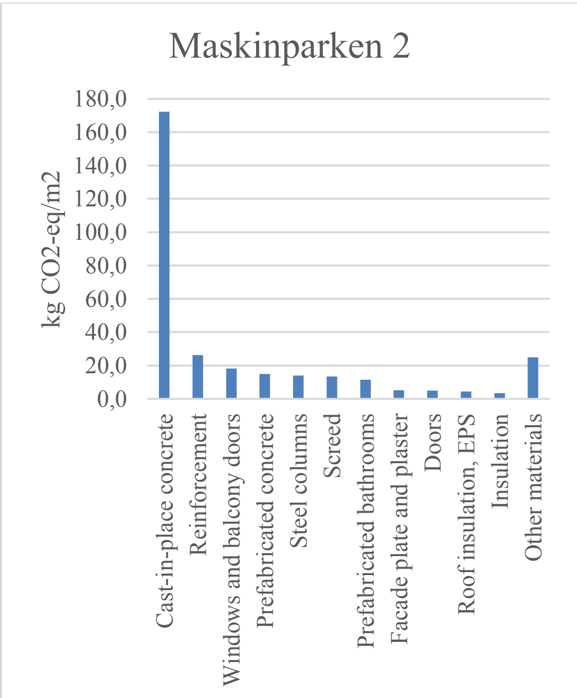

Figure 4: GHG emissions from the materials that emit the most greenhouse gases in Maskinparken 2 for the production stage (A1-A3).

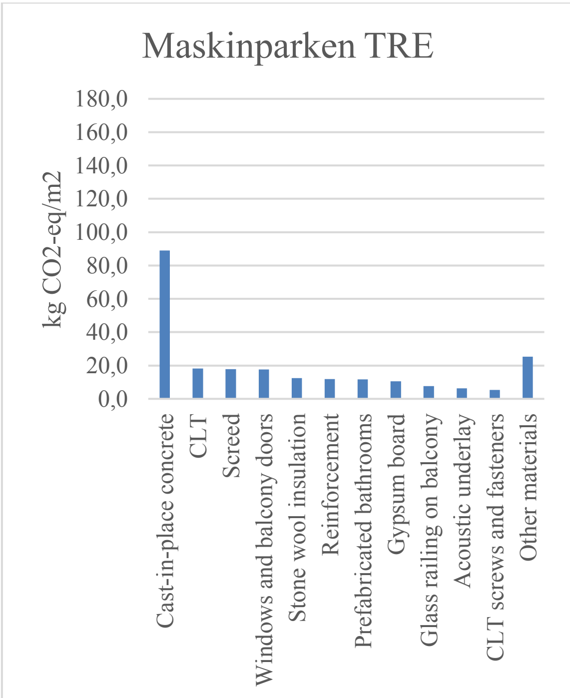

Figure 5: GHG emissions from the materials that emit the most greenhouse gases in Maskinparken TRE for the production stage (A1-A3).

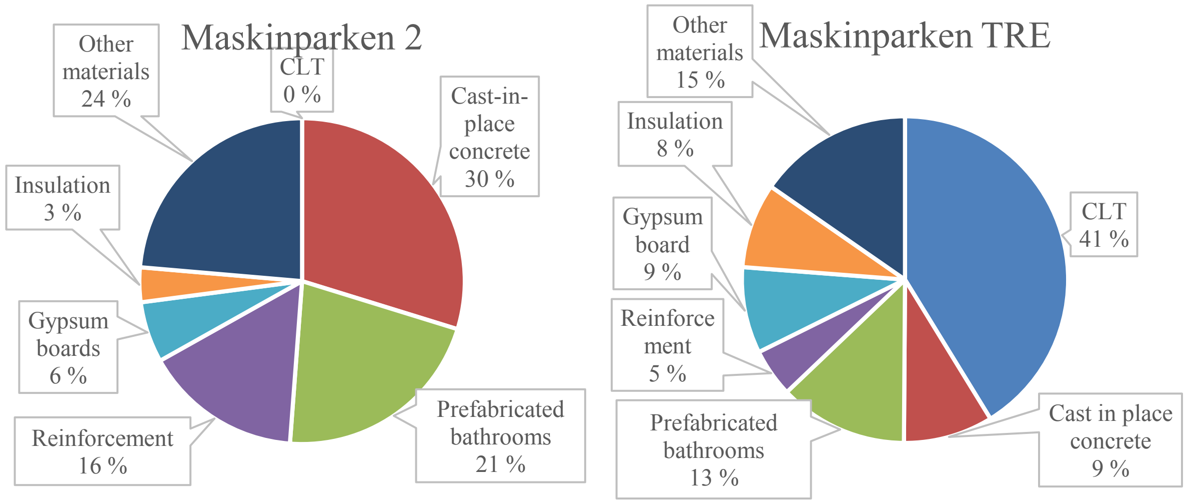

Figure 6: Greenhouse gas emissions from transport in percentage of the total emissions from transport for the products used in Maskinparken 2 and TRE.

5. Discussion and conclusion

The results in figure 2 show that in both the production phase and operational energy use, Maskinparken TRE has a lower emission of greenhouse gases than Maskinparken 2. The emissions per gross internal area (GIA) for the product phase are 25% lower for Maskinparken TRE compared to Maskinparken 2. The greenhouse gas emissions from operational energy use are 7% lower for Maskinparken TRE compared to Maskinparken 2. This was as expected, since Maskinparken TRE is built to the passive house standard NS 3700 and Maskinparken 2 is built to the Norwegian TEK10 standard, which is less strict when it comes to energy use than NS 3700. The results also show that for a 60-year lifetime of the buildings, the operational energy use is the phase that emits the most greenhouse gases. This would change if another lifetime than 60 years was chosen.

Figure 4 shows that for Maskinparken 2, cast-in-place concrete is the material that contributes with the most greenhouse gases, followed by the reinforcement used in the concrete. Cast-in-place concrete is also the material that emits the most greenhouse gases for Maskinparken TRE, see figure 5. This is because of the large amount of concrete in the underground car park. The third most emitting material for Maskinparken TRE is screed, which is used over the acoustic underlay. This means that choosing a material with low greenhouse gas emissions for screed can be important to lower the greenhouse gas emissions from CLT buildings.

As can be seen in Figure 3, the underground car park contributes significantly to greenhouse gas emissions. The underground car park contains a large amount of concrete and steel reinforcement, and this means that if the buildings were built without the underground car park, this would reduce the GHG of the two buildings greatly. Where it is possible to have parking above ground, a concrete underground car park should therefore be avoided to reduce the GHG emissions.

It can be seen in Figure 2 that greenhouse gas emissions from the transport phase are small compared to the product stage and the operational energy use. Maskinparken TRE has a higher GHG emission from transport compared to Maskinparken 2. The products that contribute the most to emissions from transport are shown in Figure 6. The main reason Maskinparken TRE has a higher emission from transport is because of the CLT-elements which are transported from Ybbs in Austria to Trondheim. This means that the greenhouse gas emissions from transport could have been lowered if the CLT was produced in a factory nearer Trondheim. It is important to note that a detailed calculation of the GHG emissions from transport has not been carried out, and values from EPDs have been used for most products. This means that there is a large amount of uncertainty in the results with respect to transport.

Operational energy use (B6) is the phase that contributes the most to the greenhouse gas emissions for both buildings for a lifetime of 60 years. The results for the emissions from operational energy use are uncertain, because they are highly dependent on the emission factors for electricity and district heating. In this paper constant energy use and emission factors are assumed. There is a high level of uncertainty in the building's future energy use and the future emission factors, and therefore this phase should be examined further to gain more knowledge of the emissions in the operational phase.

There are some differences in the two buildings other than the structural system that makes comparison of the buildings more difficult. The most important differences are that the buildings are of different heights, have different cladding, and that they are built to different energy standards. A version of Maskinparken 2 with 8 stories has been made to compare the difference in GHG emissions in buildings of 5 and 8 stories. The results show that the version with 8 stories has 3-4% lower GHG emissions per square meter in the production phase compared to the version with 5 stories when the parking cellar is not included. The cladding on Maskinparken 2, aired plaster, has a higher GHG emission than the wood paneling used on Maskinparken TRE. Because the façade and other materials are different, maintenance during the lifetime could be different on the two buildings.

Maskinparken 2 is built to the TEK10 standard, and Maskinparken TRE built to the passive house standard, and this means energy use in Maskinparken 2 is expected to be higher than in Maskinparken TRE. Material use is expected to be higher in Maskinparken TRE compared to Maskinparken 2 because of the different energy standards. For example, more insulation will be used in Maskinparken TRE to get lower u-value on the outer walls. Even though material use should be higher in Maskinparken TRE than in Maskinparken 2, embodied emissions was found to be lower for Maskinparken TRE compared to Maskinparken 2. This confirms that CLT buildings have lower embodied emissions than comparable buildings in concrete and steel. However, maintenance emissions over the lifetime of the building needs to be confirmed.

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Potential of contemporary earth architecture for low impact building in Belgium

Van der Linden J[1], Janssens B[1], Knapen E[1]

[1] Faculty of Architecture and Arts, Hasselt university, Belgium

jasper.vanderlinden@uhasselt.be

Abstract. Earth architecture during the 21st century has resurfaced worldwide as a sustainable, low environmental impact material with expressive aesthetics and textures. Contemporary projects attempt to modernize the traditional techniques of building with earth in order to adapt them to today's projecting needs. Examples of such techniques are unfired earth bricks and rammed earth. In order to disclosure and highlight future possibilities of earth construction, advantages and limitations of earth construction in a contemporary Western-European context are reviewed, based on a literature study. Because it is hard to generalise due to the case-specific context and constraints, a case study analysis of earth utilization in two contemporary architectural projects is presented. To assess if these contemporary projects meet the environmental benefits associated with traditional earth construction, several environmental aspects are taken into account, such as material sourcing proximity, production process, reuse potential, etc. Based on the literature study, case study analysis and current evolutions in neighbouring countries, promising applications for future development of earth construction for low impact building in Belgium are highlighted.

1. Introduction (context)

Earth has been used as a building material for millennia. Architecture in the ancient cultures of Egypt, the Middle East, China, Central Asia, and Latin America was closely tied to this material. In Central Europe, there is archaeological evidence of the use of earth as a building material for thousands of years [1-3]. In Belgium, after the industrial revolution, the development of brick factories contributed to the gradual replacement of the earth building construction. Nowadays, earth construction is still used significantly in developing countries. Roughly one-third of the world's population lives in buildings made from unfired earth [3-5]. Lack of advanced technology and often the availability of labour and local materials encourages the use of simple earth building techniques [6].

But also in the developed world of the 21st century, there is an interest in building with earth. Earth architecture has resurfaced worldwide as a sustainable, low environmental impact material with expressive aesthetics and textures [7, 8]. Contemporary projects attempt to modernize the traditional techniques of building with earth in order to adapt them to today's projecting needs.

Such projects have appeared also in Western-Europe countries; Germany, France and Austria (among others). In Belgium, contemporary projects have been built with earth, but in limited numbers. Despite the potential of contemporary earth architecture in the achievement of environmental sustainability, there is no widespread use of earth in Belgium. Based on a literature study and a case study analysis, in this paper, the advantages and limitations of earth construction in Belgium are studied and the potential of using the material for low impact building is discussed.

2. State of affairs: literature

2.1. Earth construction techniques

Earth suitable for building is generally a well-graded subsoil with a good distribution of clay, silt, sand and aggregate. It should be noted that the clay component is essential for providing cohesion and plasticity during construction, and strength during service [9]. The inevitable variation in subsoils, including the moisture content, has resulted in a number of manufacturing and construction techniques. According to Reeves et al. [9], it is this versatility of techniques that makes it possible to build with earth in cold wet climates such as Britain and hot dry climates such as Morocco. Among the different construction techniques are e.g. wattle and daub, adobe, cob and rammed earth [6, 8, 10]. In this paper, a project with rammed earth (RE) and one with compressed earth bricks (CEB) are studied. Rammed earth is the product of compacting (ramming) consecutive soil layers in a formwork by using a manual or pneumatic rammer [8]. The unshaped earth mixture is slightly moist [10]. A variation of the rammed earth technique consists in the fabrication of compressed earth bricks, also using the technique of compacting a slightly moist earth mixture. But as opposed to rammed earth, bricks are produced which are subsequently assembled to form masonry structures. Other construction elements are also gaining popularity including extruded raw earth bricks (mixture in plastic state put into shape by extrusion [11]) and prefabricated rammed earth panels [8].

2.2. Advantages and limitations of earth architecture

Egenti & Khatib [12] did a literature review towards the advantages and limitations of earth construction (table 1). They give a comprehensible overview of advantages and limitations commonly associated with earth construction. Although this review was done rather recent (2016), some elements need further research. Firstly, this review seems to be done without keeping a particular context in mind and is based on research in contexts varying from Europe (e.g. UK, Germany, France) to Africa (e.g. Sudan, Southern Africa, Nigeria) to Asia (India) to Oceania (Australia, New Zealand). Secondly, it is hard to generalize such aspects since each project is different, each earth construction type differs. So, some of the listed aspects depend on the contextual reality (e.g. economic, social, climatological,…conditions). In this paper, some of the listed advantages and limitations will be evaluated for contemporary Western European applications, based on an analysis of two recent projects in Belgium.

Table 1. advantages and limitations of earth construction
as listed in sustainability of construction materials, chapter 13 by Egenti & Khatib [12]

Advantages	**Publications**
Low cost	Guillaud et al. (1985), Lal (1995), Easton (1998), Minke (2006), Morton (2007), Walker et al. (2005), Zami and Lee (2007)
Encourages self-help with less skilled labour	Adam and Agib (2001), Minke (2006), Maini (2005), Hadjri et al. (2007)
Good sound insulation	Morton (2007) and Hadjri et al. (2007)
Good heat insulation and fire resistance	Binici et al. (2007), Taylor et al. (2008), Hadjri et al. (2007), Adam and Agib (2001), Walker et al. (2005)
Capable of providing strong and secured structure	Lal (1995), Rigassi (1985), Walker et al. (2005)
Promotes culture, natural material	Frescura (1981)
Improves indoor air quality	Minke (2006), Hadjri et al. (2007), Lal (1995), Walker et al. (2005)
Low impact	
Reusable	Minke (2006)
Low embodied energy	Keefe (2005), Venkatarama Reddy and Jagadish (2003)
Saves energy and no emission of CO2	Minke (2006), Glavind (2009)
Sufficiently available	Easton (1998), Adam and Agib (2001), Hadjri et al. (2007), Lal (1995)

Limitations	**Publications**
Non-standardised material	Head (1980), Minke (2006)
Non-resistant to water and less resilient	Minke (2006), Lal (1995), Walker et al. (2005)
Needs high maintenance	Hadjri et al. (2007)

Structurally limited	Hadjri et al. (2007), Maini (2005), Adam and Agib (2001)
Suitable only for in situ construction	Walker et al. (2005)
Special skills (required for plastering)	Hadjri et al. (2007)

3. Materials and methods

In the introduction of this paper (section 2), an overview of contemporary earth construction techniques was presented, together with commonly associated advantages and limitations of earth construction, based on a literature review by Egenti & Khatib [12]. In Section 4, two projects using unfired earth, will be presented (table 2). These selected projects were recently built in Belgium and contain main walls of unfired earth. Meanwhile, they reflect an image of contemporary material use. Both are public tenders, therefore needing to fulfil common standards for Belgian construction.

A semi-structured interview was done with the architects of both projects to identify important financial, technical and environmental aspects of building with earth in Belgium. A preparatory and subsequent analysis was done based on the architectural plans and technical reports and through site visit(s) of the projects.

Table 2. project case studies and interviewed architects

# Project type (earth construction technique)	Interviewed architect (affiliation)	reference
I Watchtower (rammed earth)	Jan Thys (de gouden liniaal architecten)	JT2019
II Bioclass (compressed earth bricks)	Nicolas Coeckelberghs (BC architects&studies)	NC2019

In the next chapter (section 5), the validity of the commonly mentioned advantages and limitations, as extracted from literature (table 1), will be discussed, based on the case studies. Complimentary, literature is used to compare with current insights in neighbouring countries within a similar context. The application potential of unfired earth in a contemporary Belgian context will be discussed as three reflections, i.e. on the financial cost of earth construction, its technical aspects, and the environmental impact (including energy use and transportation). In the last chapter (section 6), the reflections are combined, highlighting the importance of balance between ecological, technical, practical and economic aspects.

4. Case study projects

4.1. Case study I: watchtower, rammed earth

The first case study is a rammed earth watchtower in Negenoord, on a former gravel extraction area. The watchtower is designed as a concrete core with external rammed earth walls, with in between concrete prefab spiralling stairs resting onto the stabilized rammed earth walls of 80 cm thick and 12 m high (figure 1). The surface area of the rammed earth external walls will slowly erode, so the gravel will become visible after a while [13].

Building	watchtower
Location	Negenoord, Limburg
Year of construction	2016
Earth construction technique	Rammed earth
Architect	De gouden liniaal architecten
Earth consultant	BC studies, Craterre, Vessiere&Cie
Available documentation	interview with architect, plans, technical report
Site visit(s)	25th of August 2015

The tower is one of the first contemporary public earthen building in the Benelux region. At the moment of writing, there are no standards for earth construction technique, which makes it difficult to describe rammed earth for use in a public project.

To guarantee the quality of the earth construction, the design and construction team was supported by an international team of experts in rammed earth. These consultants defined a material mix (20% gravel, 40% sand, and 40% loess, stabilized with 6% hydraulic lime), using materials from nearby excavation sites (Section 5.3). Also, they advised on how to organize the construction site for in-situ earth mixing and rammed earth construction. Despite the consultancy, training of the contractor and follow-up, some issues arose during construction. This resulted in the use of cement instead of lime as stabilizer. The rammed earth works took 7 weeks, carried out by a professional contractor.

Figure 1 Watchtower on a hill in natural reserve (left) rammed earth walls with concrete base and core (images: ©Filip Dujardin)

4.2. Casestudy II: bioclass, compressed earth bricks

The bioclass, a class for nature education built in an existing warehouse (figure 2, right), was constructed with compressed earth bricks (CEB). These bricks, masoned into one floor high walls, are the loadbearing construction of the building. Towards the inside, the bricks are left apparent without extra finishing (figure 2, left). An insulating exterior façade and roof of hempcrete is left apparent as exterior finishing (figure 2, right).

Building	bioclass
Location	Edegem, Antwerp
Year of construction	2017
Earth construction technique	compressed earth brick (CEB)
Architect	BC architects
Structural engineer	Util
Available documentation	interview with architect, plans, technical material report
Site visit(s)	15th of December 2017, construction site visit 10th of July 2018, tour by architect

The bricks are made in-situ using clay from a nearby quarry (Section 5.3), mixed with sand (Benor, 0/8) and without addition of a chemical stabiliser such as lime or cement. During a 3 week workshop with volunteers, 19000 bricks were produced [14] using a hydraulic CEB machine [15].

The bioclass demonstrates that it is possible to construct with unstabilised CEB in a loadbearing way if construction conditions are dry. The design and detailing takes into account the nature of the material by using its compressive strength (3,3MPa) through arches and by avoiding contact with water. This was done by offsetting the brick from the floor (figure 2, left) and not using it near the bathroom.

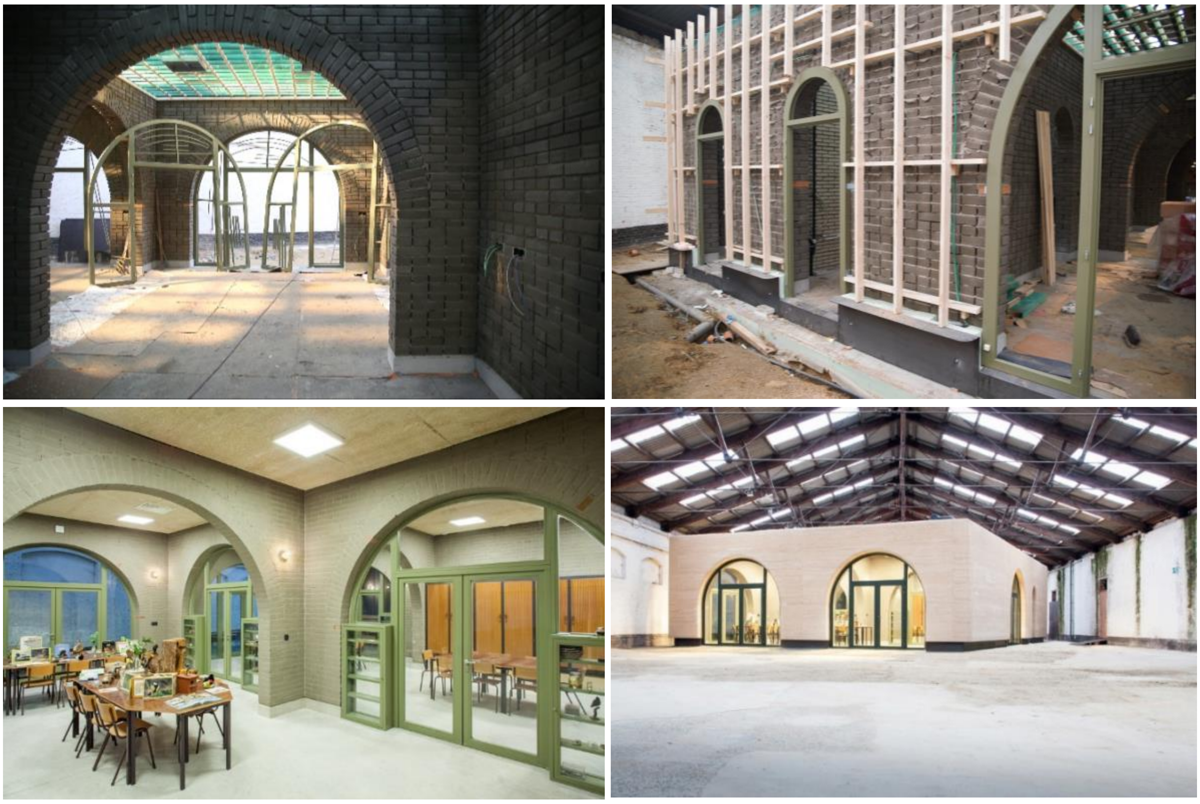

Figure 2 bioclass during construction (top), as finished building (bottom)
(top images: author, bottom images: ©Thomas Noceto)

5. Reflections on the application of earth in Belgium

5.1. Reflection on the financial cost

Whereas Eghenti & Khatib [12] present the use of earth in construction as an economic advantage, in an industrialized country with high labour costs, such as Belgium, low-quantity, non-industrial production for on-demand projects results in a significantly higher cost. In both case studies, earth was mixed on-site and processed in small amounts for the specific projects. When preparing construction materials on-site, the organization of the construction site becomes more complex and costly. Such on-demand material processing in small quantities is very different from the large-scale industrial production of conventional building materials.

Depending on the size, a non-industrial CEB would be around 30-40% more expensive than a conventional industrially produced fired brick (NC 2019). However, with greater demand the unit cost of production would reduce [16] and through industrial mass production it might be possible to make unfired bricks which are cheaper than the fired brick (NC 2019). A rammed earth construction, rammed on site, would be around 60% more expensive then exposed concrete [17].

Self-help can potentially lower the cost, but it is not always evident to do so. In the case of the watchtower, the involvement of unskilled labour in the construction process was impossible because the public client did not allow it. For the bioclass, workshop sessions with unskilled labour lowered the price of on-site brick production. During the workshops, the participants were offered practical experience and knowledge sharing. However, the cost to organize such workshop on a high level, as including the training of the participants and preparation, should be taken into account.

Although self-help is mentioned as an advantage, Schroeder warns that people should only execute the construction work under professional guidance. Earth as a building material can only be accepted by society if it is seen as a "normal" building material [1]. This requires the existence and application of current building regulations. At the moment, earth is not a conventional building material in Belgium and advice and study work of experts is needed when designing and constructing with earth. Especially when dealing with a public construction, as is the case of the two studied projects, a professional expertise is necessary to fulfil building regulations, deliver a high quality construction and provide the technical certainties necessary for a public tender. This expertise also leads to an additional cost.

5.2. Reflection on the technical aspects

Interviews with the architects of both projects did not indicate any technical reasons for not using earth construction in Belgium. But, where and how the material is applied should correspond to the potential and limitations of the applied earth construction technique. This means that in the design and detailing, the material properties should be taken into account, such as the low water resistance and low strength when compared to more conventional building materials [1, 18]. Some examples:

Water resistance:

- (case I+II) Use of a concrete plinth to prevent capillary water rise
- (case I) Specific attention to water drainage on the inside of the tower to avoid excessive contact with rainwater, special attention went to the detailing of drainage along the concrete stairs
- (case II) Earth for interior use only
- (case II) Glazed bricks instead of CEB in the bathroom area

Strength:

- (case II) Arches, loading the bricks with only compressive stresses
- (case II) The limited height of one level avoids high loads
- (case I) Wall thickness of 80cm to carry the 12meter high massive walls
- (case I) Concrete plinth to prevent that the cows grazing around the tower scrape the RE wall

Meanwhile, the limited amount of regulation, standardization and experienced craftsman might form a barrier for implementation [19]. In both projects, it was emphasised that the need of an expert in earth construction is essential. Since standards and norms are currently lacking, each project should be followed up by an expert to avoid mistakes by stakeholders that are less familiar with the material. One architect mentioned the need for a building team, with the architect, constructor, client that includes an earth consultant to follow up the project from the very start till the process of maintenance. This makes it possible to avoid mistakes in a building environment where earth construction is not common knowledge and which is not guided (yet) by standards and regulations. Among other standardization initiatives, the RILEM Technical Committee 274-TCE is critically examining current experimental procedures to propose appropriate testing methods that could be adopted as standards.

5.3. Reflection on the environmental impact

In the literature review (table 2), it was mentioned that earth construction has 'low embodied energy' and 'no emission of CO_2'. Such claims have been nuanced for contemporary earth construction by Schroeder [1]. He mentions that "the traditional manual processing of suitable excavation material into earth building materials and structures on the building site was and still is the ideal situation as far as the embodied energy is concerned". He continues with the analysis that "contemporary earth building is largely mechanized and characterized by the physical separation of building material production and product use on the building site. This automatically leads to energy consumption and transportation."

This is also the case for the studied projects. The material on the site of the watchtower was a priori not suitable for construction. The former gravel extraction area where the tower is situated has been refilled and the earth was therefore inconsistent (JT 2019). Also for the bioclass, no earth from the site has been used for the same reason. Additionally, it was practically difficult to specify a local earth mix already during the public tender phase since it would need an allocated budget for local soil investigation and specification of a reformulated earth mix (NC 2019).

However, in both projects, special attention went to the transportation distance between the excavation site of the earth materials and the construction site. The architect of the watchtower project mentioned that pre-mixed earth with specified material characteristics can be bought (e.g. from a producer in Germany), but they preferred a mix of locally sourced materials. Testing was done with different mixtures of material in the region resulting in an earth mix with material taken from within a range of 25km (figure 3). For the bioclass, clay was bought from a nearby quarry, sand was bought at a local distributor. As the exact sand source is unknown, the distance on figure 3 represents the distributor.

Figure 3 distance from site to material source

Both projects used material from quarries; such choice is made because it is practical, the continuous availability is assured and the quality guaranteed. Sand, clay and gravel are indeed sufficiently available (in those regions) but are originating from finite resources. An alternative for this would be the industrial processing of suitable 'excavation soil'—into earth building. This could result in a lower demand for landfill space and lower transportation impacts, both for excavation soil and for construction materials, which could be major environmental benefits for contemporary earth building ([1], NC2019).

In both projects, parts of the production and construction process have been mechanized. In the case of CEB, Schroeder [1] reports a duplication of the CO_2 emission as well as a tripling of the energy demand when mechanically instead of manually producing CEB's. However; it is clear that this are still very low amounts compared to fired bricks or concrete. Schroeder [1] claimed a CO_2 emission that is 63% lower for a mechanically produced and stabilised CEB compared to a fired brick.

For the rammed earth watchtower, 6% of cement has been added. Despite the absence of cement in the proposed mix of the earth consultants, cement was added. This to avoid any risk after a series of irregularities took place at the start of construction. The used mixture was differing from the prescribed mixture, either by being more wet or not respecting the prescribed particle size distribution. Although the amount of added cement is less than a common concrete construction, the 12m high walls of 80cm thick contain a not negligible amount of cement. This is negatively impacting the CO_2 emissions during production.

A last topic concerns the possible future reuse and recyclability of the material. For the bioclass, a simple wooden structure and hempcrete is mounted on the CEB. This should make it easy to take apart the pure earth material, which can then be recycled or reused. If unstabilized, reversible clay binding allows a complete and low-energy reuse of earth at end of life [18, 20]. Therefore, the lack of cement or lime as a stabiliser in the mixture is of significant importance. In the bioclass, a small amount of lime was added to the mixture, it has not been studied if this would negatively affect the recycling options. For the watchtower on the other hand, cement is contaminating the earth mixture, which eliminates the reversible binding process. Although the architect aimed to make a solid structure that will survive for a long-time, in the worst case needing some retouches (JT2019), the end of life should be taken into account. In that context not stabilizing earth to improve recyclability is an important consideration, that could be of particular value for applications which are typically changed in a shorter time span, such as indoor walls.

6. Conclusion and discussion

In the context of a renewed interest in building with earth, resurfacing worldwide as a sustainable, low environmental impact material, the potential of contemporary earth architecture in Belgium is investigated by means of a literature study and a case study analysis of two projects using unfired earth, recently built in Belgium.. The architects of both projects were interviewed to investigate the economic, technical and environmental aspects of building contemporary projects with earth. By confronting the commonly mentioned advantages and limitations in literature (table 1) with the results of the case study analysis, a reflection on the application of earth in Belgium is presented from an economic, technical and environmental perspective. Some inspiring potential suggestions for a more successful future development of earth architecture in Belgium are derived.

Firstly, the two studied projects made it clear that earth construction is not necessarily cheaper than conventional construction, even on the contrary. One way of lowering the costs would be to scale-up the production of earth material products, doing this in a more industrialized and standardized way. Another way of dealing with it could be to accept the additional price and approach earth as a unique building product, which reflects certain values such as locality and craftsmanship.

Secondly, it was clearly mentioned that earth expertise is essential in all phases of the project. Material knowledge is essential in any architectural project, but in the case of earth, it is especially important since norms and standards are lacking, and since the limits and possibilities of the material are not common knowledge. A project using earth should be designed with intelligent details and appropriately combined with other materials. This should avoid excessive contact with water, and take into account the compressive strength and its vulnerability to abrasion or erosion. Also during the phase of construction and maintenance, it is important to have access to specific technical knowledge of the material. Therefore, a good knowledge transfer and the building up of expertise, norms and standards is important.

Thirdly, earth does offer potential to construct with low environmental impact. Although zero transportation through the use of on-site excavated material was not achieved in the studied projects, clearly an effort has been done to keep the sourcing within the region. Although part of the process is mechanized and in the watchtower project some cement stabilization was used, primary energy use and CO_2 emission still is rather low compared to fired bricks or concrete. For the further development of earth as a sustainable construction material, smart sourcing and processing seems a key-point to avoid finite material excavation. Gathering suitable excavation soil and processing it to earth building products or mixtures, in a semi-centralized way, might be a useful next step in the field of earth construction.

To conclude, the findings of this study, and even more the discussed projects themselves, show that there is potential for contemporary earth architecture in Belgium. Using earth can be a low impact building solution, but this should not be taken for granted. It is the role of the architect, material producers and constructors to balance between ecological, technical, cultural, practical and economic aspects. For example, processing material on-site might lead to less transport but turns out to be rather expensive and complex in construction site organization. This could be a trigger to look more into prefabrication of earth building elements. Improving the compressive strength and water resistance by adding chemical stabilisers should be done with care as it negatively impacts the environmental impact and recyclability. Designing smartly with the right material where necessary and possible should be a priority when using earth. This preferably with a team that includes the different project stakeholders and earth construction experts, collaborating from concept phase till maintenance.

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leanWOOD – towards resilient design and building processes

Geier S

Lucerne University of Applied Sciences and Arts, Competence Center Typology & Planning in Architecture (CCTP), CH-6048 Horw

sonja.geier@hslu.ch

Abstract. With the introduction of the concept of resilience in the discourse of building design, design and building processes have to react to complex challenges presented by the extension of the perspective from physical building structure to living space. Instead of conserving effort, resilience demands integrated and argumentative processes and interdisciplinary cooperation. Forerunners in industrialized timber construction have long-standing experience and are starting points for new advanced design processes. The international leanWOOD project (2014-2017) aimed at outlining the requirements for future timber building planning processes to put them on a broader base and thus contribute to advanced processes in the future. To achieve resilience in building design, rigid and sequential process-chains must turn into flexible, argumentative process approaches. The paper illustrates the key elements for resilience-oriented design processes, discusses procurement and cooperation models, identifies pitfalls in current development and outlines the impact on resilient buildings. Finally, the outlook shows the potential of the implementation of BIM to this change towards resilient design and building processes.

1. Introduction

Building stock and cities are increasingly challenged by the consequences of climate change, such as dwindling resources, demographic trends and migration flow, and must be able to react to diverse changes. Utilising scarce resources efficiently, creating favorably priced residential space whilst simultaneously doing justice to our affluent society's demands for sustainability, barrier-free design and increasing expectations regarding land usage, all present planners with complex challenges. The dynamics of change on the timescale of a building's life-cycle cannot be predicted and present those acting according to a rational planning model with tasks that are neither clear nor readily soluble. Models with a functional/technical focus deal with symptoms (like energy consumption for example), but are unable to accommodate societal, ecological or economic changes. This is exacerbated by short-term investment perspectives and how they are reflected in current procurement practice applied to planning and construction services. Planning models able to react to this must adopt an extended perspective: from the physical building to built environment. Consideration of life-cycle during planning would constitute a necessary first step towards long-term planning horizons, whilst a systemic planning approach must then follow.

2. State-of-the-Art

2.1. Systemic planning models

It was in the 1950s that Burckhardt L was already criticising predominantly *"military-polytechnical"* planning approaches. Instead, his theories of planning react to the *"dynamics of urban realities"*. His demand was to *"accept the complexity and processual nature of the environment"* [1]. Like him, Rittel H also sees problematic scenarios holistically and the consequences of the planning process as not being clearly predictable. On the basis of this logic, Rittel speaks of *"argumentative processes"* in planning. Questions must be raised, diverse positions and points of view must be taken into account and arguments must be formulated. Here mere *"objective, scholarly"* action is not productive. He sees the solution on a *«political»* level. His planning theories are *"conspiratorial"* in the sense of sharing between all the actors involved and the cooperative manner of proceeding [2]. Habraken J also says that changing variations must be possible because of the unpredictable future within the planning horizon. He compares the rational planning models to military parades, where the greatest threat is presented by unanticipated disturbances. In contrast with this he describes a football game, which follows rules but does not obey a strict sequence: the unexpected can happen and takes place in a *"dynamic reality"*. [3]

2.2. Resilience as planning approach

As solutions were being sought, the term resilience entered the vocabulary of planning theory. The term resilience was coined and defined in psychology as *"a system's capacity and ability [...] to respond to crises and disruptions"* [1] and the ability to recover from stresses. Resilience indicates sustainability and also implies the maintenance of identity and structure [5] though it is not a conserving factor but rather leads to self-renewal and opens up creative possibilities [1]. Within the discourse on planning, resilience belongs to the third generation of planning theories and, with a systemic orientation, interconnects planning processes with political, economic and social causal networks [6].

Consideration of this systemic planning model shows that resilience-oriented planning depends on the diversity of position and arguments from the point of view of the various actors, and on the possibility of discussing variations and flexibility in the running process permitting reaction to the unexpected. In contrast, inflexible, hierarchical and rationally-based procedural models are susceptible to disturbance and cannot deal either with complex problem scenarios or with the unexpected.

3. Outstanding issues

Thus resilience-oriented planning means integrative and discourse-oriented processes that offer scope for the debate of involved actors and a buffer for unplanned happenings. This results in the demand for more cooperation between disciplines. This is not new, at least in theory. Currently resilience is indeed in demand as a buzzword in urban and building planning (e.g. Brenet Status-Seminar, ETH Zurich, 6-7/9/18), albeit insufficiently represented in current planning practice. Either it is shifted into the area of soft skills and/or falls victim to rationalization in the course of raising process efficiency.
It is therefore desirable to put forward approaches for how this can also be effectively implemented in the planning process in future.

4. Proposition

In seeking solutions, the forerunners in prefabricated timber construction come to one`s mind. The timely integration of knowledge of construction and manufacturing processes is a prerequisite for any prefabricated timber construction. The actors in prefabricated timber construction are more or less forced into early interdisciplinary cooperation by the logic underlying timber construction design. Their experience and findings point out ways of implementing resilience-oriented design and building processes in the practice of future planning.

5. leanWOOD (WoodWisdomNet 2014-2017)

Forming the basis of this paper is the work done in leanWOOD, a project which was carried out from 2014 till 2017 [7] on the WoodWisdomNet platform.

The methodological approach of the leanWOOD project was based on detailed analyses of case studies realised in industrialised timber construction with high levels of prefabrication. The bottom-up-oriented approach taken in the project was based on intensive dialogues between theory and practice -

between research and business partners as well as a broad variety of stakeholders in the sector. The objective of the leanWOOD project was to establish a new understanding regarding prefabricated construction with timber and the foundations for process innovations still required. The central fields of work were the development of planning processes aligned with timber construction and the analysis of procurement and cooperation models in relation to their strengths and weaknesses regarding prefabricated construction with wood.

6. The timber-construction-aligned planning process

6.1. Results

However, analyses in practice forming part of the leanWOOD-project showed that exploitation of the technical as well as economical potential of prefabricated timber construction is limited because of inflexible, sequential, hierarchically organised planning processes and traditional procurement practices and cooperation models [8].

On the basis of these analyses, the leanWOOD-project team put together the «ideal» timber-construction-aligned planning process (as shown in Figure 1).

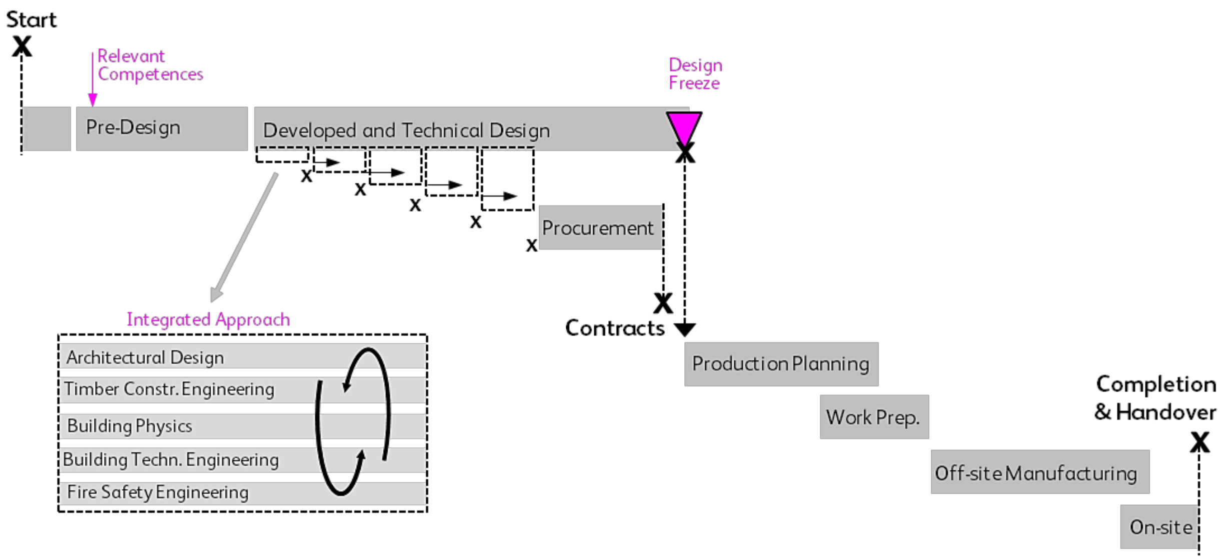

Figure 1. The elements of an "ideal" planning process aligned with timber construction

This ideal process offers many advantages with regard not only to confidence in compliance with timing and cost targets but also the far more extensive scope for decision-making for building contractors in comparison with "rolling" planning. This advantage is explained in the 2018 Brenet Status-Seminar contribution of Geier S and Zöllig S [9].

For it to be possible to profit from the advantages too, it is necessary to understand the logic underlying timber construction and to lay out the process accordingly: In timber construction, insulation, fire and noise protection are provided collectively by the primary and secondary structure, so all structural components and layers must be given collective consideration at early phases of design [10]. Thus the increasingly overly-differentiated range of products in timber construction, in combination with diverse construction options, which offer distinct solutions that are production and thus company-specific, demand a great deal of detailed knowledge which has to be integrated in these early phases. The process of technical and economical optimisation must begin at the same time as architectural design. Basically, recognising this is nothing new (cf. the McLeamy curve), the early design phases has the biggest influence on costs [11]. This integrative approach during design must be continued in a synchronised manner as the project progresses. It is necessary to open and close decision gates at appropriate times [12]. Here, each stage has a zoom factor (one might speak of a more finely resolved

"Level of Detail LOD"), which has to be reconciled within the individual disciplines. At each stage, decisions have to be arrived at through argument and finalised before the next stage. The "Design Freeze" constitutes an important milestone before the start of production planning, assuming a concluded and complete implementation planning process.

Decisive in this integrative approach is the discourse-based development of arguments. As mentioned earlier, fire protection and sound insulation can be achieved in a variety of ways. As to which solution can best be realised with reference to the tasks at hand, whilst being fault-tolerant in its execution and economical, this has to be determined within the field of activity covering architectural layout, design and structure, construction with reference to building physics, fire protection concept as well as the routing of building services. This covers not just fire protection and sound insulation, but given that humidity protection, ventilation concepts, installed components like solar protection and integrated ventilation components must be also designed and planned integratively. In these early stages, approaches that are isolated according to discipline can later result in far-reaching plan revisions or sub-optimal solutions.

6.2. Conclusion

One can say that the "ideal" planning process in prefabricated timber construction illustrates by example how disciplines must cooperate in an integrated manner, as distinct from *"poly-technical planning"*. The diversity of potential solutions demands an *"argumentative process"* that brings together all relevant competences in early design phases, preferably including the timber construction company too. Thus, forerunners in prefabricated timber construction are role models for integrative, discourse-oriented and systemic planning approaches paving the way to resilient design and building processes. Nevertheless, the question of whether this bringing together can, in organisational terms, also be realised in practice is discussed below.

7. Procurement and cooperation models aligned with timber construction

7.1. Selection of suitable procurement and cooperation models

Project team collaboration in the planning process is organised and regulated by procurement and cooperation models. During the leanWOOD-project detailed analyses were carried out regarding procurement and cooperation models aligned with timber construction [13].

It is evident that the decision regarding selection of the actual procurement and cooperation models (in the analysed projects) was reached essentially by the building owner/prinicipal according to their own profile and/or corporate mission statements. The criteria for the decision were founded on confidence in cost and timescale planning, questions of liability, administrative outlay for contract and payment management, albeit also the possibility to take part in or withdraw from the design and building process themselves.

The criteria for selecting a suitable model, from the point of view of a planning process aligned with timber construction, differ from the above mentioned ones. Playing an important role here are the potential for early, integrative planning, i.e. cooperation between disciplines during early stages, ideally including a timber construction company, along with coordination of execution tailored to timber construction.

Thus, the selection of procurement and cooperation models is not straightforward, instead requiring recognition of the strengths and weaknesses for individual cases and selecting the best models with respect to building owner/principal and timber construction.

7.2. Classical procurement and cooperation models [13]

Figure 2 shows a comparison between differing procurement and cooperation models. The horizontal bars depict the course of the design and building process from project start to completion. A precise designation of individual project stages has been omitted, given that various models throughout D-A-CH-territory were analysed and discussed. The individual stages differ according to country, so the diagram only delineates the overall structure, without further resolution: preliminary design («pre-design»), developed and technical design, construction. The message of the diagram focuses on the comparable approximate moment at which it is possible to cooperate with the executing companies according to model.

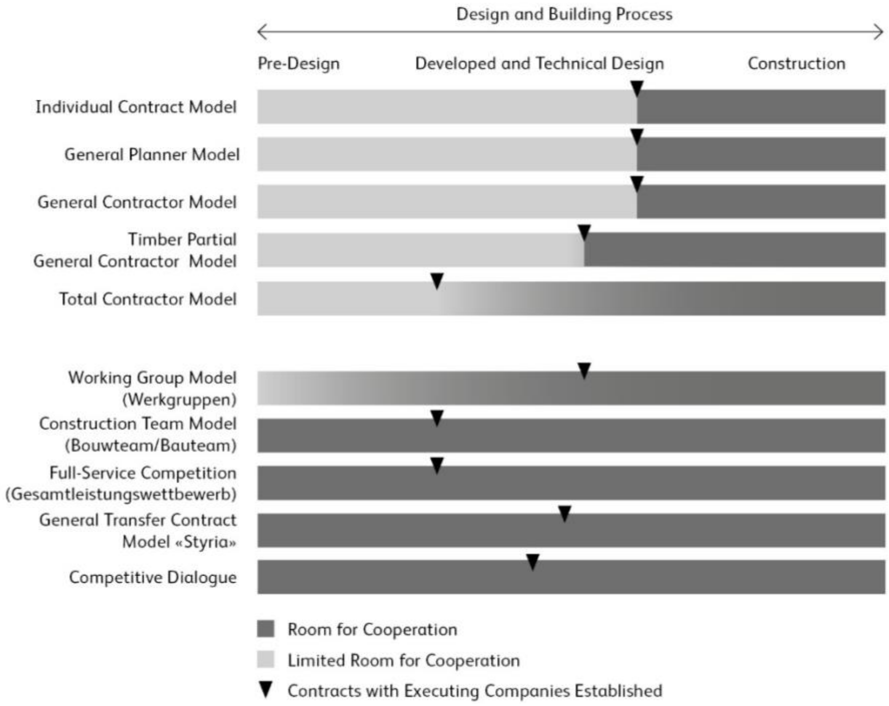

Figure 2. Overview of cooperation potential for businesses responsible for planning and execution in selected procurement and cooperation models. [14]

The upper group in Figure 2 depicts the primarily “classical” models. These are still highly respected, not only by building owners/principals but also by businesses. The Individual Contract Model, as well as the General Planner Model, offer good comparability of offers from the building owner`s/principal`s point of view, and a precise definition of work in relation to quality and quantity. In these models, businesses value the small effort required for calculation that results from the detailed performance descriptions. In both models, the choice of specialist planners is decisive. If choices are solely based on the lowest fee or the building owner`s/principal`s preferences, there is a great risk that the planning team will not be optimally aligned. The General Contractor Model is also very popular and often proves to be practicable, because one business coordinates the interfaces between the firms executing the work. This has led to the establishment of the Timber Partial General Contractor, because in this model the timber construction company can control execution of the work in a manner attuned to timber construction. The timber construction company takes on only the specialist work directly connected with timber construction (mostly being the “airtight building shell”) and not the entire construction (which is also advantageous regarding liability law). In both models, Partial and General Contractor Model, cooperation between the businesses depends on the General Contractor’s policy. Again, if price is the controlling factor here, the quality of cooperation also suffers.

The black triangles in Figure 2 mark the dates of the conclusion of contract with the businesses executing the work and indicate the split between the planning and implementation teams. Before that date, the inclusion of the timber construction company is not permissible (at least in public sector procurement). These models, which do not enable inclusion of the timber construction company before procurement, reach their limits when the necessary competences regarding product selection, manufacturing and assembly technique or logistics are not present (as a specialist planner or expert) in the project.

With the Total Contractor Model, these limits are removed. They bring together several disciplines and specialist planning departments within their corporate structure under one roof. Most often these are the market`s big players. Opinions of the Total Contractor Model diverge: whilst it constitutes a “black box” for some building owners/principals, for others it is an opportunity to be relieved of contract and payment management as well as the coordination of all interfaces.

Yet, the analyses carried out in the leanWOOD-project showed that there are still few big players in the timber construction sector who could deliver total contractor services. However, the structure in the sector, as well as in the domain of architectural and specialist planning within D-A-CH-territory, is more often small-scale and also characterised by changing teams. Even though industrialisation in the timber construction sector demands structural change through capital-intensive production lines, one must ask oneself whether it is desirable for the characteristic elements of the culture of construction in D-A-CH-territory to be lost.

7.3. Alternative procurement and cooperation models [13][15]

In the lower group in Figure 2, alternative models for procurement and cooperation are shown. They offer more scope for cooperation with executing (timber construction) companies. However, the desire and search for alternative models is nothing new. For example, the idea of Working Group Models originated in Switzerland in the 1990s and, among other things, focused on better cooperation between those planning and those executing. In the Netherlands, the Construction Team Model (“Bouwteam”) was established and also developed further. Here the intention is for the team of those planning and executing to develop commercially and technically optimised solutions. This model is less successful in D-A-CH-territory, the disadvantage being the lack of clarity in terms of responsibility for coordination within the team and also liability. Depending on the configuration, there is a risk that the architect may be confronted with joint and several liability. A solution for this was created in the form of the Full Service Competition in Switzerland, which is regulated in SIA 142:2009. The General Transfer Contract Model of the Styrian housing subsidy organisation also works on a very similar basis. Whilst the Full Service Competition directly addresses a consortium of architects, specialist planners and businesses, in the Styrian model it is only the architect and one timber construction company. Both need a very clear description of the tasks to be accomplished from the building owner/principal, neither is decided upon on the basis of a competition over simply price or design, but rather a jury evaluates the solution and awards on the basis of the fixed price. The great advantage of both models is that instead of the big players it is rather the large variety of businesses on the market, ranging from small to medium-sized, can become part of a team on the basis of trust and good experience in preceding joint projects. In both cases, the final contracting of planning and construction services is handled by the business charged with execution by means of a kind of total contractor service contract, which includes all the others via subcontracts. To avoid a mess with the reimbursement of fees, along with architectural aspects, good preliminary agreements are necessary. With the Competitive Dialogue of 2004, the EU created an instrument that does justice to the complex tasks at hand. The Dialogue includes the project team and the building owner/principal, with procurement taking place based on a solution and award criteria defined at the start. In Germany and Austria, the Competitive Dialogue can be used whilst, in Switzerland, currently only the federal government has this option. According to expert opinion, this model only makes sense for large (infrastructural) construction projects. However, there is some indication as to why models like Full Service Competition have spread even less: the effort that the building contractor must put into clear formulation of the task to be accomplished and the jury process is not insubstantial.

7.4. Pitfalls in current practice

The investigations conducted during the leanWOOD project highlighted the reality that current procurement practice mostly takes place according to the classical models, which offer limited scope for legitimate cooperation between planning offices and executing companies. What is altogether possible in these models is integrative collaboration between specialist planners. Yet here too, many building owners/principals hesitate to integrate the necessary specialist planners to a sufficient extent (with corresponding payment) in the planning team before the official building permission is issued. The much more frequent practice is to include timber construction companies by means of informal (and hence cost-neutral) consultancy. Many architects and building contractors are too little aware of how they are thus operating in a grey area and risking procedural delays or stoppages.

Here a distinction is to be drawn between procurement practice and the possibilities afforded by EU directives and national legislation. It was already in 2014 that EU directive 2014/24/EU rang in a change of culture. The changes in the area of award criteria actually form the basis for the integration of sustainability aspects and requirement-oriented service procurement, and thus constitute a step towards quality-based competition [16]. These are thus anchored in Germany and Austria. In Switzerland too, currently with the revision of procurement law, not only price but also quality and sustainability have become decisive in procurement.

8. Conclusions

Implementing a resilience-oriented design and building process means having to worry about not only the process, its progress and the potential for raising efficiency in the process. In particular it means carrying over the process model via the organisational form, legal circumstances and also the actors' personal skills into the implementation. Timber construction with high levels of prefabrication has the potential to be a role model for resilient design and building processes. However, implementation in practice is largely hindered by traditionally rooted actors and organisational issues.

Hence, the task in future is to enable these in practice through legally secure procurement and cooperation models. The analyses in the leanWOOD project showed that models already exist, which make this possible. But in order to achieve the step to widespread implementation, there is still a need for efforts towards simplification of the outlay in these models and cultural change among the actors.

9. Discussion and Outlook

An aspect of the current roll over of Building Information Modelling BIM in the building sector is the change towards resilient design building processes. Similarly to prefabricated timber construction, BIM is committed to change in planning culture: methods, processes, and strategies must change with its implementation. Prefabricated timber construction is already very well positioned in the adoption of BIM. With BIM, integrative planning is also supported at early stages and technical/economical optimisation can be combined with architectural layout from the early design phases. If, as a result, one creates space for argumentative processes and thinking in terms of variations, one then enables flexibility in the process and a buffer for the unexpected. If, through visualisation, one also improves communication between experts and laypersons and thus enables the competent integration of building owners and users in the process, then prefabricated timber construction can make a great contribution to resilience in buildings and in cities.

If one closes the loop to those attributes of resilience-oriented design and building processes mentioned earlier, it is also necessary to cast a critical eye over the objectives of BIM implementation. If the focus of BIM implementation is directed towards further efficiency improvement in the process to reduce planning time, misusing BIM solely for economical optimisation, then planning is reduced to a polytechnical collaboration in planning models, which cannot coincide with the process of transformation to a resilient building stock.

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Construction, deconstruction, reuse of the structural elements: the circular economy to reach zero carbon

Bertin I[1,2], Lebrun F[2], Braham N[2], Le Roy R [1,3]

[1] Laboratoire Navier, Ecole des Ponts ParisTech, 6-8 avenue Blaise Pascal, Cité Descartes, Champs-sur-Marne, F-77455 Marne-la-Vallée cedex 2, France
[2] Setec tpi, Immeuble Central Seine, 42-52 quai de la Rapée, 75012, Paris, France
[3] ENSAPM, Laboratoire GSA, 14 rue Bonaparte, 75006 Paris, France

ingrid.bertin@setec.com

Abstract. The research work presented aims at setting up an infinite cycle of use of materials by their reuse and answering in particular to the problems of circular economy. Structural work and foundations represent the majority of the embodied energy of a building. The research effort is therefore focused on the structural elements. Reuse is here defined as the reuse of an element without transformation, unlike recycling which induces a new industrial cycle. It is therefore about reducing the consumption of materials and lowering GHG emissions. Today, it is impossible in France to reuse structures because of responsibilities, insurance and lack of traceability. How to make possible the reuse of structural components in order to reach a low carbon building? The challenge of this work is to find the best structural configuration making the components reuse easier at the EOL. The methodology we are implementing aims to design the structural elements by increasing the BIM parameters (6D, LCA), to attach the mechanical information, material durability, ageing to each object of the digital mock-up. A digital and physical traceability makes it possible to follow the evolution of the element over the years and to feed a database. At the end of its life the database is accessible and searchable for the design of a future building. A development of tools and gateways will then allow from a model of calculation to go to query the database to find an element resulting from the deconstruction that can be reused in the future structure.

1. The need for solutions to environmental issues

The environmental findings require rethinking our construction methods to fight against the depletion of natural resources and greenhouse gases (GHGs) emissions.

1.1. The environmental impacts of construction

The construction and building industry is the principal emitter of GHGs [1] with 116 million tonnes of CO_2 equivalent (according to the Global Warming Potential, EN 15804), i.e. 33% of total GHGs, and the biggest consumer of material with, for example, in the USA in 2017, the total value of industrial minerals production which was $48.9 billion, a 3% increase from that of 2016. Of this total, $23 billion was aggregates production (construction sand and gravel and crushed stone), that is to say around half dedicated to concrete. [2].

These emissions have two distinct causes: energy consumption or functional energy (electricity, heating, ventilation, etc.) and energy used during its construction, known as embodied energy (production of materials, transport, site, etc.). Buildings are now capable of producing their own functional energy and providing the required level of user comfort. Environmental impact assessments show that for recent buildings, the majority of total GHG is due to this embodied energy [3]. In his study [4], Peuportier shows that for a RT 2005-compliant building (RT 2005 for the French thermal regulation for buildings), approximately 12% of total contribution is due to embodied energy but this figure rises to 29% for a passive building, as confirmed by [5]. Research work must now focus on reducing embodied energy due to construction activities.

In terms of where a building's embodied energy is used, structural works is found to be the main culprit. To this effect, Hoxha, in his doctoral thesis defended in 2015, analysed 16 collective buildings and concluded that concrete was preponderant for impact indicators: waste, renewable energy, and climate change [6]. Accordingly, elements of superstructure linked to elements of infrastructure and foundations make up more than half of a building's embodied energy with 58% of the LCA Global Warming Potential impact of a building's component products and systems [7]. This makes civil engineering a key focus to reduce environmental impacts over the coming years according to Figure 1.

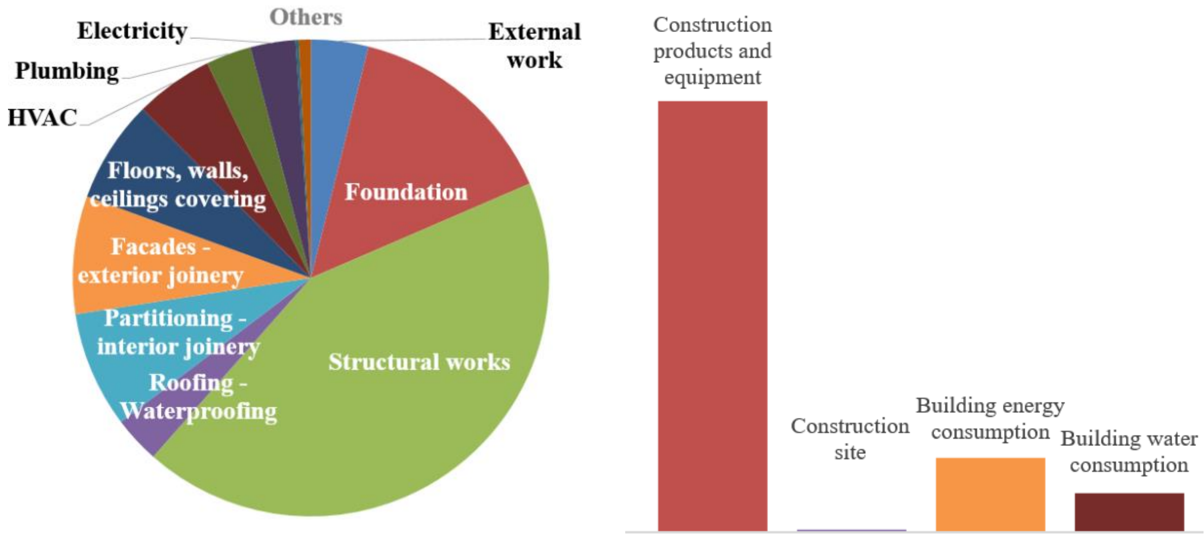

Figure 1. (a), (b), Distribution of impacts over 50 years for climate change in kg of CO_2 equivalent and breakdown for products and systems (unit-less) [7].

1.2. The circular economy (CE) applied to structural works

The research presented suggests solutions to the issues of the CE. The ultimate objective of the CE is to break the pattern of economic growth depleting natural resources. The idea is to extend the useful life of material (reuse, recycling) and products (eco-design) over the product's entire lifespan. This model is based on creating positive feedback loops for each use or reuse of the material or product before its final destruction. The material is passed on indefinitely from stakeholder to stakeholder until a new use process is found. The research is focused on structural elements, which have a greater impact in terms of GHG as the Global Warming Potential according to EN 15804 reveals, and establishing the conditions for their reuse, which is more sustainable before recycling and then energy recovery. In France, legal definition for reuse is: particular preventive action designating any operation by which substances, materials or products that are not waste are reused for a use identical to that for which they had been designed. To this effect, in April 2018 the French government presented its roadmap to develop a 100% CE. It wants to "turn existing buildings into a bank of future construction materials".[1]

1.3. Reuse of structural elements

Reuse induces additional operations for its establishment as dismantling, transport, storage, reprocessing and reconstruct. Brière, in his doctoral thesis defended in 2016, has established five parameters to evaluate the environmental impact of re-use: I_c (collection impact); I_s (storage impact); I_t (transport impact); I_r (reprocessing impact) and I_e (avoided impacts) [8]. Brière proposed re-employment specific impacts that were not included in the current standardization. With these parameters he studied three scenarios for a reinforced concrete beam in an existing housing building: its reuse, recycling and landfilling. He showed that the reuse scenario was for many indicators the most relevant solution in the case where 10 beams from the recovery would replace 7 new beams. Now if we consider a structure designed to be disassembled, impacts I_c and I_r will be substantially reduced. Better traceability will allow keeping the same number of reused beams as the number of new beams. The present study of ten tall buildings structural configurations for easy reuse leads to the best 86% of reusable hinged posts (for the posts parameter), so that is 18% of the climate change impact of the structure. The database presented here may also decrease I_s.

So the idea is to reduce consumption of materials and cut GHG emissions. Eventually, anticipated design in terms of end-of-life (EOL) reuse will prevent any waste being produced. The primary energy will also necessarily be reduced if we avoid the manufacture of new elements thanks to the reuse of the elements manufactured in the past. However, materials already used in the structures of the buildings surrounding us, known as "stockpiles", will be difficult or even impossible to reuse. Technically, there are no major obstacles but as far as liability and consequences in terms of insurance and above all due to the cost involved, reuse of current structures is not worth a client considering. However, methods and processes are progressively being consolidated, as explained in the "Repar 2" paper [9], which looks at the loadbearing wall deconstruction and reuse methodology. However, today re-use implies the downgrading of the structural elements. To achieve the minimum environmental impact, the structural function should be maintained at the same level.

The lack of traceability of material characteristics and the loss or inexistence of documents such as as-built records faced by prime contractors working on existing real-estate, often prevents them from making any attempt to reuse materials. The residual performance characterisation and assessment process can become an obstacle to decision-making.

To enable this reuse of structural elements, it is essential that it be anticipated in current designs of structures that will be built tomorrow.

2. The need for data traceability from the design

In the same way that information on the existing structure is to be found in the case of rehabilitation, reuse induces an anticipation of the necessary information in 30, 50 years or more for future engineers.

2.1. Liability data

By being properly insured in France, the engineer can cover their mandatory ten-year liability. From an insurance point of view, evidence of use of a standard technique must be provided to be insured without having to pay any additional premiums. However, reuse is neither covered by standardised technical documents. So for the moment reuse cannot be recognised as a standard technique.

To this end, all structural data essential for the engineer recovering the element in 30 or 100 years' time will need to be linked during the design phase. On a structural level, knowledge of at least the physical and mechanical properties of the materials is expected. The list must be drawn up based on the structural function: column, beam, loadbearing wall, crosswall, slab, but also the type of material:

[1] https://www.lemoniteur.fr/article/economie-circulaire-les-5-mesures-qui-impacteront-le-btp.1966709

concrete, steel, wood, etc. Additional studies by structural engineers may be required based on the degree of complexity of the dismantled structure and the project featuring the reused elements. Traceability must be made reliable using digital tools to guarantee the data linked to the structural elements.

2.2. 6D BIM : sustainable development data

A study shows that existing DfD practices and tools are not BIM compliant [10]. Tools are developing to optimize deconstruction and EOL but have not been thought for reuse and DfReu (Design for Reuse) practices. The described methodology here aims to design structural elements by increasing the BIM 6D[2] and life cycle assessment (LCA) parameters. 6D is the "dimension" covering environmental data[3] relating to sustainable development. The BIM tool then helps the designer and client to assess the environmental impact of decisions taken throughout the project until its EOL. Engineers can react to this carbon footprint and propose the most environmentally-friendly construction systems.

2.3. Structural calculation data: BIM to reuse structure

For essential reasons of liability, a structural engineer who decides to reuse an element previously used in another building must make sure he is fully aware of the characteristics of this element and possibly the conditions of life of the entire structure of which it was a component. The principal structural data for high-rise buildings can be divided into four categories:

- the properties of the element (static): geometry, composition, resistance class, relevant standard, etc.;
- the behaviour of the element (mechanical): position, type of loads, stress applied, connection conditions, creep, ageing characteristics, etc.;
- the overall behaviour of the structure (mechanical): exposure class, differential shortening, soil compaction, top displacement, top acceleration, differential displacements between floors, scaling criterion, useful life of structure, etc.;
- information for the reuse process: checks required, residual performance tests, deconstruction phasing, etc.

3. Types of traceability

As previously seen, many pieces of information needed for the reuse of structural components have to be obtained through specific traceability.

3.1. Digital traceability: BIM model

Each stakeholder tends to take ownership of a model by modifying part of the initial data for their own use. At the end of the chain, some data is definitively lost as a result. For reuse, digital building models and as-built records are particularly crucial. A system of filters to manage access to certain data based on stakeholders concerned must be set up to prevent deletion of data not used at this stage of the project but also guarantee a level of confidentiality.

3.2. Passive physical traceability: RFID chips

Passive physical traceability refers to systems that can be integrated into materials for a very long time (life of the element) and that will be self-sufficient over this time. So most will not have a built-in power supply but rather the reader, e.g. "Near Field Communication" (NFC) system, will supply the power needed to read the data built into the material. The most fully-developed technology is currently the "radio frequency identification" (RFID) chip. Start-ups plan to incorporate RFID chips into concrete before or during its implementation. RFID chip are self-sufficient and could potentially last forever.

[2] *6D*: Covers all issues concerning a building's sustainable development, e.g. energy assessments and estimated carbon footprint for each phase.

[3] http://www.mediaconstruct.fr/ba-ba-bim/fondamentaux-bim

Today the RFID chips used are designed to withstand attacks (especially in concrete). Once trapped in the material, nothing can come to damage the chip as the structural element is not damaged either. However, this contemporary technology has a very short experience feedback (2013 for the first chips in concrete in France). But current designers point to a potentially infinite lifespan inside the elements. The information is hosted digitally and remotely. Potentially, this information could be corrupted (malicious modifications, deletions). RFID chips can also internally store an unmodifiable text file but it must be extremely limited in size. Today, there are three types of RFID chips [11]: passive, semi-passive, and active. Active chips have a power source. This means they have a significant read-write range (5 to 30m), further than passive chips (approx. 2m or under). But this makes these active chips more expensive than passive labels. Passive chips, however, are very cheap and very resistant to harsh environments, which means they can be submerged in concrete when its pouring.

The problem with these contemporary technologies is their immaturity. There's still only very limited user feedback, well the reuse process covers periods of 20, 50, 100 years, or even more. Passive traceability is better suited to recording the properties of the element (static).

3.3. *Active physical traceability: sensors, IoT*

Though active RFID chips are available, it's preferable to use sensors to benefit from full-building instrumentation. Using sensors linked to the Internet of Things (IoT), changes to the element can be monitored over time and data progressively added to the database. The IoT's potential was initially identified for the operation and maintenance of smart buildings. It is also very useful for reuse, offering comprehensive monitoring of a structure's functional behaviour.

To reuse structural elements, their full history, particularly in terms of specific stresses and strains to which they have been subjected, needs to be known. Today, it can help to improve knowledge of the structure, for example including: monitoring of the structure's overall behaviour, direct marking of materials for geolocation purposes, real-time strain alerts. So instrumentation monitoring can be easily adapted for reuse purposes. Structural health monitoring (SHM) methodologies provide information on the ageing of elements and data for updating and checking calculation models.

Finally, it should be noted that active traceability is better suited to the needs of monitoring the structure's overall behaviour (mechanical).

4. Design to reach total reuse

As previously discussed, reuse of existing building is not optimal. However today it is necessary to build differently to systematize the reuse of the elements implemented in new buildings.

4.1. *Bank of available materials*

The reuse process is anticipated in the very long term. The objective is of course to integrate the principles of this methodology into contemporary design. The actual lifespan of buildings varies according to criteria that cannot always be predicted when they are built (real-estate market trends, changing development project needs, etc.). Current trends show a sometimes very short lifespan of around twenty years (mainly for offices) and the history of architecture is littered with buildings that practically last forever. The reuse process is based on a certain level of renewal of existing real-estate, which is estimated to have a lifespan of between 20 and 100 years.

So a materials bank created today, from the structures we are currently building, must be designed to remain effective over the next 100 years or at least to enable its upgrading to ensure compatibility with future technologies. The materials bank can be designed for a multi-owner client who wants to become self-sufficient in raw materials and who would use his material resources to supply materials for the entire renewal of his existing real-estate, just-in-time. It can also be designed at a national level on a very large scale based on the trend set by the French government with the objective of achieving a

100% CE. If data on all new-builds is added to this database, there will be sufficient choice to integrate a large number of reuse elements into new structures.

4.2. New paradigm of design

High-rise buildings have potential for reuse due to the repetitiveness of its structural elements. For this exercise, structural elements subjected to simple stresses (compression) are preferable and overly complex elements are to be avoided (combined bending and axial load). In fact, the more an element is subjected to a simple stress, the less specific it will be, which will increase its chances and fields of subsequent reuse. For a complex element, it will be even more difficult to find a use configuration similar to its initial use.

The connections between these elements play a decisive role in determining whether the structure can be deconstructed [12]. Use of reversible connections [13], which do not damage the materials or its characteristics, must be anticipated during the design phase. This means that their impact on the overall model must be assessed. An in-depth structural analysis is then required to determine the points that should be hinged and the ones that need to be fixed. The choice of the structural typology is also essential [14] and must be analyzed for its reuse potential. Accordingly, a study conducted at **setec** tpi (the French engineering and civil engineering company that finances this PhD research) analysed 10 models (based on four different concrete load-bearing systems rated M1 to M4 in Table 1) of a high-rise office 41-storey building, attempting to hinge as many elements as possible and comparing their carbon impact. The variants of a single load-bearing system are rated A to D (none / façade / interior / façade + interior) with a varying number of hinged elements illustrated in Figure 2. For M2C (Model with "Outriggers + cross bracing" and 540 hinged posts) to M2D (Model with "Outriggers + cross bracing" and 1452 hinged posts), an increase in the number of articulated poles of 269% causes an increase in the climate change indicator of only 0.56% in 1st cycle. This study promises also an 18% decrease for this impact in 2^{nd} life cycle, if the posts are reused. It is particularly important for there to be a balance between types of connections, deconstructability, quantity of material used and safe disassembly.

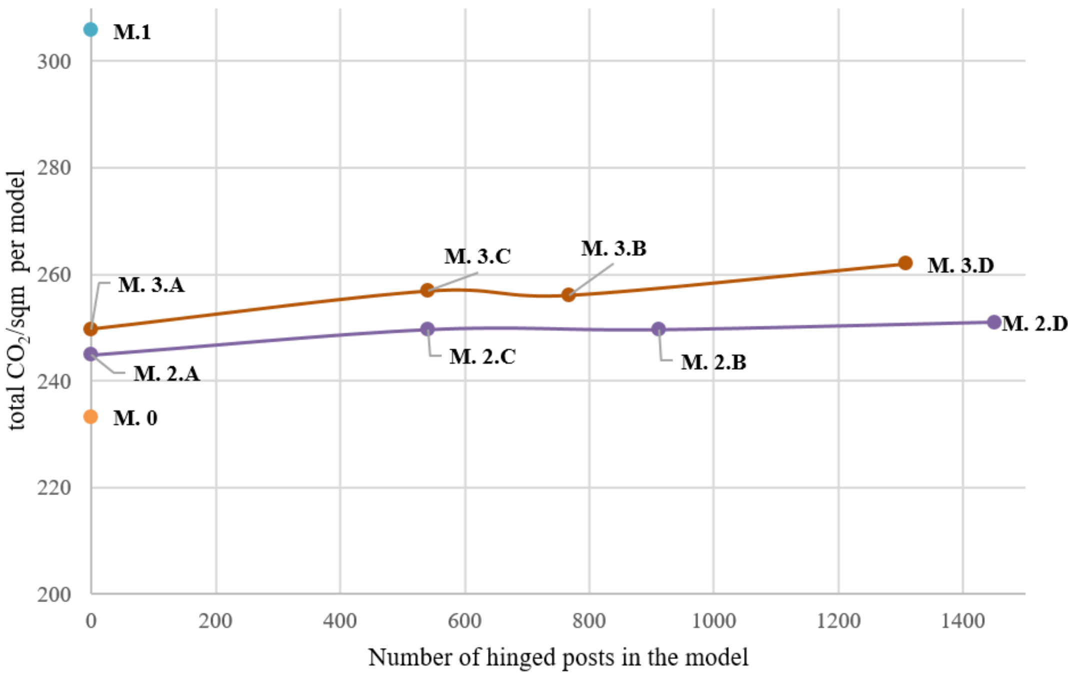

Figure 2. Study of structural variants of an office tower with the aim of hinging as many columns as possible.

Table 1. Relationship between increasing articulated posts and increasing the climate change impact of the structure.

	Number of hinged posts (maximal increase)	Total CO_2/sqm (maximal increase)
M0 "Concrete tube"	-	-
M1 "Tubed mega frame + outriggers"	-	-
M2 "Outriggers + cross bracing"	268,89%	0,56%
M3 "Crosswall + cross bracing"	242,22%	1,99%

5. End-Of-Life (EOL) reuse process to design a new building

Therefore, the first effort is to build reusable buildings today. But tomorrow, we must learn to build anew with these components from deconstructions.

5.1. Conceptual margins

Designing a new building using reused elements is different from the "traditional" design process that we use on a daily basis. Depending on what element are available in the database, the geometry of its structure will have to be more or less flexible. One of the challenges is setting acceptable margins for the choice of elements. For the span of a beam, for example, a range will have to be determined such as plus or minus 50cm for the span of a batch of beams, according to the materials available in the database. The new geometry of the building must then be adapted according to the batch of available beams. These margins inevitably have an impact on the overall design. However, it is expected that most reused elements will be available in batches and it will be easy to find several identical elements, which will mean only one criterion will have to be adjusted. If the span of the beam is adapted by increasing it by +50cm, this will be the case for all the beams. The more beams on the database, the easier it will be to find the right span, without margins.

The same applies for ceiling height, which is today calculated for maximum gain with a view to building the maximum number of floors for operational profitability. With reuse, increased structural height can be expected, but also a considerable economic gain on the cost of the reused materials. For safety reasons, an additional margin in the safety coefficients is to be expected. Even if in the very long term, design needs to be adapted to reuse as many reused elements as possible, the transition will be progressive, with first, integration of vertical elements, which are more structurally suited to recovery.

5.2. Compiling this information: the database

This database is a bank of materials for future buildings. When the existing building, of which the elements feature in this database, is set to be deconstructed, the elements become available for a new structural project. When the structural engineer designs their new project, they create a calculation model. Based on this calculation model, queries are sent to the database to identify a structural element that could fulfil a new function over its second life cycle. This process is illustrated in Figure 3.

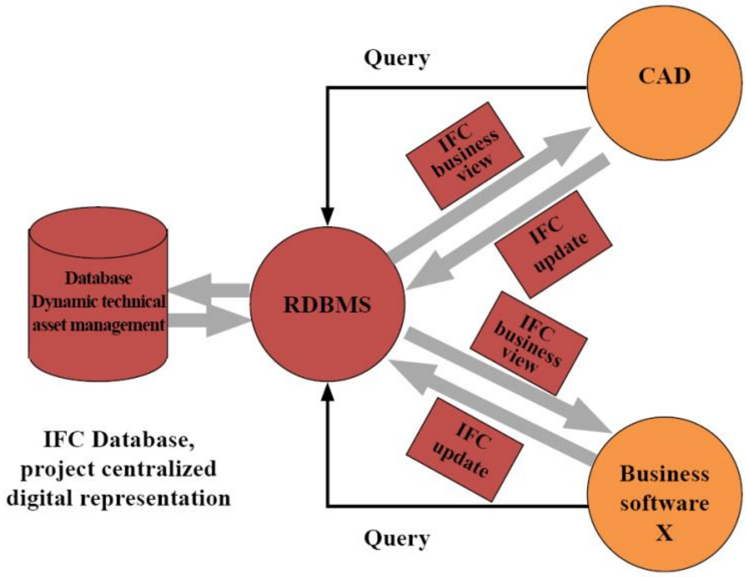

Figure 3. Dynamically shareable database [15].

This database system, to which data is added whenever a new building is constructed, makes it possible to work on a just-in-time basis with these structural elements and avoid storage issues, particularly in areas with little space available such as metropolises. However, the amount of data must be limited and optimised. Reducing the amount of data will, *inter alia*, make it possible to save both calculation and database search time, plus energy on the servers that are used.

For this research, the parameters were listed by materials and by phase according to the different stages of the project and entered in the BIM model. The information is attached to the objects in the BIM model. The methodology proposes to export, at each end of phase, these parameters on the database (ultimate normal effort, etc.). A gateway between the BIM model and the database and then the software for calculating reused structures has been developed.

5.3. Database queries

Depending on the stage of the project, queries will be more or less complex. For a column, for example, the initial issue may be to find a column in the database with an allowable stress enabling it to bear the load determined in the calculation model following analysis of the distribution of loads in the building. Next, the compatibility of the existing reinforcement drawing with the new use must be thoroughly checked.

This database query process will be an iterative process as a series of hypothetical uncertainties will have to be examined. Clearly, if the modelling of the new structure requires the use of a 50x50cm section beam and, in the database, the beam best meeting the stresses of the model has a section of 60x60cm, the structure's overall weight will be modified. As a result, a certain number of iterations are to be expected.

6. Concluding remarks and work to be continued

The contribution of the article concerns the reflection on the properties that must be known for reuse and the best tall building structural typology to achieve this. The environmental assessment of this unusual design questions impact allocations, especially for future reuse benefits. This research work has so far focused on the design of high-rise buildings to make their structure removable. Decommissioning scenarios must now be clarified and optimized to reach zero carbon. Data from traditional demolition sector must be refined for deconstruction. Then the data from deconstruction, transport, storage and reconstruction will make it possible to specify life cycle assessments with all the environmental impact indicators.

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Sustainable design of vegetated structures: Building freshness

Cravero J[1,2], Feraille A[2], Versini P-A[1], Caron J-F[2], Tchiguirinskaia I[1], Baverel O[2]

1. HM&Co, École des Ponts, UPE, Champs-sur-Marne, France

2. Navier, UMR 8205, École des Ponts, IFSTTAR, CNRS, UPE, Champs-sur-Marne, France

julien.cravero@enpc.fr

Abstract. City revegetation strategies seem appealing to mitigate urban heat island effects through shading and transpirational cooling. Moreover, other potential benefits that may derive, e.g. biodiversity enhancement, the reduction in buildings energy consumption, stormwater management, acoustic insulation or air purification, earned them the designation 'no-regrets approaches' for adapting to climate change. However, the lack of understanding and quantification of green infrastructures' environmental impacts prevents urban planning policies to be consistent and to turn attractive initiatives to effective implementations. The monitoring of existing green infrastructures is required to evaluate their cooling effect. For this purpose, an elastic gridshell in composite materials has been designed as a support for climbing plants at *Ecole des Ponts ParisTech* (Champs-sur-Marne, France). The life cycle assessment of the vegetated structure is performed in order to develop sustainable design strategies. Based on an energy balance approach, the collected thermo-hydric data can be used to determine which mechanisms are the most suitable for urban vegetation to enhance outdoor thermal comfort.

1. Introduction

City revegetation strategies seem appealing to contribute to urban heat island mitigation in a sustainable manner. However, current technical solutions employed to green dense urban areas are rarely adaptable to existing buildings and need major works to be carried out, as in the case of extensive green roofs. Supports of vegetation that are lightweight, cost-effective and compatible to various urban configurations are lacking. Moreover, the cooling effects provided by different types of urban vegetation are not yet properly understood and quantified, which prevents an effective implementation of green infrastructures in the townscape.

2. Vegetated structures

2.1. Elastic gridshells with composite materials

Given the constraints specific to dense cities, vegetated elastic gridshells (see figure 1) may represent an interesting type of green structure or furniture for enhancing thermal comfort on public spaces. Elastic gridshells aim at simplifying the construction of freeform structures and reducing the amount of material needed to cover large spans. Frequently, the fabrication process consists of assembling straight and slender beams into a flat regular grid. During the erection process, the elements are elastically bent so that the grid becomes doubly-curved. Once the desired geometry is obtained, it is braced to keep this final shape. Large-scale elastic gridshells that contributed to the reputation of active-bending structures were mainly manufactured out of timber, like the Mannheim Multihalle in 1975, the Weald and Downland Museum in 2002 and the Savill Garden in 2005. During the past, elastic gridshells used steel, aluminum, bamboo, cardboard and more recently carbon fiber reinforced polymers (CFRPs) and glass fiber reinforced polymers (GFRPs) [1].

Based on Ashby charts [2], Douthe [3, 4] showed that technical composites were perfect candidates for gridshell applications. In particular, pultruded pipes in composite materials display better results than timber laths when their respective mechanic properties (i.e., deformability, stiffness, toughness) are compared and GFRPs stand out from CFRPs when cost and embodied energy are considered. However, the environmental impacts due to materials and fabrication processes are expected to be greater for GFRP elements than for timber ones. As GFRPs exhibit a good resistance to many kinds of chemical attacks, the relevance of GFRP gridshells is thus amplified by the harshness of the environment. For example, GFRP gridshells are well-suited to any long-term outdoor exposition whereas timber gridshells would need regular maintenance operations under continental climatic conditions, hence increasing (environmental) costs. As the energetic content index in Ashby's method only reflects partly the environmental footprint of a material, life cycle assessments (LCAs) of the whole system are preferred to have a comprehensive mapping of its environmental impacts. More details on the LCA of GFRP rods are given in section 3.

Figure 1. Vegetated "tree-shaped" gridshells. [credits: Théo Mondot]

2.2. Climbing plants

The choice of the plant species depends on biological criteria (hardiness with respect to the climate, soil, growth rate, competition between species), esthetical criteria (shape, flowering, fructification, integration in the surrounding landscape), technical criteria (maintenance, stresses exerted on the structure), etc. According to gardeners working for the City of Paris, a mix comprising about two-thirds of deciduous trees and one-third of perennial ones is adopted in the parks and streets of the city to ensure shade in summer without blocking the incoming sunlight in winter. As the pots depicted in figure 1 contain one cubic metre of substrate, it has been decided to plant three climbers per pot in the same proportions. Possible candidates for the climbers in the Paris region are vines (e.g., *Vitis coignetiae, Parthenocissus quinquefolia, Parthenocissus tricuspidata*), clematis (e.g., *Clematis armandii, Clematis montana, Clematis 'Jackmanii')*, honeysuckles (e.g., *Lonicera japonica, Lonicera caprifolium*), hops (e.g., *Humulus lupulus 'Aureus'*), passifloras (e.g., *Passiflora caerulea*), jasmine (*Jasminum officinale*) or false jasmine (*Trachelospermum jasminoides*). Some of these climbing plants have been studied recently for green facades in Reading [5] and in Berlin [6] and demonstrated cooling potential through transpiration and shading.

2.3. Prototype

An experimental vegetated gridshell has been designed (see figure 2(a)) and will be built at Ecole des Ponts ParisTech in Champs-sur-Marne to assess the cooling effect provided by such structures. The grid comprises 32 pultruded composite rods made from vinylester resin and glass fiber, each rod having a length of 6m and a diameter of 18mm. The rods are assembled every meter with polyamide connections (see figure 2(b)) that are designed to let the rods rotate freely along their longitudinal axis. As the rods are initially straight and have equal principal moments of inertia, this free-rotation condition at the nodes and the supports ensures that the rods are not subjected to torsional stresses [3]. The stress level in the rods is capped at 25% of their limit stress to minimize creep and comply with recommendations for long-term mechanical performance of GFRP rods in actively-bent structures [7]. The gridshell is braced by 3mm-diameter steel cables at the top and the middle and by a steel sheet at the bottom. This metal cylinder envelops a pot containing three climbing plants, the substrate, pozzolan for drainage and a water reserve.

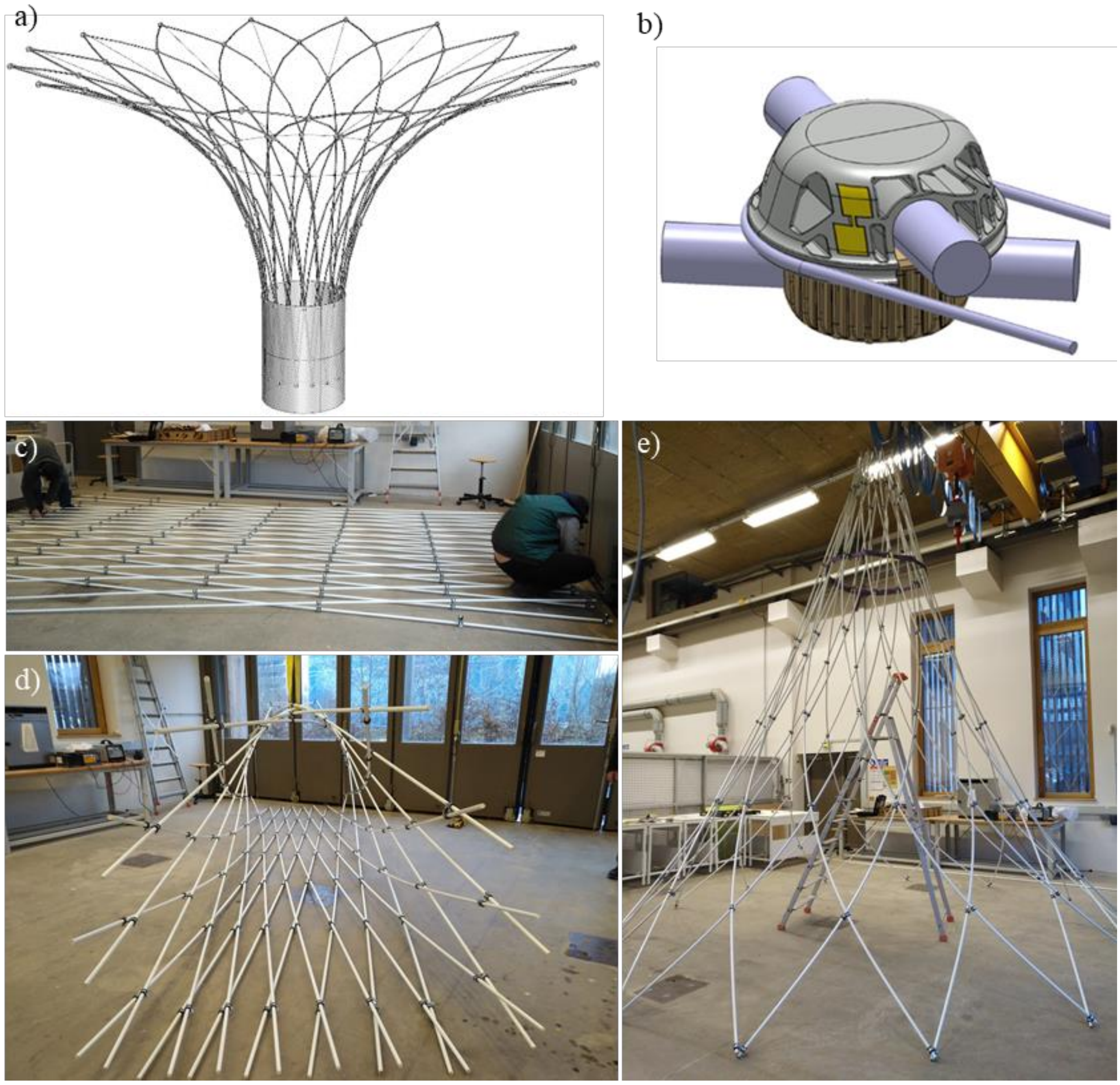

Figure 2. (a) Perspective view of the experimental prototype; (b) connection between two rods; (c) assembling of the rods into a flat grid; (d) closing of the grid into a cylinder; and (e) bending of the rods before bracing the grid.

The structure is 4.5m high, 1m wide at the base and 7m wide at the top, hence covering a projected area of circa 40m². The mass of the gridshell alone is 100kg. The whole vegetated structure weighs approximately 500kg when the water reserve is empty. A few pictures illustrating the main construction steps are shown in figure 2.

3. Life-cycle assessment

3.1. Description of the system

Processes are modelled with OpenLCA v.1.7.4. Ecoinvent 3.2 database is used for the life cycle inventory (LCI). The life cycle impact assessment (LCIA) method is based on NF EN 15804 [8] and NF EN 15804/CN [9] standards that apply to construction products. French national complement NF EN 15804/CN is employed to characterize air and water pollution. The nine impact categories proposed by NF EN 15804/CN are considered: acidification of soils and water (kg SO_2 eq.), ozone depletion (kg CFC-11 eq.), eutrophication (kg PO_4^{3-} eq.), photochemical ozone formation (kg ethylene eq.), air pollution (m^3), water pollution (m^3), global warming (kg CO_2 eq.), mineral and fossil resource depletion (MJ), and non-fossil resource depletion (kg Sb eq.). The model graph of the processes considered in the analysis is shown in figure 3. Each process is detailed below.

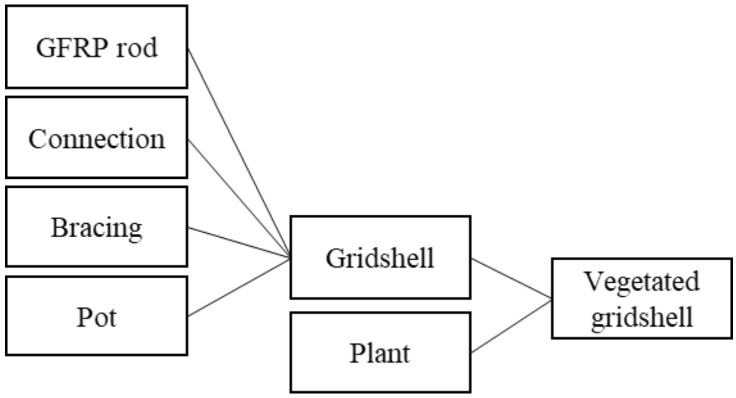

Figure 3. Flowchart of the system.

The LCI for similar glass fibre reinforced polyester resin composite elements has been performed previously [10]. It accounts for energy consumption, material consumption, types of packaging and transport, wastes related to production (such as raw material wastes) and the treatment of the latter. It does not consider the end of life of the end product. As vinylester resin is not yet available in ecoinvent 3.2 database, the process *polyester resin, unsaturated | polyester resin production, unsaturated – RER* used in [10] is kept to model the LCI of GFRP rods.

Gridshell connections are made in glass fibre reinforced polyamide and weigh 90g each. The process *injection moulding | injection moulding – RER* is employed. The mould is modelled as a 100kg-low-alloy-steel element with average metal working (*metal working, average for steel product manufacturing | metal working, average for steel product manufacturing*) and 800km aircraft transport pending further information from the manufacturer. According to the manufacturer, one million connections can be fabricated with this mould. Hence, an amortization of the mould is considered.

The braces (3mm-diameter steel cables with cable clamps) and the 40kg pot are modelled as low-alloy steel elements with average metal working.

The gridshell fabrication needs the production of 96kg of GFRP rods, 112 connections, 35m of braces and one pot. Transport from the production sites is not yet taken into account because of a lack of information.

In a first approach, waiting experimental results, the water consumption (i.e., irrigation) is estimated to 200L per plant per year. Based on [11], the potential productivity per plant is estimated to 4kg of dry matter per year. Assuming a carbon content of 50%, each plant stores 2kg of carbon per year, which corresponds to 7.3kg of carbon dioxide used for photosynthesis. Thus, each plant is modelled in OpenLCA by a single process that uses 200L *tap water | market for tap water* for irrigation as an input and avoids 7.3kg of carbon dioxide yearly. These figures consist in rough approximations and will be refined later experimentally (see sub-section 4.2). Processes used for the production and transport of the soil, sand and pozzolan are not considered at this time. The data will be collected and analyzed when the prototype is built.

Finally, a vegetated gridshell comprises the production of one gridshell and three plants as modelled above. The lifetime of the plants is estimated to 30 years but the service life of the structure is expected to be larger based on durability studies carried out on GFRP rods [7]; the treatment or reuse of the structural elements is beyond the scope of this study.

3.2. Results

The potential impacts due to the gridshell production alone and to the vegetated gridshell after 30 years are given in table 1. As the plants only need tap water for irrigation in this model, the differences in the impacts of the gridshell and the vegetated gridshell are very limited, except for the global warming potential. This is due to the amount of carbon dioxide removed by the plants in their surroundings because of their growth. However, this carbon is stored temporarily and will be released sooner or later depending on the end of life of the plants: they may be burnt at the recycling centre to serve as fuel for heating the district, shredded to be used as mulch, decomposed by composting, etc. These scenarios will be considered in future works.

Table 1. Impacts of the gridshell production and of the vegetated gridshell (the results are shown for a lifetime of 30 years).

Impact category	Gridshell	Vegetated gridshell
Acidification of soils and water (kg SO_2 eq.)	2.9	3.0
Ozone depletion (kg CFC-11 eq.)	$6.3\cdot10^{-5}$	$6.3\cdot10^{-5}$
Eutrophication (kg PO_4^{3-} eq.)	0.46	0.47
Photochemical ozone formation (kg ethylene eq.)	0.17	0.17
Air pollution (m^3)	1700	1700
Water pollution (m^3)	$4.8\cdot10^{5}$	$4.9\cdot10^{5}$
Global warming (kg CO_2 eq.)	690	40
Mineral and fossil resource depletion (MJ)	$1.0\cdot10^{4}$	$1.0\cdot10^{4}$
Non-fossil resource depletion (kg Sb eq.)	$1.4\cdot10^{-8}$	$1.4\cdot10^{-8}$

Figure 4 shows how the GFRP rods, the connections, the pot and the braces contribute to the environmental impacts caused by the gridshell production. The graph indicates that in this case, the share among the four processes follows a similar pattern for all the impact categories. The impacts due to the production of the GFRP rods accounts for approximately two-thirds of the total, which suggests that future designs should aim at decreasing this material quantity. For the gridshell to keep a similar global structural behaviour, this could be achieved with a denser grid of rods of smaller diameter (at the cost of a greater number of connections) or with GFRP tubes (i.e., hollow instead of solid rods). Natural fibre reinforced polymers (NFRPs) could also be utilized to reduce the amount of glass fibre in the structure. However, this may lead to mechanical long-term issues [7] and one has to ensure that their industrial production does not require more polluting processes. This has still to be assessed.

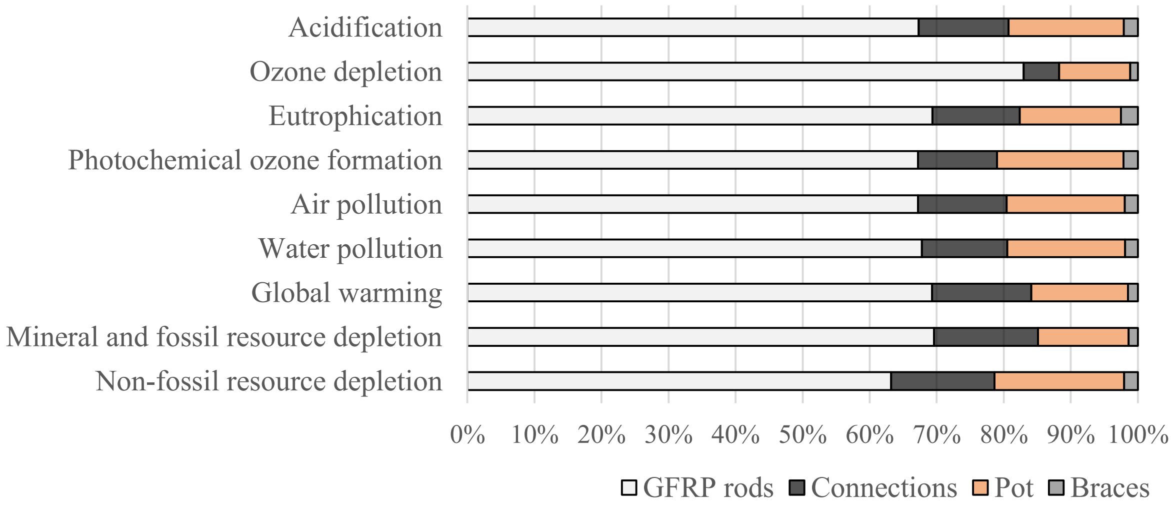

Figure 4. Relative contribution of each element production to the total environmental impacts of the gridshell production.

Table 1 shows the interest that urban vegetation could play in terms of climate change mitigation, as it temporarily stores carbon, but other potential benefits, such as cooling effects, are not reflected by the LCA. This is discussed in the following section.

4. Evaluation of the cooling effect at a local scale

4.1. Cooling mechanisms

Oke [12] proposed in 1982 a sound theoretical framework to advance knowledge in the field of urban meteorology and overcome the mere description of urban heat island effects. His approach popularized the use of surface energy balance models for predicting the thermal response of cities to various urban forms and environmental conditions. Since, numerous works have attempted to improve the modelling of energy, mass and momentum exchanges at stake in the energy balance. A general way to write the energy balance at the interface between the urban area and the atmosphere is given by Offerle [13]:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A + S \qquad (1)$$

in which Q^* is the net all-wave radiation, Q_F the anthropogenic heat flux, Q_H the sensible heat flux, Q_E the latent heat flux, ΔQ_S the heat storage, ΔQ_A the net advected flux and S all other heat sources or sinks. All these terms are homogeneous to heat flux densities and are expressed in W.m^{-2}. The rationale of this approach is detailed in many works, e.g. in [14]. Neglecting anthropogenic and advected fluxes, and in the absence of heat sources and sinks, equation (1) may be rewritten as per Masson [15] to highlight the dynamics of the energy exchanges:

$$eC\frac{\partial T_s}{\partial t} = Q^* - Q_H - Q_E - Q_G \qquad (2)$$

in which e is the layer thickness (in meters), C the heat capacity (in J.m^{-3}.K^{-1}), T_s the temperature of the surface and of the layer (in kelvins) and Q_G the conduction heat flux between the surface layer and the underlying layer (in W.m^{-2}). The terms used in equation (2) may be written as:

$$Q^* = (S_\downarrow - S_\uparrow) + (L_\downarrow - L_\uparrow) = (1-\alpha)S_\downarrow + L_\downarrow - \varepsilon\sigma T_s^4 \qquad (3)$$

$$Q_H = h_{ch}(T_s - T_{air}) \qquad (4)$$

$$Q_E = LE = Lh_{cm}(p_{sat}(T_s) - p_w) \qquad (5)$$

$$Q_G = -\lambda \left(\frac{\partial T_s}{\partial z} \right)_{z=e} \qquad (6)$$

where $S\downarrow$ and $S\uparrow$ are the downward and upward short-wave radiations (in W.m^{-2}), $L\downarrow$ and $L\uparrow$ the downward and upward long-wave radiations (in W.m^{-2}), α and ε the surface albedo and emissivity, σ the Stefan-Boltzmann constant (σ=5.67·10^{-8} W.m^{-2}. K^{-4}), h_{ch} the convective heat transfer coefficient (in W.m^{-2}. K^{-1}), T_{air} the air temperature (in kelvins), L the specific latent heat of vaporization of water (in J.kg^{-1}), E the evaporation rate (in kg.m^{-2}.s^{-1}), h_{cm} the convective mass transfer coefficient (in s.m^{-1}), p_{sat} the saturation vapour pressure (in pascals), p_w the partial pressure of water vapour in the air (in pascals) and λ the thermal conductivity of the layer material (in W.m^{-1}. K^{-1}). Equation (2) may be used to model the temperature evolution of the substrate, of the ground under the gridshell shade or of one leaf, irrespective of the surface area. However, the area of the surface under consideration may play an important role in terms of fluxes repartition, as smaller objects have greater heat transfer coefficients according to Sakai [16]. Note that "surface" often denotes a control volume with homogeneous properties that could represent a large urban area (e.g., [14]) or a crop canopy (e.g., [17]). The energy balance of a thin layer as described above is graphically summarized in figure 5.

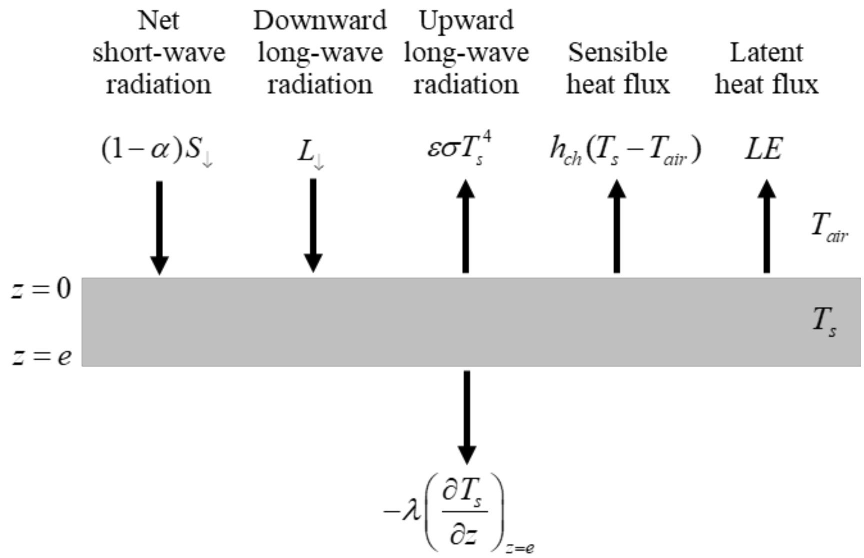

Figure 5. Energy balance for a thin layer of material.

The quantification of these energy exchanges enables to predict the urban surfaces temperature evolution and to better understand by which means heat island effects could be mitigated by vegetation. As trees transpire, they cool down their leaves, which then cool down the air by convection if their temperature is lower than that of the air (i.e., Q_H < 0). This is not always the case, as demonstrated by measurements of tree crown temperatures in Basel that were found to exceed air temperature by 5 K [18]. Recently, Manickathan [19] showed with computational fluid dynamics (CFD) simulations based on leaf energy balances that the top of a tree crown could warm the air (even if the transpiration is high) whereas cooling occurs at the bottom of the tree where the absorbed radiation is low. This small amount of direct cooling caused by trees agrees with previous CFD simulations [20, 21]. As the amount of air cooling seems to be limited based on a meta-analysis on the cooling effect provided by parks and green spaces [22], the main impact of urban trees upon thermal comfort is attributed to their shade as reported by Armson [23]. Based on equation (2), shading an artificial surface (i.e., lower $S\downarrow$) decreases its surface temperature, hence reducing the convection of heat to the air (i.e., lower Q_H) and the radiation towards pedestrians and other surfaces (i.e., lower $L\uparrow$). Decreasing absorbed radiation also reduces thermal storage in materials and release of the heat during the night [24]. Moreover, during summer trees may be able to keep a foliage temperature closer to the air temperature compared to surrounding artificial surfaces thanks to their numerous small leaves [16]. Hence, they would act as a radiative screen for pedestrians. This agrees with studies assessing the human comfort in outdoor environments based on the Universal Thermal Climate Index (UTCI) [19, 25].

4.2. Instrumentation

The gridshell prototype described in section 2 will be instrumented to assess the cooling effects due to air cooling and surface shading. Load cells will be placed under the pot to measure the evapotranspiration (i.e., the mass of evaporated water), as with a lysimeter. This data will also be used to measure the water needed for irrigation and refine the plant growth model. The radiation balance is measured with pyrgeometers and pyranometers. Temperature sensors are employed to get the temperature of the air, of the substrate and of the ground. Leaf temperature is obtained by a thermal imaging camera. These experimental results will permit to have a deeper understanding of the dynamics of heat exchanges around an isolated vegetated structure and to compare their cooling efficiency with other species of climbing plants [5, 6] and other types of landscape strategies (e.g., [26]).

5. Conclusions and perspectives

An innovative 40m²-gridshell in composite materials has been designed as a support for climbing plants in order to provide shade in urban areas. A life cycle assessment of this structure has been performed to evaluate the environmental impacts due to its construction. Modelling the end of life of both the materials and the plants is still needed to develop sustainable solutions that may contribute to heat island mitigation. Experimental results are also required to assess the cooling effects and the maintenance costs provided by this vegetated urban furniture and by urban vegetation in general. This will allow to derive indicators describing the cooling performance of various landscape strategies and to establish trade-offs between outdoor thermal comfort and resource use, e.g. materials utilized for the structure and water needed for irrigation.

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Design concept for prefabricated elements from CDW timber for a circurlar building

Klinge A, Roswag-Klinge E, Paganoni S, Radeljic L, Lehmann M

ZRS Architekten Ingenieure, Schlesische Str. 26, 10997 Berlin

klinge@zrs.berlin

Abstract. The EU funded project RE[4] (REuse and REcycling of CDW materials and structures in energy efficient pREfabricated elements for building REfurbishment and construction) looks into opportunities for prefabricated, CDW timber elements (structural and non-structural) for circular buildings. Main goal is to minimise resource consumption for building construction but also waste generation related to building dismantling. An innovative design concept for a fully reversible, prefabricated, multi-story residential building from waste wood has been established that reflects robust but flexible and adaptable solutions to extend the buildings-life cycle. Reversible connections, reusable elements and recyclable materials shall minimise future waste generation, when such buildings reach their end of life. A prefabricated façade element manufactured for a two-story prototype shall deliver figures for easy installation, dismantling and future reuse. The study aims to show how current challenges can be overcome and design for disassembly can be promoted.

1. Introduction

In 2014 the building sector contributed with approx. 750 million tons of construction and demolition waste (CDW) significantly to the overall waste generation in Europe [1]. Recovery rates (50%) are relatively low, especially as recovered materials are mainly used for low-grade applications or diverted to energetic recovery [2]. Vast amounts are still directed to landfill, as existing buildings were not designed for disassembly. The dismantling of timber elements (columns, beams etc.) from existing buildings illustrates evidently the wasteful approach the industry is still pursuing. To avoid time consuming investigations related to the application of wood preservatives, timber elements are predominantly classified as Waste Wood Class AIV. This in turn implies thermal recovery as only exploitation method. As a result, high quality timber is lost for future applications. Furthermore, CO_2 stored in the element is released back into the atmosphere. In light of the forthcoming legal changes that stipulate the reduction of CDW by 70% in weight until 2020 (2008/98/EC), the industry needs urgently innovative concepts for circular construction that minimise the reliance on fossil resources and high-tech solutions in order to meet such ambitious goals set out by the European Union [3].

2. Requirements

2.1. Prerequisites

Although waste wood is one of the few materials that offer unique opportunities for direct reuse, this resource is mainly diverted to landfill or send to energetic recovery. Cheap access to fresh wood, low disposal cost and time-consuming detection methods for application of wood preservatives are currently the main barriers for circular timber construction. If waste wood shall be reused or recycled for construction purposes, the following prerequisites have to be addressed. Recovered sections must be free of:

- wood preservatives;
- other pollutants, resulting from previous uses that might have penetrated the wood;
- wood-destroying fungi and insects;
- any metal impurities that could damage machinery for reprocessing and
- demonstrate sufficiently strength, large cross-sections and lengths.

2.1.1. Harmful substances. The Waste Wood Ordinance regulates the handling of salvaged timber and implies that the absence of harmful substances must be proved in order to allow its reuse or recycling [4]. In the absence of any commercial rapid on-site test, material samples from retrieved elements (Figure *1*) have been examined in a certified lab. Instructions for removal of timber layers were given by the respective expert, in case of evidenced wood preservatives, which in turn permitted the utilization of salvaged sections instead of thermal recovery.

2.1.2. Pollutants from previous uses. In case harmful substances or pollutants were used or applied in a building identified for dismantling, suitable investigations must prove that timber identified for reuse or recycling is not affected. As such cases could be excluded for the salvaged waste wood within the RE^4 project, no special investigations in this field were carried out nor required.

2.1.3. Metal impurities. Metal fittings are one of the main barriers that prevent the reuse and recycling of waste wood, as such impurities can considerably damage wood working machinery, if they remain undetected. All timber sections have therefore been examined by means of simple metal detectors to identify any kind of metal impurity, which have then been removed by means of hand tools (Figure 2).

2.1.4. Strength grading. CDW timber has to be strength graded according to harmonised standards [5], [6], [7] and national grading rules. On-site inspections have been carried out by an expert to categorise the timber, measure available sections and identify the extend of decay, defects and damages. Based on these results, timber sections have been sorted and separated on site for further reprocessing and strength grading. All impurities (paints, coatings etc.) were removed to obtain clean raw material that was cut and planed into rectangular cross sections. As access to a drying chamber could not be established, timber was not technically dried so that the average moisture level of 20% required for strength grading was not always achieved.

Figure 1. Timber for recycling

Figure 2. Metal detection

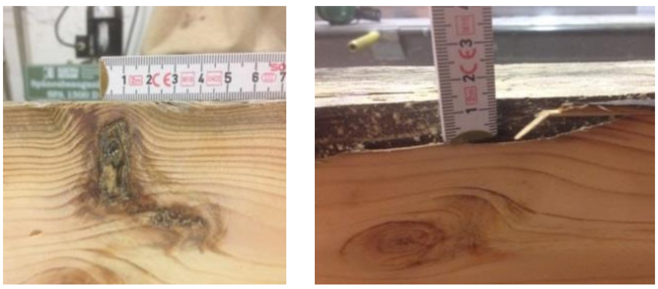

Figure 3. Strength grading: assessment of defects, decays, cracks and dimensions, location + orientation of branches

The actual strength grading process was carried out on cleaned timber sections, which were assessed with regards to dimensions and location of cracks, branches and slope of grain (Figure 3). Classification according to DIN 4074-1:2012 [8] into the relevant sorting classes led in turn to the respective strength class according to EN 338:2016 [9]. Additional requirements for lamellas, designated for glued laminated timber, regulated in superior standards were applied during production [7]. Lamellas were then used for the production of timber beams and columns as well as thresholds, plates and studs for non-load bearing façade elements.

3. Design concepts

3.1. Load bearing timber beams and columns

The general design for load bearing timber elements for the bearing structure of the building complies with EN 14080:2013 [7] and follows the principal of glulam timber, where single lamellas are joined together. Glueless connections of single lamellas have also been investigated but will not be elaborated in this study. The design concept pursues the idea of maximisation and optimization of usable sections from waste wood, which is illustrated in Figure 4.

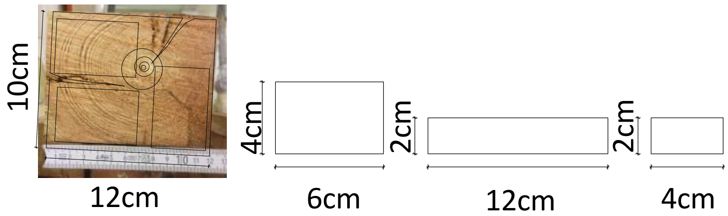

Figure 4. Possible division of salvaged timber sections

For the construction of the elements, cracks have been cut away from salvaged sections and obtained dimensions were assessed for suitable use in beams and columns. Initial trials have been undertaken and lamellas of 4/6/12 cm x 4 cm have been joined with glue in vertical and horizontal direction. (Figure 5 - Figure 7).

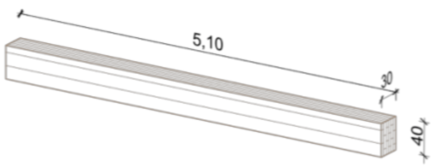

Figure 5. Design concept for glulam timber beam from CDW timber

Figure 6. Glulam beam

Figure 7. Glulam timber beam, with lamellas joined in vertical and horizontal direction

3.2. Non-load bearing, prefabricated timber façade elements

The design concept for a prefabricated, reversible, rear ventilated façade element made from CDW timber proposes a non-load bearing timber frame construction. A self-supporting stud system is covered either side with stiffening wood fibre boards. In certain load cases a wood fibre hardboard might structurally be required to replace the wood fibreboard on the inside. The panel is insulated with a blow in insulation, based on recycled timber flakes or fibres. The weatherboards are fixed with screws to a batten and counter batten system to enable future dismantling. An earthen plaster made from recycled aggregate is applied as final finish to the interior, to provide a healthy and comfortable interior climate. All connections are either screwed or plugged as carpenter connections. Figure 8 shows the general design concept for the prefabricated timber façade element and illustrates the single components.

Similar as for beams and columns, the general design aims to minimise material usage. In addition, the concept follows the approach of a cascading use and looks into opportunities for using cut offs from reprocessing and manufacturing for production of other components that are part of the element. Exemplary investigations regarding source material (Figure 9) and possible outcome (Figure 10) after cutting have been carried out on planks, which were the main source for the production of the façade element. At first, the plank was cleaned and planed. In a second step, required sections for structural members were cut to size. As a result, different usable sections, various cut offs, shaves and sawdust were obtained. Table 1 provides an overview about the different sections and provides details regarding dimensions and final amounts. Larger sections were used for the structural parts of the element (threshold, plate, stud), whereas smaller sections were applied as weatherboards. It is intended to use cut offs and sawdust for the production of stiffening boards (wood fibre hardboard) and wood chips or shavings as insulation material. Smaller cut offs shall be separated further for production of wood fibreboards. For the time being, commercial products have been used for such components.

Figure 8. Design concept for timber element, Model: 1:20

Figure 9. Source material (plank)

Figure 10. Outcome of usable material

Once the element has reached its end of life, single components can be reprocessed and recycled. Weatherboards can be dismantled, planed to remove decayed parts and further processed for the use of wood chips, suitable for the production of chip boards or wood fibre boards or insulation. All structural parts offer similar potential for a timber cascade.

Table 1. Outcome of usable material after cleaning and cutting

Piece	Length in dm	Width in dm	Height in dm	Vol. in dm^3	Vol. in %
Total	**32.9**	**2.35**	**0.558**	**43.14**	**100**
Usable wood 1 (UW 1)	22.5	1	0.5	11.25	26
Usable wood 2 (UW 2)	19.73	0.92	0.55	9.98	23
Usable wood 3 (UW 3)	26	0.48	0.18	2.25	5
Off cut 1 (metal) (OC 1)	6.35	2.35	0.58	8.66	20
Off cut 2 (metal) (OC 2)	6	0.95	0.58	3.31	8
Off cut 3 (cross) (OC 3)	4.1	1	0.5	2.05	5
Offcut 4 (longitude) (OC 4)	27.2	0.05	0.53	0.72	2
Offcut 5 (cross) (OC 5)	0.25	0.48	0.18	0.02	0.5
Offcut 6 (longitude) (OC 6)	26.7	0.05	0.22	0.29	0.5
SUM				**38.53**	**90**
Sawdust	**25 liters / 1.74 kg**			**4.61**	**10**

For material efficient studs, different design concepts have been developed (Figure 12 - Figure 14). A supporting framework allows the optimised use of different timber sections obtained from processing CDW timber. Dimensions and layout of the single lamellas are set out according to static calculations but consider sizes of salvaged cross sections and possible divisions (Figure 11). For thresholds and plates massive sections were produced.

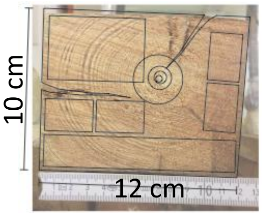

Figure 11. Salvaged cross section, division for material optimised studs

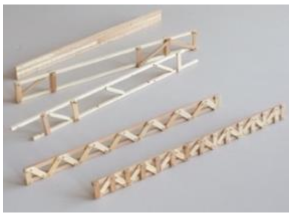

Figure 12. Models of material efficient studs

Figure 13. Framework studs, battens with different or same sizes, assembled eccentrically

Figure 14. Framework stud, different sized battens, assembled centrically

For the final production of the panel, the structural components (threshold, plate and studs) have been assembled to a frame, based on the standard grid for timber construction. The frame has then been covered with the wood fibre hardboard, to provide the required stiffness for the element. As a next step, wood fibreboards and blow in insulation have been applied in parallel (Figure 15 - Figure 16). Finally, weatherboards have been fixed to a support structure of battens and counter battens (Figure 17). The CDW earthen plaster will be applied on site. Reversible connections have been provided by means of screws and metal brackets. In a next step, it is intended to apply timber in timber connections where possible, to minimise metal fasteners.

Figure 15. Timber frame with studs, incorporation of blow in-insulation

Figure 16. Application of wood fibre boards

Figure 17. Weather shell

3.3. Reversible connections

Reversible connections at component and element level but also within elements are key to enable the reuse and recycling of building parts. Investigations at component and element level have been carried out. Different timber in timber connections (carpenter connections) or metal ones have been tested. For corner connections of the frame (façade element), initial tests have been conducted (Figure 18 - Figure 19). For connection of structural components, commercial solutions have been taken into consideration, that offer viable options (Figure 20 - Figure 21).

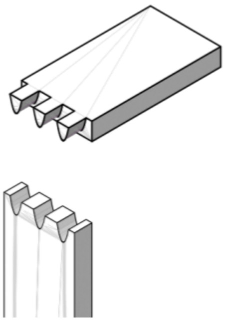

Figure 18. Carpenter connection (dovetail)

Figure 19. Screwed connection facade element

Figure 20. Bolted connection column - foundation

Figure 21. Reversible joist hanger (© Sherpa)

3.4. *Design concept for reversible buildings*

The design concept for a reversible building focuses on the lifespan of various building elements and enables meaningful divisions so that elements demonstrating a significantly shorter lifespan can relatively easy be maintained or exchanged. In addition, a high level of flexibility, decent ceiling heights and opportunities for adaptation shall generally increase the service life of a building (Figure 22). Although building elements are modular, they offer variation in size and shall be designed in such way that they can easily be dismantled and reused in future applications. In addition, they follow the concept of material purity or allow for easy dismantling so that different components can be separated and reused or recycled if necessary [10]. Additionally, the use of high quality materials shall further increase the durability as well as the lifespan of the component and therefor also the building.

The design proposal suggests a timber skeleton support structure with reversible connections in combination with a stiffening core and a wooden non-load bearing façade system (Figure 22). All elements and components are made out of CDW timber. The column system offers the highest level of flexibility when it comes to adaptation of floor layouts (Figure 23). The non-load bearing facade system allows for a complete exchange of the elements, once they have reached their end of life or in case of a use change of the building requires a different configuration. Reversible connections, still under investigation, are planned for all connections. It is anticipated that they can either be realised as carpenter connections or through reversible, metal fasteners or connections.

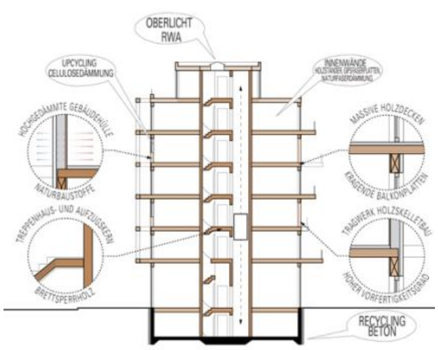

Figure 22. Design concept for a reversible timber skeleton building

Figure 23. Skeleton system with stiffening core

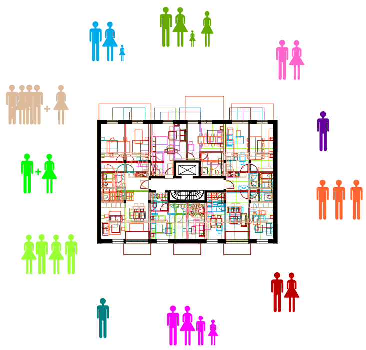

Figure 24. Adaptable floor layouts offer a high level of flexibility

4. Results and discussion

4.1. *Prerequisites*

On-site inspections have proved to be an appropriate strategy to identify whether existing timber structures might be suitable for a direct reuse or recycling. Although, strength grading according to standard has been carried out on cleaned timber sections, initial on-site assessments delivered reliable results regarding the general structural capacity of the installed timber components and elements.

Furthermore, it could be established through firm lab testing that not all constructions were treated with wood preservatives so that salvaged timber could be directly reused. On-site investigations were also suitable for the assessment of timber regarding insect and fungi infestation. Furthermore, it could be proved by means of simple metal detectors that all metal impurities were identified. The final strength class of the assessed timber achieved either C16 or C24, which is suitable for the development of structural timber elements.

4.2. Material and design concept for load bearing timber elements

The material and design concept for load bearing timber beams and columns could successfully be implemented. Material efficient construction could be achieved through application of standardised sizes for lamellas. Cracks and branches were cut off without major losses of material. Although not tested in the lab, industrial finger joints enable the incorporation of shorter sections. The use of glue for connection of single lamellas has proven to be very time and cost efficient and delivers frictional connections also for waste wood. As developed elements can be classified according to DIN 68800 as use class 0, the application of wood preservatives is not required [11].

4.3. Material and design concept for non-load bearing, prefabricated timber façade elements

The concept for a cascading use of timber for facade element seems very promising. The overall material that could be recycled from processed planks summed up to approx. 90 %. Nail plates would have to be removed to bring sections covered with metal back into the material cycle. Although only solid sections have been manufactured so far, the usage of cut offs for production of other components seems a viable solution. The industry is following this concept already, although with fresh wood. The concept for material efficient studs delivered also promising results. However, this approach was more time consuming in comparison to the production of solid ones. Encouragingly enough, the production of the final element was entirely carried out with hand machinery. Similar to beams and columns, the façade element can be classified according to DIN 68800 as use class 0, due to special constructive measures, set out in [11]. Therefore, the application of wood preservatives is not required. The environmental benefit regarding the reduction of environmental impact due to the reuse and recycling is currently under investigation.

4.4. Reversible connections

Initial studies were only carried out at lab scale. However, both concepts, timber in timber but also metal connections are suitable to enable reversible connections at component but also element level. Carpenter connections were more time consuming due to the lack of appropriate machinery. Additional studies and testing are required, to investigate and deliver solutions for the various different applications. However, results so far enabled the complete dismantling of elements and components.

4.5. Design concept for reversible buildings

Although the developed concept needs to be approved in real application, skeleton systems are well known for a greater level of flexibility. Also, the separation of elements according to their life spans seems to deliver viable and long-lasting buildings. The use of timber in construction offers generally much higher potential for reversible buildings in comparison to massive construction. The material is much lighter and enables dry connections. Furthermore, the concept of material purity is easier to achieve for structural elements as timber is able to take compressive, tensile and shear loads.

Regarding the service life of the single elements that have been developed, it is expected that the use of waste wood that grew under less harmful environmental impacts in comparison to today increases the lifespan of the single elements and therefore of the entire building. This however has to be verified through further investigations.

5. Conclusions and recommendations

5.1. Prerequisites

Investigating aged timber, different factors have to be taken into account. The state of conservation, dismantling damages, and previous load condition can have an influence on the load capacity of the timber. Since the 1950's different research projects established that the influence of aging can be neglected if the state of conservation and other impurities are surveyed carefully [12].

The use of standardized cross sections can help to avoid storage costs and increase the market acceptance for salvaged timber. Finger joints make the recycling of CDW timber very attractive as defects can be cut out and shorter pieces can be finger jointed into an endless lamella that in turn can be cut into the required length.

Today, visual strength grading can be assisted by machines, which can lead to a better yield in higher strength classes. Traditionally grading machines work by bending the timber and assessing the stiffness. Today machine grading also includes technologies as flexural resonant frequency, x-ray measurements and ultrasonic wave speed.

To address the issue of wood preservatives, a kind of rapid on-site test would be desirable, as sampling and lab analysis is costly and time intensive. The Fraunhofer Institute developed a prototype for an on-site measurement device, which could be an opportunity to upgrade the classification of wood from demolition sites [13].

5.2. Material and design concept for load bearing and non-load bearing timber elements

The high level of CDW timber that could be integrated into all components and elements demonstrates the enormous potential of this approach for minimisation of both, CDW generation but also resource consumption. However, unless holistic costs for construction and deconstruction are imposed or incentives for more sustainable solutions are granted, such solutions will experience difficulties to enter the highly economically driven market.

5.3. Reversible connections

Reversible connections based on metal fittings are not common in modern timber construction to date. Without modern industrial trimming machines, carpenter connections are economically not viable. However, if circular construction becomes mandatory, suitable solution shall be implemented relatively easy.

5.4. Design concept for reversible buildings

New material and construction concepts must be developed to enable the adaptation of buildings. In addition, today's planning process of new timber structures needs to take possible disassembly and reuse into account. Reversible connections, most often more expensive, are key for the success of such concepts. The growing digitalisation and increased use of Building Information Modelling (BIM) may support the implementation of circular construction. Especially in timber construction 3D modelling is a common approach. Engaged component producers and suppliers in the aftermarket of products offering e.g. take-back systems for construction left-overs and possibly end-of use products, upgrades and repairs services etc. could support the reuse of building elements. However, without governmental interventions, attempts for circular construction might remain at pilot level.

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Prototypology for a circular building industry: the potential of re-used and recycled building materials

Heisel F[1], **Schlesier K** [2], **Hebel D E**[1]

[1] Sustainable Construction, Faculty of Architecture, KIT Karlsruhe, 76131 Karlsruhe
[2] Structural Design, Faculty of Architecture, HafenCity University, 20457 Hamburg

felix.heisel@kit.edu

Abstract. The growing scarcity of resources calls for a paradigm shift from linear material consumption to circular economy – especially in the construction industry. This shift involves a complete rethinking of design principles, materials, construction technics and technologies, as well as the introduction of new business models evolving from these reconfigurations within the field. This paper will show on-going research on these themes with a focus on direct material re-use and recycling through the discussion of a prototypology – the recently concluded Mehr.WERT.Pavillon (MWP) at the BUGA 2019 in Heilbronn. The research specifically addresses a reversible, mono-material structure that is made from re-used structural steel and recycled glass. The concept of cycles therefor is significant: Utilized materials are not consumed and disposed of; instead, they are borrowed from their material cycle for a certain period of time and later returned there at equal value and utility. Sourced from recycled materials, the prototypology is a built example of urban mining; designed for disassembly at the end of its service time, it also represents a material banks for future projects – while proofing the claim, that it is possible already today to build within a circular system.

1. Introduction: towards a closed-loop building industry

A transition from the currently still dominantly linear economic system towards the Circular Economy (CE) is widely accepted as essential for the implementation of global commitments taken by the European Union (EU) and its Member States, notably the U.N. 2030 Agenda for Sustainable Development and the G7 Alliance on Resource Efficiency [1]. The most-widely accepted characterization of the concept has been framed in 2013 (and revised in 2015) by the Ellen MacArthur Foundation: "A circular economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles" [2]. On December 2nd, 2015, the EU adopted the Circular Economy Action Plan [3] aiming to develop and implement a regulatory framework for the shift towards the CE in its single markets, as well as send clear signals and provide concrete actions to be carried out before 2020. The plan addresses four phases (production, consumption, waste management and closing of loops) in several priority areas of high impact – one of them being Construction and Demolition. Within the union, the building sector represents one of the biggest consumers of raw materials and one of the biggest producers of waste and emissions: construction and use of buildings account for about half of all extracted materials and energy consumption as well as about a third of water consumption and waste production [4]. Article 11.2 of the Waste Framework Directive (WFD) stipulates that "Member States shall take the necessary measures designed to achieve that by 2020, the preparing for re-use, recycling and other material recovery (...) of non-hazardous construction and demolition waste excluding naturally occurring material (...) shall be increased to a minimum of 70 % by weight" [5].

This EU-wide mandatory target however includes (in the majority) down-cycling and backfilling operations using waste to substitute other materials – procedures that do not fulfil the requirements of the above-mentioned characterization of a CE, where materials or components circulate at their highest utility and value. Consequently, increased efforts have to be spent on direct and high-value re-use and recycling processes in the building industry in order to realize a true shift from linear to circular economy. The article at hand describes an exemplary case study building – a prototypology for the circular building industry (section 2) – and its re-use and recycling (section 3) related steps and decisions in regard to design, construction, structure and permit process for two selected material categories (section 4). A discussion on future work (section 5) and conclusions (section 6) are provided in the end.

2. Prototypology: *Mehr.WERT.Pavillon* at BUGA 2019

Joined from the terms *prototype* and *typology*, the prototypology represents a full-scale building, that is experiment and proof in itself to effectively and holistically discover connected aspects and unknowns of a specific question. Yet, at the same time, it is part of bigger, and systematic test series of different such types with similar characteristics, yet varying parameters [6].

The 2019 German Federal Garden Show (BUGA) in Heilbronn is both garden and city exhibition. The newly built city quarter *Neckarboden* is intended to be a test bed for new urban development scenarios concentrating on highest living standards and qualities for a socially diverse population group within a densely populated central urban setting [7]. Economic and ecologic aspects are foregrounded. Within this context, it was found necessary and relevant to implement a new thinking about resource application, leaving the present linear take-make-throw mentality behind [8].

Situated on a central lot of the BUGA terrain, the *Mehr.WERT.Garten* (translation: *Added.VALUE. Garden*) and its pavilion address the question how we can perform a paradigm shift in the way we use our resources towards a CE of closed and pure material cycles. The *Mehr.WERT.Pavillon* (MWP) is the shell, as well as main element of this exhibition on local and global resource use, alternative materials as well as their applications in circular design and construction. On the one hand, the pavilion makes use of the existing urban mine: all materials used in the project have already undergone at least one life cycle, either in the same or in a different physiognomy. On the other hand, it acts as a material depot, which will become available and productive again for future constructions at the end of the exhibition: Materials utilized in the construction of MWP are specified and employed in a way that allows their complete re-introduction into pure and type-sorted material cycles for re-use, recycling or bio-degradation after the decommissioning and deconstruction of the building. The pavilion's objective is to proof that it is possible already today to design, detail and construct according to the principles of the CE [9].

Figure 1. View of The Mehr.WERT.Pavillon

Figure 2. View of the façade from the inside

The pavilion's building materials are separated into four groups: (1) the load-bearing structure is largely made from re-used steel originating from a disused coal-fired power plant in north-western Germany. It consists of four inclined supports that fan out like tree branches and are connected to each other by a rigid steel frame structure. (2) The façades and roof are clad in panels manufactured from recycled bottles glass and industrial glass waste. (3) The furniture is built from recycled HDPE plastic waste, while the chairs are 3D printed from plastic household waste. (4) The floor of the pavilion as well as the landscape design of the garden forms an assemblage of various re-used and recycled materials and products made from mineral construction and demolition waste (Figures 1-2).

MWP serves as a laboratory and test run for future construction projects as well as building processes. The aim is to discuss important issues of construction and the associated use of resources with decision-makers from politics, construction planning and implementation and to develop new innovative concepts, applications and methods from these, both in practice and in teaching. Therefore, it is all the more important to note that the concept of MWP originated in a student design studio by the Professorship of Sustainable Construction at the Karlsruhe Institute of Technology [10].

3. Re-use and recycling in construction

The WFD defines waste quite broadly as 'any substance or object which the holder discards or intends or is required to discard' [5], whereby this action can be both intentional or unintentional / involuntary / accidental and neither commercial value nor storage location of the substance or object have an influence on the waste status. Article 4 of WFD introduced a legally binding 5-step hierarchy of waste management operations, which member states must apply in the following order: (1) prevention, (2) preparing for re-use, (3) recycling, (4) other recovery, and (5) disposal [5]. Technically, *prevention* is not a waste management operation, as both quantitative as well as qualitative waste prevention concern substances or objects before they become waste. Obligations under waste management legislation consequently do not apply. This important distinction also applies to *re-use*, defined as 'any operation by which products or components that are not waste are used again for the same purpose for which they were conceived'.

Steps 2-5 together comprise *waste treatment*. Steps 2-4 are defined as *recovery*, where 'the principal result of a recovery operation is waste serving a useful purpose by replacing other materials'. In contrast, step 5 is negatively defined as their opposite: *disposal* includes all operations that are not recovery. Recovery is divided into three sub-categories: preparing for re-use, recycling, and other recovery. *Preparing for re-use* includes all 'checking, cleaning or repairing recovery operations, by which waste, products or components of products (…) can be re-used without any other pre-processing'. *Recycling* on the other hand is defined as 'any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes'. This includes any physical, chemical or biological treatment creating material, which no longer is considered as waste – as long as it closes the economic material circle. Consequently, operations that reprocess materials for fuels or backfilling activities are excluded from recycling and represent *other recovery* – as long as the primary purpose of the treatment still is the substitution of other materials rather than the elimination of waste [11].

Within the EU, construction and demolition waste (CDW) is the single biggest waste stream (by weight): In 2014, CDW accounted for 33.5% of EU waste or 871 million tonnes [12]. This total mass consists of several different material groups such as concrete, bricks, gypsum, wood, glass, metals, plastic, solvents and excavated soil - many of which have a (high) re-use or recycling potential [13]. In fact, most EU countries already today report a recovery rate of CDW above the mandatory 70% target, which applies to the above described steps 2-4 of the waste hierarchy, including material recovery however (contrary to the WFD definition) excluding energy recovery.

Unfortunately, the reported data is still based on varying waste and reporting definitions in separate Member States, which makes comparison and interpretation difficult. It is however very clear that the reported recovery rates always include a high percentage of operations that do not fulfil the criteria of closed material cycles in the CE, where materials, components and products should be kept at their highest utility and value at all times. In terms of the waste hierarchy, only step 2 at the moment satisfies these criteria, while step 3 would need to exclude any downcycling processes, which in a CE understanding belong to the category of other recovery. Steps 4 and 5 both represent economical, ecological and socio-cultural losses and are to be prevented, remaining within above described hierarchy of steps. A possible definition for recycling within the CE could be: any recovery operation by which waste materials are reprocessed into products, materials or substances *of equal or better purity in fractions* whether for the original or other purposes. Within waste treatment, preparing for re-use remains the favourable operation as it conserves embodied energy, water and knowledge while reducing the need for re-processing and associated emissions.

In all cases it is essential that a material, component or product achieves the end-of-waste (EoW) status after undergoing a recovery operation and thus falls outside the scope of waste legislation before beginning its next life cycle application. In regard to the aspired paradigm shift towards the CE, ideally however materials, components or products never fall into the scope of waste legislation in the first place. Various CE-concepts such as *Design for Disassembly* [9], *Product as Service* [14] or *Extended Producer Liability* [15] aim to prevent the intention, the need or the interest in discarding substances or objects by ensuring their utility and value of a closed-loop application at all times.

Annex I of EU Construction Product Regulation (CPR) summarizes a list of basic requirements for construction works, whereby paragraph 7 addresses issues of sustainable resource use. 'The construction works must be designed, built and demolished in such a way that the use of natural resources is sustainable and in particular ensure the following: (a) re-use and recyclability of the construction works, their materials and parts after demolition; (b) durability of the construction works; and (c) use of environmentally compatible raw and secondary materials in the construction works' [16]. Written in 2011, this document lays down important principles of the CE for construction as described above – unfortunately by now not a single Member State has transformed Annex I into national law, keeping CPR at the status of a non-binding recommendation.

3.1. *German legislation on re-use and recycling*

The case study MWP is located in Heilbronn, Germany. Additionally to EU regulations, it is thus necessary to consider German waste and construction legislation when re-using and recycling materials or products within this specific setting. The German definition of waste can be found in the 2012 Waste Management Act (Kreislaufwirtschaftsgesetz), which transposes WFD into national law. However, there are no national legislative instruments governing the requirements for the recycling of mineral waste or for the use of recycled building materials or spare building materials so far, as these are within the competence of federal state legislation [17].

Because of these legal differences, the Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety (BMU) started working on an overarching national legal framework for ground water, substitute building materials, landfill and soil protection, the so called Mantelverordnung already in 2006. So far, unfortunately no approved version exists, but a 2017 version by the Federal Cabinet includes a new Substitute Building Materials Ordinance (Ersatzbaustoffverordnung), which aims to provide legal certainty with uniform national requirements that apply when discharging substances into groundwater, when constructing engineering structures with the use of mineral substitute building materials, and when backfilling with soil material [18].

One key element of the ordinance is its EoW definition (after extensive testing and documentation) of recovered wastes as a product with specific classes and specifications, e.g. RC-1 for recycling materials or BM-0 for soil materials, allowing their direct application in high value applications [19]. At the current state, application of recycling materials continues to be based on case-by-case approval, where materials certified and approved by an accredited laboratory in one state might not be applicable in the other 15 federal states. Section 4.2 explains the procedure based on a product from recycling glass for application in Baden-Württemberg.

In regard to re-use, legislation makes no distinction between use phases. Re-used products or materials need to be able to comply with the standards of DIN or EN norms in respect to e.g.

structural, fire, health or other specification. The problem here is that most of the times no producer or owner will certify these as the manufacturer of virgin products or materials does. Also, missing documentation on origin as well as treatment during use phases makes this step additionally difficult. As a result, often extensive testing is necessary to specify material or product properties before re-using them. Section 4.1 explains this procedure based on structural steel for Baden-Württemberg.

4. Structural application of re-used and recycled materials on the example of MWP

In general, materials used in construction are subject to numerous national standards and regulations. When used in load bearing elements, however, the demands are particularly high. The approval of a material for a structural application requires strict quality assurance during its production. In addition, it also requires a comprehensive investigation of its mechanical and physical properties as well as the knowledge of its behaviour in different load situations and climatic conditions. In Germany, structural applications must comply either with national building standards or a general technical approval (Allgemeine bauaufsichtliche Zulassung), which corresponds to a European technical approval for construction type and construction product. If there are no such corresponding approvals for the material, an exception can be obtained for the type of construction and construction product in the form of a so-called *approval in individual cases* (Zustimmung im Einzelfall - ZiE). This ZiE is approved by the building authority of the respective federal state. However, its validity is limited only to the specific construction project for which it was requested.

4.1. *Re-used structural steel*

Due to economic incentives, the recycling of steel scrap has been well established for a long time "without any need for stimulation or subsidy. The recycling rate is 88%" [20]. The direct re-use of structural steel, on the other hand, is currently practiced only to a minor extent with a re-use rate of 11%. In addition to a careful dismantling from the building stock here the knowledge of the material quality (classification) and the previous use is required. It must be determined what imperfections and damage to the disassembled element exist after its use. Furthermore, the nature and frequency of the previous stress situations may be relevant. The re-use of steel elements still has a high development potential, "the biggest challenge here is quality control" [20].

As mentioned, the steel structure of the MWP largely consists of steel tubes that were dismantled from a disused power plant. In addition to an exact visual inspection to determine any possible damage of the elements, the steel was examined for various properties. Tests on tensile strength, elasticity, notched impact strength (Table 1) and chemical composition (Table 2) made it possible to draw the necessary conclusions regarding the material quality. The steel quality proofed to be equal to that of standard structural steel (S235JR or S235J2), which allowed the direct re-use of the elements in a new structure.

Table 1. Test results of notched bar impact tests according to DIN EN ISO 148-1.

	length [mm]	width [mm]	thickness [mm]	consumed impact energy [J]
Dimensions of each specimen	55.0	10.0	5.0	
Average of all samples				67.7

Table 2. Test results of the chemical analysis.

	C	Mn	P	S	Cu
Requirements S235 DIN EN 10025-2	≤ 0.17	≤ 1.40	≤ 0.035	≤ 0.035	≤ 0.55
Maximum of all samples	0.16	0.70	0.006	0.014	0.20

4.2. *Recycled glass products*

The use of glass in structural applications in Germany is governed by national standards (DIN 18008 Glass in Building). However, the standards only apply to the use of certain approved glass products. The panes from recycled glass used for the MWP are not covered by such product approval. Although technical approvals exist for certain building applications in facades, these differ from the type of use in the MWP. For this reason, applying for a ZiE for the use of recycled glass products in the MWP was essential. The application was based on the specifications of the existing glass standard and the stress analysis was carried out following the standard's design philosophy respectively. The ultimate stresses determined by standardized tests carried out by independent, accredited test laboratories provided the basic data for design stresses. In accordance with the glass standard, an additional mechanical safety measure was applied below the linearly mounted glass panes of the pavilion's roof through a close-meshed steel net. In addition, the manufacturer was obliged to issue a declaration of conformity for the quality control of the production by means of standardized mechanical tests.

5. Conclusions

MWP proofs the feasibility of re-used and recycled materials in structural applications within a full-scale prototypology. However, as described above, the process of planning and building according to CE principles currently still shows many administrative, financial, legislative and physiological hurdles which need to be reduced quickly in order to allow a paradigm shift. Common hurdles to recycling and re-using CDW in the EU are the lack of confidence in the quality of recycled materials, missing documentation on material composition and history, a mismatch of supply and demand (both qualitative and quantitative), insufficient time allocation for audits and deconstruction works, a lack of facilities and expertise and the often low value of high quantity products. There is also uncertainty about the potential health risk for workers both deconstructing and using recycled materials. This lack of confidence reduces and restricts the demand for recycled materials, which inhibits the development of waste management and recycling infrastructures in the EU [21]. Analysing these hurdles, many of the mentioned restriction can be addressed through increased and better documentation and declaration/ certification measures.

5.1. *Material documentation*

The built environment represents a massive stock of material resources, which is in most cases unfortunately undocumented and unspecified. Even though much research is currently undertaken towards the development of material passports or cadastres [22], the status quo of building construction still continues undocumented. In order to prevent the costly and timely steps of section 4 and allow a circular use of materials and products, it is essential that we begin detailed libraries of materials, their specifications, dimensions, locations, connections, durability, and treatment over the time of use, regarding all buildings as material depots for future constructions [9]. Material documentation is equally essential for both recycling and re-use, whereby in the first case a focus is placed on the exact chemical composition of the material and toxicity, while the second case requires a focus on a detailed history of the materials' or products' life. Both cases require detailed information on the necessary steps in disassembly to return to pure-type material cycles. Additionally, material documentation can significantly reduce building costs if done properly and consistently [23].

5.2. *Product declarations*

The level of building products offers an additional chance for increased documentation through extended product declarations. Especially on EU level, much research efforts are invested into the development of harmonized Environmental Product Declaration (EPD) or Product Environmental Footprint (PEF) which not only include the above mentioned data points but additionally a description and Life Cycle Analysis (LCA) calculation of the products' recycling potential (module D) [24]. Such information can help steer decision makers and designers in their material and product selection towards elements, which are designed for re-use and recycling in closed material loops, as long as they are also applied according to CE design and construction principles. Integrating such information into Building Information Modelling (BIM) could offer a possible tool for the communication and documentation of material and product specifications, in connection to their location and disassembly guidelines.

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The secret ingredient – the role of governance in green infrastructure development: through the examples of European cities

Körmöndi B[1], Tempfli J[2], Kocsis J B[1,3,4], Adams J[5], Szkordilisz F E[1,6]

[1]: MUTK (Hungarian Urban Knowledge Centre), Hungary;

[2]: University of Bamberg; Faculty of Humanities and Cultural Sciences; Department of Geography;

[3]: Budapest University of Technology and Economics; Dept. of Sociology and Communication, Centre for Socio-Spatial Development Studies;

[4]: Institute of Geography, Geoeconomy and Sustainable Development;

[5]: University of Tennessee, CURENT - Center for Ultra-Wide-Area Resilient Electric Energy Transmission Networks;

[6]: University of Debrecen, Faculty of Science and Technology, Doctoral School of Earth Sciences

f.szkordilisz@mut.hu

Abstract. The first signs of considering green infrastructure in the process of urban planning appeared long before WWII with the developments of Chicago and Paris, for example, in the late 19th century. In order to relieve the increasingly crowded centres of fast-growing cities, the afforestation of public spaces and the creation of more liveable existing spaces became increasingly important; this includes the development and renovation of parks and water surfaces to adapt to urban needs and requirements, making the development of urban green infrastructure more important than in the past. Over time, green infrastructure developments grew more detailed and complex; since the end of the 20th century, they have become one of the most important goals of urban development, focusing on the environment and healthy living conditions. In the early stages of project development, the needs of urban residents and the active utilisation of green areas are factors of growing importance; refining design and construction has also become a more intricate process. Significant changes to the original style of plans has taken place over the past decades, evolving with the needs of the era and technological advances, requiring suitable action to maintain pace with enhanced developments.

1. Introduction

The increase in city dwellers and the expansion of urban areas has been an accelerating process since the industrial revolution. The development of urban habitation was most significant in the twentieth century. In 1900 there were 16 cities with over 1 million inhabitants (Montgomery et al. 2003), and in 2010 this number grew to 449 as a result of the continuous urbanisation process. These changes in urban development are mainly due to social and economic transitions that have occurred in the last 150 years. The dimension of urbanised areas has also grown immensely (Seto et al. 2014; UN 2018), due to the population increase in cities. New socio-economic factors have recently brought about novel urban patterns usually put under the term polycentric development (Clark 2003). As a result, the structure of suburban areas has changed (new industrial, logistic and residential areas have been erected within a very short time), and thus new forms and functions – mainly due to digitalisation and post-Fordist economic transformation – have appeared.

Suburban areas usually occupy territories with traditional green belts around cities, resulting in enormous and contiguous urban areas; this increases both the territorial dimensions of urbanised areas and the diameter of urban heat islands. In fact, the Urban Heat Island (UHI) (Unger 1999), is one of the most important challenges to address. An urban heat island is traditionally defined as closed isotherms that delineate an area warmer than its surroundings (Unger et al. 2010; Voogt and Oke 1997). UHI is a complex result of various interrelated phenomena (Unger et al. 2000). Among many, one cause of the urban heat island is global warming, which has steadily accelerated in past decades; however, disappearance and lack of surfaces with cooling effects due to expansion of built areas and new trends in urban design are among the key factors. The effects of an urban heat island become particularly unbearable in summer when heat stress occurs. Besides this, a related index contains significant by measurements of UHI with satellite imagery - this is the NDVI (Normalised Difference Vegetation Index) (Chen et al. 2006; Dezso et al. 2005; Owen, Carlson, and Gillies 1998).
There are many other concerns in urban areas. First, cities usually have a great deal of sealed surfaces which enable quick stormwater runoff, causing severe problems such as infrastructure overload, quick evaporation, and a low albedo. According to Oke (Oke 1987), cities tend to have an albedo 5-10 per cent lower than the surrounding rural areas. Second, from a social perspective, traffic is believed to be a major, if not the biggest, source of stress in our lives. (APS 2008). Third, those living in less developed neighbourhoods are particularly vulnerable, as they have limited access to good quality green areas and housing estates tend to be of poorer technical conditions. Finally, and importantly, urbanisation has a negative effect on biodiversity (McKinney 2006).

2. Aims of research

The aim of this paper is to collect and analyse the processes that lead to successful green infrastructure development in the cities of London, Copenhagen, Budapest and Graz. The hypothesis posits that success lies not only in the coherence and consistency of plans, but also in governance that ensures the implementation of community priorities. To underline this, an investigation of strategic plans, governance and participation projects was conducted. The intention is to find differences and similarities on how the four cities are reacting to the drastic changes of recent decades, such as the ongoing urbanisation process and climate issues described above.
The main driver of this study was to check the effectiveness of different approaches towards green infrastructure planning and highlight those planning and governance tools that led to success in the past.

3. Methodology

In order to analyse the current situation of green space development, a multi-method approach was used. This was mainly carried out by literature research (studying documents, webpages and other grey literature). For this, operative and valid plans of the investigated municipalities and linked organisations were analysed. Aside from plans, policy implementations in each city were examined, which gave a rough impression on the process of green space management; however, local characteristics could also be understood through examining the green and nature-based projects of linked third parties and non-governmental organisations. A society's sensitivity can be also measured through bottom-up projects not directly initiated or funded by the local authority and not linked to official processes. Civic engagement into municipal decision-making processes is an issue not only in planning activities but also in managing green spaces. Based on these understandings and through the literature review, a framework of key factors for success in green development was constructed. For a graphic organising and explaining these factors, see *Figure 1,* below.

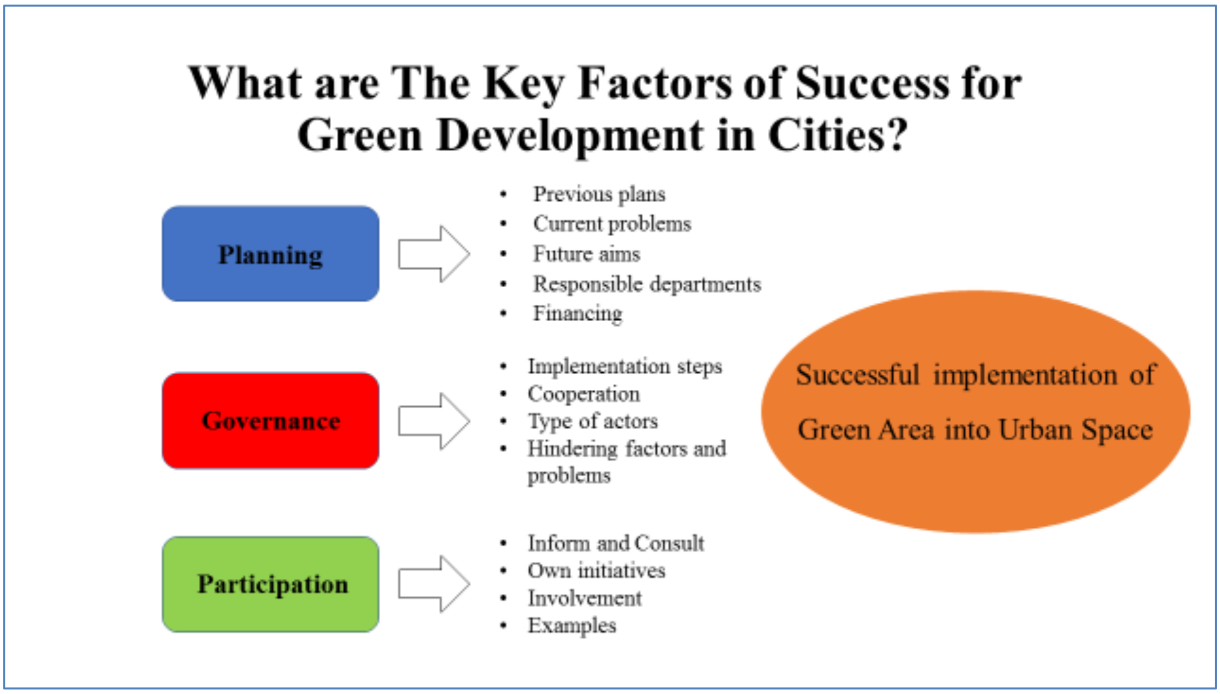

Figure 1: Key Factors of Success for Green Development in Cities; Developed by Jennifer Tempfli

Given these factors, comprehensive interviews were conducted with partners involved specifically in green infrastructure planning within municipalities. From the four selected cities, tow partners answered; therefore, the Greater London Authority and the Green Office of the 12th District of Budapest were approached. During the interviews we focused on the following topics:

- What is the main political motivation towards nature-conscious or green infrastructure planning?
- What is the governmental background of green planning at the municipality?
- What is the financial background of plans?
- Which types of actors are involved and to what extent do they have a hand in the planning process?
- To what extent can residents participate in programs and how successful is this involvement?
- Are there any issues that hinder or cause problems in the participatory process?

4. Understanding the planning context

To understand the context of green infrastructure planning, differences and similarities in planning must be highlighted. Europe has a long history of urban planning that differs due to the varied history, culture, economics and social development of the countries. We can distinguish four different planning traditions according to the literature (European Commission 1997; Newman and Thornley 1996; Williams 1984). The four traditions originated from different countries; however, during the European integration of planning systems, they have become widespread and a country's planning is surely influenced by more than one approach. *Figure 2* highlights the four distinct traditions and the countries that utilise them. We will explain the various plans in the context of our focus cities in greater detail below.

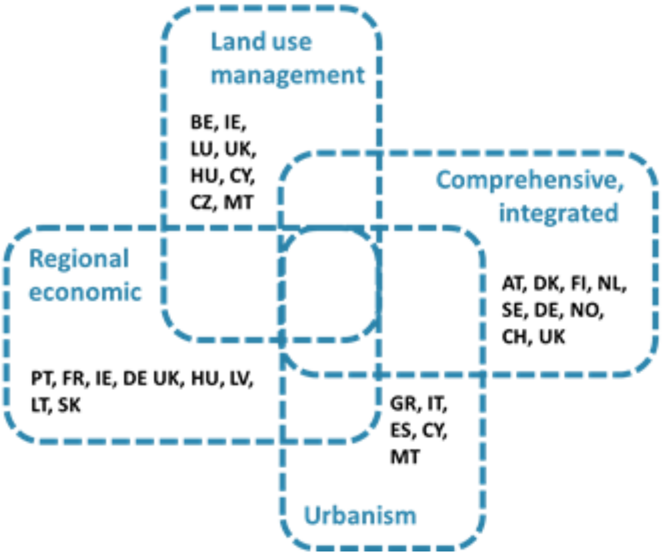

Figure 2. The four planning traditions of Europe. (Salamin 2018)

London represents the ***land use management*** approach, which emphasises the regulation of changing land-use by utilising strategic and local plans. This approach focuses on the management of physical space by applying urban planning tools as regulations. In this respect, green infrastructure planning is a basic and well-used tool to influence land use. Green infrastructure planning exists on multiple scales: regional (for example, Abercrombie's *Greater London Plan,* 1944), local and object scales (where the share of green space is defined when giving a planning permit). One should also not forget the importance of neighbourhood planning in the UK, in which Ebenizer Howard left an influential legacy (Howard, 1902).

Copenhagen's Fingerplan is one of the most famous urban plans in Europe and has been a success story due to its easy-to-understand metaphor: using a human hand to cover urban patterns (Vejre, Primdahl, and Brandt 2007). The Finger plan was established in 1947 and emphasises that Danish planning systems are characterised by a ***comprehensive integrated*** approach, a Dutch tradition that involves the various tools of space-shaping. The focus lies in the spatial effects of policies and the coordination of actors and sectors; further, vertical and horizontal coordination is highly important.

Austrian planning is also based on a ***comprehensive integrated*** approach. Spatial planning is the autonomous responsibility of the states, but the plans are only binding for state administration and public administration at the lower levels. Municipalities and cities have autonomy in local planning. They have enacted three plans: Local Development Programme, a strategy plan determining the needs of communities; the Zoning Plan, defining the types of use for different spaces; and the Development Plan, which defines the requirements of buildings on a plot-scale.

Hungarian planning is nearest to the ***land-use management*** approach. However, in Hungary, physical spatial planning is very much divided from urban development planning. This duality is well represented in the fact that physical land-use planning and building control activities are regulated, but urban development activities are not well defined. Green infrastructure planning usually is represented in conceptual planning. Deficiencies occur because overall concepts should be broken down into smaller levels and scales of decision-making. Recently, many small-scale green projects have been implemented; however, it is still difficult to integrate plans to achieve connectivity of green spaces through the city. Regarding Budapest, the capital city (also an independent municipality) is divided to 23 district local authorities. This leads to multiple problems, especially in green infrastructure management.

4.1. Historical overview

London and Copenhagen were the first pioneers in terms of urban green planning in Europe in the 19th and 20th centuries, respectively. More space for better provisions and infrastructural function were among the main concerns, as huge growth in the city's population was expected in the coming years. London`s first attempts towards a green planning were made in 1829 when the "Breathing Places Plan" by John Loudon was published (Johnson, 2012). He was initiating a tenfold expansion of the city and planned on implementing infrastructure for water, gas, fresh air and removal of filth, while planning alternate rings of green space around London. This was pursued later in Abercrombie and Forshaw`s County of London Plan (Forshaw &; Abercrombie, 1943), which focused on the quality of green spaces, their separation from industries and the cultural relationship. These plans are considered the cornerstone of London`s green space development. London's Green belt came to existence in 1955 and the whole planning of the city was aligned with the concept.

A similar approach is represented in Copenhagen`s Finger plan. The Finger plan was established in 1947 (Cervero 1998), and aimed mainly to manage a mass of commuters in the area and provide suitable places for industrial and commercial activities. Today, the master plan affects over 30 municipalities in the metropolitan area of Copenhagen. The importance of the Finger plan in green space network development is that the plan designated the areas between the "fingers" as green spaces, preserving them from urban sprawl, creating well-defined green corridors around the city. The finger plan concept was later adapted by Helsinki and Stockholm. Looking at the development of the last years, we can see a clear focus of the city's policies. The aim is to enable people to stay in public places and use them for a multitude of activities. But also, the green spaces should be liveable and accessible for tourists and residents. Future needs of modern businesses must also be considered. Copenhagen puts a big emphasis on the disassembling of open spaces and its accessibility for people. Copenhagen even received the Green City award in 2014. The city's overall aim is to combine natural and urban development to impact people's well-being on a long-term basis.

In 1989 a regime change took place in Hungary, and this shift from the previous socialist regime led to big changes in the country. Urban areas were in want of green space and Budapest itself was densely built without equally distributed open spaces. The city offers great potential in restructuring brownfield areas that are located throughout the city, especially in a ring around its eastern parts (Kocsis, 2015). The utilisation of these places promises to transform regions partly used for green spaces and would, at the very least, integrate green infrastructure. Research has been done on this topic, and first attempts at implementation are already occurring. Other potentials can be found in widening river fronts or improving parks. Further, existing parks located in the city centre can be rearranged or provided with other functions that contribute to the greening of the city. Similar measures were part of local plans in several districts of Budapest, in an effort by local authorities to address the greening of the city. But also, several policies were set up by the capital municipality to make Budapest more adaptable to address the issues of urban heat island, climate change and lowering greenhouse emissions. Since one solution for these problems is to integrate green spaces, there is a large focus in this area.

Looking at Graz, we see parallels in the development of cities and green areas over time, but these areas were not planned in the same extent as in the other cities. The central green are of historical significance and are still the most important and frequently used nowadays (Hlawka, 1990). The city of Graz also has developed several campaigns for greening the city, while supporting other campaigns with similar aims. The city relies on already existing resources and green areas, with attempts to improve or reclaim them. The aim is to bring green areas closer to the citizens and develop an average area of 3 -10 square metres per person.

4.2. Governance

Although development policies initiated by city councils are usually based on green development, other actors should not be discounted, as they can have a large influence. Recent changes in development policy have raised. Especially the last years made a change in rising the awareness on environmental problems like air pollution, and the involvement of other actors besides city councils can better address these concerns.

Governance is successful if the different levels of decision-making, planning and implementation are harmonised. While the governance of green infrastructure developments can be coordinated at city level, so individual projects can be harmonized to multiply the effectiveness of this process. All cities seek the best solutions and good practices, but conscious development requires a lot of time.

For example, in London, the Greater London Authority (GLA) is mostly responsible for the key planning. In order to increase their impact, the Authority frequently exchanges and collaborates with London's boroughs and other non-profit organisations. Since subsidies for green infrastructure projects have increased in recent years, it is important to find applicable solutions to problems related to green infrastructure and flood management. Also, we see that economic players have a larger role in green infrastructure development; these are players willing to invest in green development based on individual aims of companies and the results of cost-benefit analyses. Additionally, housing association owners that invest money into measures like green roofs in order to profit from rising rent prices, fall into this category.

Emanating from London`s example, we see that all four cities use extensive concepts and policies. Since it is not always possible to reach project aims with city plans alone, due to city size and growth, other actors need to be involved. These actors deepen involvement and help accomplish district-based initiatives and smaller project-focused plans through increased cooperation.

4.3. Participation

In recent years, several public engagement projects are partly cooperating with or financed by municipalities or other non-profit organisations. It is possible to see similar developments, in terms of public engagement, that are independent from countries or cities. These developments focus on initiatives like urban gardening, addressing environmental issues, but also contribute to the well-being of residents, as we can see in the 'Guardianship Programme' ('gondnokság program'), established by the Municipality of the 12th District in Budapest. The programme allows residents to take part in replanting and taking care of self-chosen green spaces in the district. The municipality develops a plan to manage these areas and provides tools and assistance in cooperation with professional gardeners. The challenge that the Green Office of the district has faced was to provide enough incentives to make people participate in these programmes. Changes have been made in the concept has changed since its first introduction, and it now aims at offering more transparency about the whole project and mediating between the municipality and the needs and goals of residents. In general, municipalities tend to focus on the improvement of ecological concerns, whereas residents are more inclined to focus on the enhancement of social well-being.

Besides, movements like urban garden initiatives have arisen in past years in many cities. Topics like air pollution and concerns about urban heat islands have been gaining weight and presence in urban discourses. These concerns may be different and dependent on local resources and circumstances, but we still see increasing environmental awareness in society as a whole. As a result, people are more willing to take part in planning decisions. The number of private-led initiatives and collaborations in this vein are accumulating.

An example of a city-led campaign that involves the public relates to front-garden culture in Graz. It attempts to enthuse people to take part in revitalising these private areas with monetary incentives. Also, the project "Jacky_Cool_Jack" originated in the city. This project aims to override the urban heat islands in the Jakomini district, an area which lacks green infrastructure and spaces.

Table I. shows a selection of interesting projects from the cities where public engagement was essential.

City	Name of campaign	Aim
London	London Environmental Network	Supporting local Non-profit and community groups with an environmental focus
	Capital Growth	Supporting people to grow food in London, whether at home, on allotments or as part of a community group.
	Skip Garden at King`s Cross	A community garden that uses recycled materials and connects people of all ages and backgrounds
	Urban Farms in London	Urban Farms that make a positive impact on the environment and social well-being. Connecting people and creating communities
	South West London Environment Network (SWLEN)	Focus on preserving green spaces and biodiversity, promoting sustainability and supporting environmental groups
	Urban Bees	Encourage people and businesses to plant more pollinator-friendly trees and flowers
Graz	Bürgerinitiative für die Erhaltung von Grünflächen	Preserve south Graz from industrialisation. Make the area more liveable, improve the air quality and calm traffic pollution
	Mehr Zeit für Graz. Themengruppe Grün- und Stadtentwicklung	Preservation existing and safeguarding new urban green areas
	Several Urban Gardening Projects	Projects that are establishing urban gardens
	Förderung urbanen Begrünung	Promotion of urban greening like urban gardens, green roofs or walls
Budapest	Revitalization of Mátyás square	An initiative of the 8^{th} District of Budapest, which involved local people to plan and plant the open space of the square in a deprived area. Social security improved and the neighbourhood developed a lot through the project.
	Zöldfelület Gondnokság Program	Improve the green space in the 12^{th} District of Budapest (Hegyvidék) district with involving residents in the fostering process
	Revitalization of Teleki square	Transform the till then decrepit parc into a public parc with residents' participation. The project has an important social aspect. (8^{th} District of Budapest)
	Közösségi Kertek	Inform people about climate change and processes that harm the cities environment. Creation of about 30 urban gardens
Copenhagen	Urban Beekeepers of Copenhagen	Possibility to host hives and join events and skill training in return
	DYRK Nørrebro	Urban Farming Initiative in Copenhagen to expand vegetable cultivation. Focus on sustainability with the intention "think globally and acting local"
	GivRum	Facilitation of user-driven urban development with local communities. Social mobility and activation of local resources, people and stakeholder is intended.
	Outdoor Council	Request to spend more time in the nature and improve the circumstances and frame conditions for this
	KlimaKvarter Østerbro	Turn the neighbourhood into the greenest inner-city area and integration urban spaces, courtyards, buildings, streets and the neighbourhood within this

Table I. An overview of important participation projects in the four cities.

5. Results

Our analysis shows that **coherence of consistency plans** is an important part of the implementation of green space development. These plans are the cornerstones of implementation. We also need to consider that most plans were formulated around the beginning of the 20th century. As such, the whole process of green space implementation was more focused on architectural, and in some cases symbolic, values and concerns. This was minting infrastructural development, primarily. These plans were developed on a more objective basis due to geographical location and other circumstances.
As a result of the social and economic changes of the past centuries, the **planning process** has become more complex and involves more actors and fields than ever before. City councils are limited in different ways, such as lack of monetary support or other constraints; therefore, the complexity of social and economic situations requires that other methods and measures be found to ensure the integration of green areas into the urban infrastructure. This makes the involvement of other actors necessary in the entirety of the planning process. The question is: Are all affected people profiting in an appropriate way and have a say in the planning process?
In order to successfully introduce new structures, other local stakeholders or residents should be involved in the **participation process, especially in the case of small-scale projects**. The focus here lies on discovering and considering all the needs and interests that will influence the effectiveness of the implementation of the programmes. Moreover, people tend to favour such actions and take more care of the result if they feel their needs and interests are met. Transparency of all steps in the process is crucial to gain participation and acceptance for all involved actors.
From an interferential point of view, one must draw attention to the fact that cooperation has gained much weight in past years. Practice of green space planning is to incorporate, and make essential part of, cooperation and combined efforts of stakeholders and local actors. For a good implementation, the right communication with transparency is important, since the size of cities and the dissimilarities and distinct characteristics between districts, for example, may create a big difference.
A novel phenomenon of recent years is the connection of green infrastructure and climate issues in planning. In the past, green areas were more preferred in residential quarters mostly due to aesthetic values, but nowadays the positive effects in abating negative effects (e.g. heat in summer and cold in winter, dust and noise) have been realised, and thus green infrastructure has become an acknowledged measure in urban planning against climate issues.

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Mitigation strategies of the urban heat island intensity in Mediterranean climates: simulation studies in Rome (Italy) and Valparaiso (Chile).

Palme M[1,2], Clemente C[2], Cellurale M[2], Carrasco C[3], Salvati A[4]

[1]Universidad Católica del Norte, Escuela de Arquitectura, Antofagasta, Chile
[2]Università di Roma "La Sapienza", Department PDTA, Rome, Italy
[3]Universidad de Valparaíso, Facultad de Ingeniería, Valparaíso, Chile
[4]University Brunel, Institute of Energy Futures, London, UK

mpalme@ucn.cl

Abstract. The Urbanocene, a proposed new geological epoch characterized by the urban living condition, is pressing the humanity to respond shortly to important challenges. Cities are at the same time the places where we live in and the big dissipators of the final energy to the environment. The simultaneous rules of heat dissipator and place to live are quite contradictory, because of the increasing temperatures of the dissipator surfaces, phenomenon known as Urban Heat Island (UHI). Mediterranean climates should suffer, in the next years, changes in the thermal needs of buildings and in the outdoor comfort sensations. A change in the energy demand from heating to cooling is probable and overheating reduction could be a priority in the future. Many mitigation strategies of UHI are being discussed in these years, such as the city greening, the use of cool materials for roofs and soils, the reduction of automobile dependence, the shift to new urban morphologies. In this paper an evaluation of impacts of different possible strategies is done, by using computational simulations for various sectors of Rome and Valparaiso. Results show the importance of greening and traffic reduction to achieve better comfort; while to reduce building energy consumption changes in urban morphology and traffic are suggested as the best strategies.

1. Introduction

The domain of our specie on the planet has been continuously rising since we appear on the Earth. Today, the concept of Anthropocene is being proposed as a new geological epoch (and even as a new stratigraphic epoch [1]). Besides geological discussion on the appropriateness of the concept, one of the characteristics of the last 1.000 years has been the urban condition of the humans, and this condition is growing so fast since the "great acceleration" times that some scientist propose the name "Urbanocene" as an alternative to "Anthropocene" [2]. One of the specific aspects of living in cities is that such adaptive complex system has the behavior of a dissipative structure [3]. So, cities are the places where most of the humans live; the places where most of the final energy is consumed; and the most important: the places where the heat that results by all these energy transformations is dissipated to the environment. The phenomenon is known as Urban Heat Island and has been investigated since the 19th Century, but it was formalized under an energetic point of view recently at the end of the 20th Century [4-5]. Recent studies underlined the possible impact of UHI on the cooling needs of buildings

[6-7] and on the summer outdoor comfort [8]. Even the interrelationship between extreme events (heat waves) and UHI has been assessed [9]. Advancing in urban climate studies, many models and methodologies to estimate temperature and other environmental parameters variations in urban conditions have been developed [10]. Specifically focusing on UHI, one of the validated tools that is being used to generate weather files is the Urban Weather Generator [11]. This tool couples an atmospheric model whit a building simulation model to generate a weather file useful to conduct building energy simulation considering the UHI effect.

2. Methodology

In this paper the Urban Weather Generator tool is used to obtain urban weather data to be used in comfort and building energy simulations. Four cases of study are explored, two in the city of Rome, Italy and two in Valparaiso, Chile. Comfort evaluations have been done using PMV calculator [12], while building energy simulations have been carried out using the TRNSYS tool (version17). Then, three possible mitigation strategies (greening the cities, reducing traffic, and changing pavements and roofs materials) have been tested to obtain the improvement in outdoor comfort and the reduction of cooling needs generated by each and combining all.

2.1. Cases of study

Rome (lat. 41.54 N, long. 12.29 E) and Valparaiso (lat. 33.02 S, long. 71.36 O) are both placed in Mediterranean climatic context, whit dry hot summer and cold wet winter. Koppen climate classification for both cities is Csa (a climate that is present in the Mediterranean area, in Chile, in California and in some parts of Australia and South Afica). Such climates present some sensitivities to climate change and to urban heat island phenomenon [13]. Cities' morphologies are different: Valparaiso is smaller than Rome and it is placed on the coast, while Rome locates about 20 km far from the Sea. Mediterranean Sea and Pacific Ocean have also a very different impact on urban microclimate: the Humboldt Current is cooling both air and water of the Chilean coast much more than the Mediterranean Sea currents could do in the case of the coast close to Rome. Orography presents some similarities: both cities have many small mountains that obviously influenced the urban planning. In Rome two sectors have been selected for this analysis, one corresponding to the center of the city (Tridente) and other corresponding to a residential neighbor close to the center (Prati). In Valparaiso, the selected sectors are the city center (Center), with its system of places, and a residential neighbor sparsely built (Recreo). Figures 1 and 2 shows both cities and their sectors selected for analysis.

2.2. Urban weather and building energy simulation

Urban Weather Generator is a tool developed at MIT. The tool couples an atmospheric model and a building performance simulator to obtain modified urban weather files from a base rural weather file. Many information is needed by the tool to conduct simulations, however some of the most sensitive parameters are: the anthropogenic heat production, the morphology parameters (built up area, façade ratio, average building height, green areas) and the material properties (albedo and emissivity) of streets, walls and roofs [14-15]. Table 2 resumes the parameters used in UWG simulations for the four cases. Building energy simulations have been carried out using the TRNSYS tool (version17). A five stories building is used as test building, E-W oriented, with windows representing a 27% of the main façades. Each story is divided in four apartments of 50 m^2. Table 1 resumes parameters used in BES.

Table 1: Building Simulation Parameters

U wall (W/m^2K)	U roof (W/m^2K)	U floor (W/m^2K)	Infiltration (h^{-1})	Glazed surface main façade (%)	Occupancy (people)	Gains ($W7m^2$)	Cooling set point (ºC)
2.15	0.57	1.88	0.7	27	2	5	26

Figure 1. The city of Rome and its neighbours "Prati" and "Tridente".

Figure 2. The city of Valparaiso and its neighbours "Center" and "Recreo".

Table 2: UWG Simulation Parameters

	Rome Tridente	Rome Prati	Valparaiso Center	Valparaiso Recreo
Reference site				
Latitude (º)	41.54		33.02	
Longitude (º)	12.29		71.36	
Urban Area				
Site coverage (-)	0.7	0.49	0.49	0.62
Façade ratio (-)	1.96	1.43	1.24	1.48
Average height (m)	16.5	19.5	14.4	8.36
Tree coverage (-)	0.03	0.05	0.01	0.05
Vegetation coverage (-)	0.04	0.1	0.02	0.1
Anthropogenic heat (W/m^2)	25			
Materials				
Wall materials and thickness	Bricks 43 cm			
Roof materials and thickness	Insulated 38 cm			
Roof albedo (-)	0.25			
Road albedo (-)	0.2			
Rural				
Albedo (-)	0.2			
Emissivity (-)	0.95			
Vegetation coverage (%)	48			

2.3. Outdoor comfort evaluation

Comfort evaluations have been done using PMV method initially proposed by Fanger and then developed by many authors. Please notice that actually PMV is not the most appropriated method to assess outdoor comfort, as noticed by many authors that proposed alternative adaptive evaluations [16-17]. However, the obtention of a value for the body stress generated by gains or losses of heat, is correct in both indoor and outdoor conditions. It is only the thermal sensation vote that changes, influenced by phycological expectations, culture and adaptation. We take PMV results just as indicative of a theorical situation that in reality could be felt as a little more comfortable because of adaptation. The estimations have been done without considering short wave radiation, this means, always on shadow. The variables considered are: metabolism, clothing, air temperature, relative humidity, wind velocity and mean radiant temperature. MRT was assessed as the average weighted by view factors of surfaces temperatures of the urban environment (walls and pavements). View factors are representative of a person placed close to one of the building walls on shadow.

2.4. Improvements

Considered possible improvements that should be done in order to build adaptive capacity and mitigate urban heat island are:

- Increasing the green areas of neighbours in a 100% respect to actuality
- Changing the materials of pavements and roofs for selective cool materials
- Reducing anthropogenic heat generation by cars in a 50%

To test the impact of each improvement on thermal comfort and cooling needs in summer period, a new set of UWG simulations is done, changing the respective parameters. In the case of city greening the "vegetation coverage" and the "trees coverage" parameter are changed UWG. In the case of the pavements and roofs, "albedo" parameters for urban streets are changed in UWG and "albedo" parameters for roof are changed in TRNSYS. In the case of anthropogenic heat, "sensible heat" is changed in UWG.

3. Results and discussion

3.1. Comfort

Table 3 resumes the environmental parameters (air velocity, relative humidity, air temperature and mean radiant temperature) used in the PMV evaluation for the case of Rome. Metabolic activity was set to 2 met (116 W/m^2) and the mechanic efficiency of the human body is considered 50%. Respect to clothing, thermal resistance of the clothes is set to 0.5 Clo and the clothes factor is set to 1.15. As stated in the methodology section, the evaluation is done without consider direct radiation from the Sun. Wind velocity value was approximated to 0.5 m/s for the rural case and 0.2 m/s for the urban.

Table 3: PMV parameters, Rome

	Rural Rome	Prati	Tridente	Prati green	Tridente green	Parti 50% traffic	Tridente 50% traffic	Prati cool pavement	Tridente cool pavement	Prati combined	Tridente combined
V (m/s)	0.5	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Hr (%)	45	40	38	41	40	40	38	40	40	41	40
T (ºC)	28	30	31	29.5	29.8	29.9	30.9	30	31	29.3	30.8
Tmr (ºC)	30	32	33	28	29.5	29.9	32.9	31	32	27	28.3

Figure 3 shows the results in terms of PMV and PPD. It can be observed that the rural outdoor comfort evaluation leads to an acceptable situation, very close to thermal neutrality and with a PPD of 5%. Urban conditions are worse, with a PMV value close to 1 (slightly warm) and a PPD of 20-25% depending on specific urban environment. Proposed improvements combined permits to reach an intermediate situation (PMV 0.6-0.7 and PPD 11-15%). The best improvement is obtained by increase the green (trees) surface of a 100%.

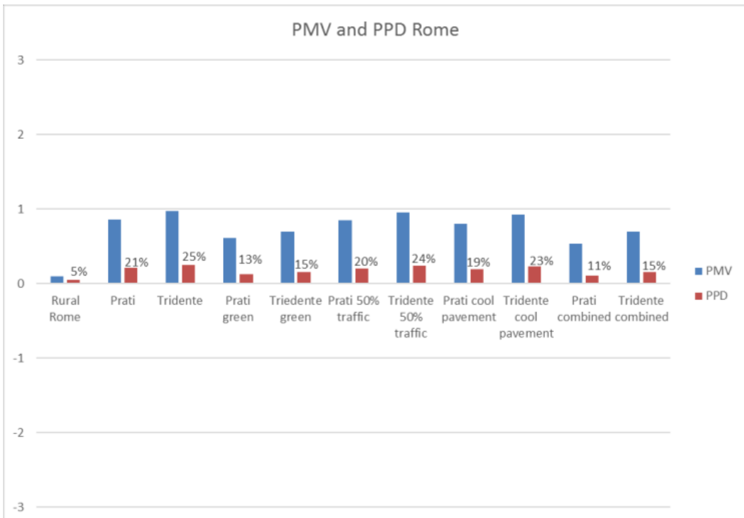

Figure 3: PMV and PPD, Rome

Table 4 resumes the same parameter for Valparaíso. The same metabolism and clothing of the Rome case are used. Because of the city emplacement, on the Pacific Ocean, air speed is considered 1 m/s in the rural case and 0.5 m/s in the urban configurations.

Table 4: PMV parameters, Valparaíso

	Rural Valparaíso	Centre	Recreo	Centre green	Recreo green	Centre 50% traffic	Recreo 50% traffic	Centre cool pavement	Recreo cool pavement	Centre combined	Recreo combined
V (m/s)	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Hr (%)	30	28	28	29	29	28	28	28	28	29	29
T (ºC)	33	34	33.5	33.5	33	33.9	33.4	34	33.5	33.3	32.8
Tmr (ºC)	34	37	35.5	35	30	36	32	36	34.5	34	29

Figure 4 shows the PMV and PPD values obtained. Comfort situation seems to be a little more difficult to be reached in this case. However, the green improvement is again the best strategy between tested improvements.

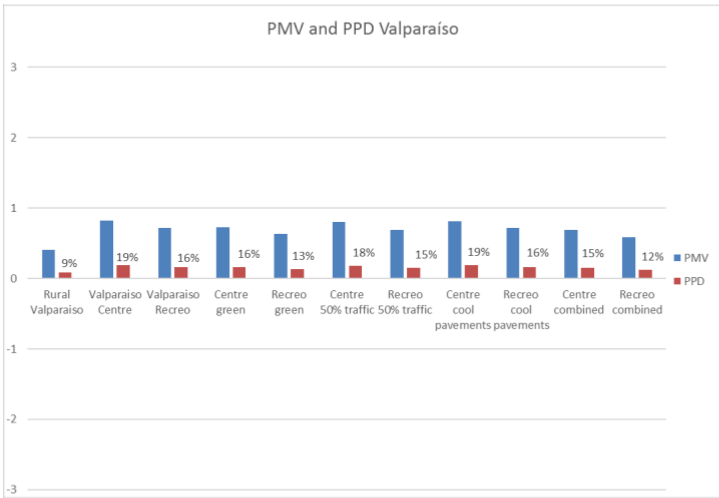

Figure 4: PMV and PPD, Valparaíso

3.2. Cooling needs

Figures 5 and 6 show the cooling needs across the year for Rome and Valparaíso. It can be observed that if Valparaíso has maximum values of temperature higher than Rome (as detected for the comfort analysis), this case has also lower temperatures during the nights, leading to a total cooling need quite lower than the case of Rome. The effect of city morphology (density and façades) is detected as the most important factor in the case of Rome. In Valparaíso, the increase in height of building of the Centre is counteracted by the reduction in density respect to Recreo case. Cool pavements and roofs are suggested as the best strategy to reduce cooling needs in both cases, but especially in Valparaiso.

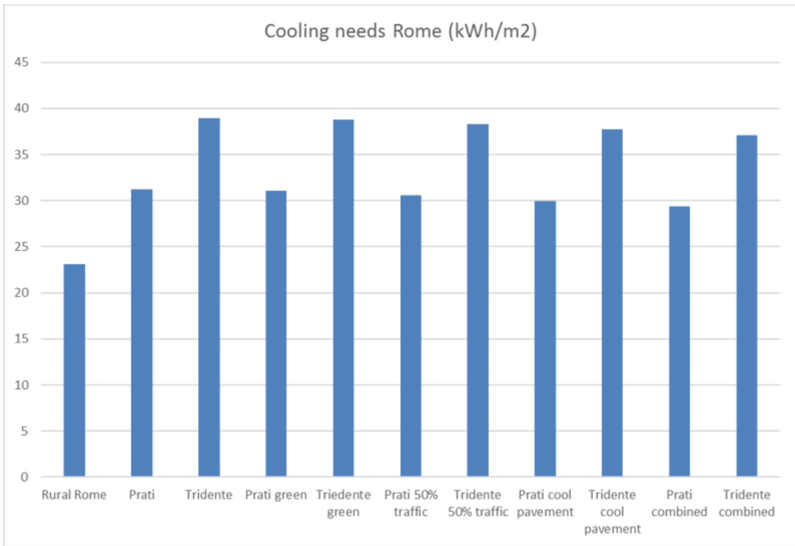

Figure 5: cooling needs, Rome

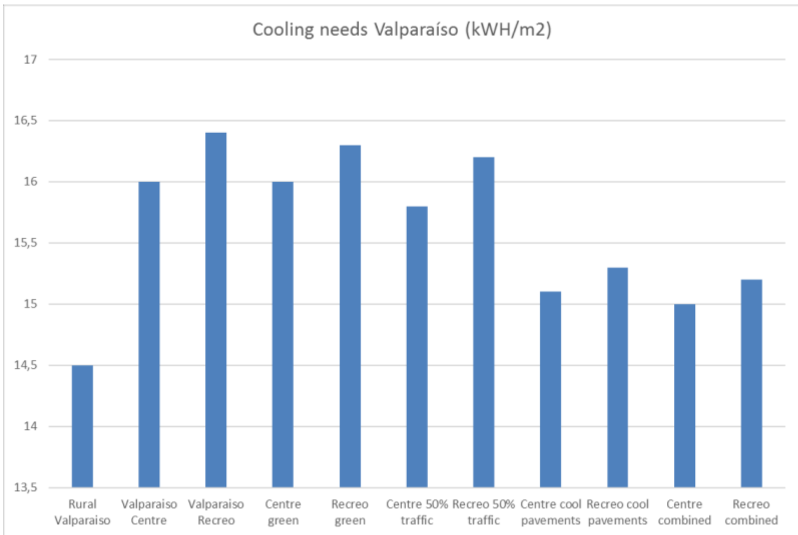

Figure 6: cooling needs, Valparaíso

4. Conclusion

This paper analyzed comfort and cooling implications of the urban environment in Mediterranean climates, by studying the cases of Rome, Italy and Valparaíso, Chile. Results show that the impact of urbanization is important both on outdoor comfort than on cooling needs. A set of mitigation strategies has been tested, suggesting that greening the city is the best strategy to improve outdoor habitability, while using cool selective materials on the pavements and (especially) roofs the total cooling need could be reduced up to the 40%. Research limitations suggest also that the effect of traffic reduction and city greening could be in reality more than detected in this study. If a more exhaustive comfort evaluation would be done, including direct Sun radiation, it is very probable that the use of trees should evidence an impact on psychological perceived temperature of more than the difference between “neutrality” and “slightly warm” detected by approximate PMV analysis. Respect to traffic, this is a very local condition. The average impact on the urban area is clearly reduced. However, outdoor comfort close to a busy street would be probably influenced mainly by the quantity of cars present. Future studies should be addressed to these observations. Cooling analysis can also be improved. In this paper, only the UHI effect has been considered replacing the “base” weather file with a “urban” weather file generated by UWG. Recent studies [18-19] put in evidence that also shadows, infra-red environment and wind distribution changes have to be included in analysis. However, the impact of city morphology and materials is a fact that has been stated clearly [20]. In any case, further research on the calibration of BES including urban climate effects is needed

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Using a budget approach for decision-support in the design process

Hollberg A[1], Lützkendorf T[2], Habert G[1]

[1] Institute of Construction and Infrastructure Management, Chair of Sustainable Construction, Swiss Federal Institute of Technology (ETH Zurich), Stefano Franscini Platz 5, 8093 Zurich, Switzerland

[2] Centre for Real Estate, Department of Economics, Karlsruhe Institute of Technology (KIT), 76128 Karlsruhe, Germany

habert@ibi.baug.ethz.ch

Abstract. The use of Life Cycle Assessment (LCA) during the design phase can help to improve the environmental performance of buildings. However, designers and clients find it difficult to set environmental performance targets and interpret the results obtained through LCA in order to improve the building design. Therefore, performance levels or benchmarks are needed that provide design guidance towards reducing the environmental impacts of buildings in the life cycle. This paper uses a dual benchmark approach. The main concept consists in combining building-related top-down targets with building component-related bottom-up benchmarks. The overall top-down targets per capita and year are derived from the capacity of the global eco system. The bottom-up benchmarks for building elements are calculated following a best-in-class (top 5%) approach. A workflow of applying these benchmarks is proposed. It provides guidance on how to optimize the environmental performance of a building and its components efficiently by differentiating between material and design-related options. The approach is exemplified by means of a case study of a multi-family house.

1. Introduction

Until now, the efforts to reduce greenhouse gas (GHG) emissions in the building sector mainly focused on the use phase of buildings. Due to the achievements in reducing the operational energy demand, amongst other reasons, researchers have turned to other fields to investigate additional saving potentials. An important aspect are the so-called embodied GHG emissions related to the manufacturing of construction products and to the construction, maintenance and end of life of buildings. Early design decisions largely determine the environmental performance of the building [1] for the next 50 to 100 years. Therefore, designers are key actors for reducing global GHG emissions during the life cycle of individual buildings. Life Cycle Assessment (LCA) is a suitable method for evaluating the building's environmental performance, however, currently, designers often find it difficult to interpret the LCA results and use them to improve the building design. The importance of environmental benchmarks has been recognized early [2]. There is a demand for benchmarks on GHG emissions in the different phases of the building's life cycle that serve as an orientation for designers [3]. Therefore, benchmarks should provide design guidance from the beginning of the design. A number of software to facilitate LCA for designers has been published in the last years, e.g. Tally [4], oneClickLCA [5], Athena [6], or CAALA [7]. However, they do not provide benchmarks that indicate the potential for improvement during the design.

The goal of this paper is to propose the application of LCA-based benchmarks in the design process to support the reduction of the environmental impact of buildings - mainly through the choice of construction type and materials.

2. Method

This paper uses a *dual benchmark approach,* developed by the authors and described in detail in [8]. The main concept consists in combining top-down targets with bottom-up benchmarks. The top-down targets per capita and year are derived from the capacity of the global eco system. The bottom-up benchmarks for building elements are calculated following a best-in-class (top 5%) approach. In this paper, the overall target of 1 t CO_2-e per capita and year by the year 2050 is used to define a top-down target. According to the Swiss 2000 Watt society [9], but also according to the German Environment Agency [10], this value is sufficient to achieve "climate neutrality". The target values as defined in SIA 2040 [11] are employed, however, they are adapted to meet the global target of 1 t CO_2-e/(c·a). To describe the potential impact on climate change the indicator Global Warming Potential 100 (GWP) expressed in kg CO_2-equivalent as defined by IPCC [12] is used. The target values per capita and year for the domain of housing in Switzerland are shown in Table 1.

Table 1. Target values for GWP per capita and year for the domain of housing in Switzerland based on SIA2040 and adapted to the global target of 1 t CO_2-e per capita and year

	GWP [kg CO_2-e/(c·a)]
Embodied (including manufacturing, replacement and end of life)	270
Operation (building-related part)	90
Total	360

The bottom-up reference values for building elements are defined based on a statistical best-in-class approach (top 5%) using the market share of different construction products. The minimum, weighted mean and target values are shown in Table 2. The target values are based on 1 m^2 of surface area of the individual building element. Only the target values for columns are given per m length. Target values for technical equipment are provided per floor area of energy reference area (A_E), which corresponds to the gross floor area of the heated building zones.

Table 2. Minimum, weighted mean and target values (0.05 quantile) for GWP for the building elements for Swiss multi-family houses

Building element	Sample size	Reference unit (unit)	GWP [kg CO_2-e/(unit·a)] Minimum	W. mean	Target (0.05)
1. Base slab	80	$m^2_{element}$	1.32	2.23	1.87
2. Exterior walls underground	3	$m^2_{element}$	3.52	3.72	3.35
3. Exterior walls aboveground	404	$m^2_{element}$	0.82	2.11	1.37
4. Windows	16	$m^2_{element}$	1.49	3.16	1.85
5. Interior walls	35	$m^2_{element}$	0.59	1.28	0.82
6. Partition walls	30	$m^2_{element}$	0.58	1.05	0.83
7. Columns	7	m	0.43	2.01	0.64
8. Ceilings	1260	$m^2_{element}$	0.66	2.24	1.37
9. Balconies	4	$m^2_{element}$	1.2	1.48	1.13
10. Roof	273	$m^2_{element}$	0.79	4.05	2.32
11. Technical equipment*	29	m^2_{AE}	1.18	-	1.18*

* Due to a small number of solutions in the building component catalogue, no benchmark is calculated, but the minimum is used. The target value is the sum of minimum values for electric equipment, heat generation, heat distribution and delivery, ventilation equipment and water (sanitary) equipment of residential buildings.

The dual benchmark approach allows distinguishing between the different available options to reduce the embodied environmental impact of a building, namely the choice of type of construction/material and the design. Clearly, the choice of material is part of the design, however, in this context, both aspects are analysed separately. Design options refer to the shape and size of the building, but also the organization of floor plans or the window to wall ratio. Further aspects, such as the building's adaptability to react to changes in the use phase as well as building components' ability to be deconstructed and recycled are excluded here, but could be added in the future. Finally, the aim in the design phase should be reducing the environmental impact of the building holistically, including the operational part. There are many approaches for energy-efficient design described in the literature, see Energy Manual [13], for example. Here, the focus is therefore on the embodied part.

The proposed workflow of using the dual benchmark approach in the design process is visualized in Figure 1. EN 15643-1 [14] explicitly states that targets for the environmental performance shall be defined among others. Therefore, the workflow proposes to first calculate the environmental performance target based on the top-down benchmark. Then the environmental impact of the initial building design is calculated and compared to the top-down target. The impact of the individual building elements is calculated and compared to the bottom-up benchmarks to indicate the material-related optimization potential. If the selected "material/type of construction"-solution for an element is not within the top 5% of one or more assessment criteria – in this case the GWP, it is recommended to modify the material/type of construction and redo the analysis. There are exceptional cases where a specific material or type of construction cannot be changed due to other characteristics needed, e.g. fire or earthquake resistance. If the chosen solution is within the top 5% of a specific assessment criteria, the improvement potential is considered as small. In this case, it is assumed that the most efficient way to reduce the embodied impact is through design changes. For example, the compactness of the building can be increased, or the floor plans can be modified to decrease the built area. The change of the design has many consequences on other architectural and functional aspects, for example daylight availability and energy demand for lighting. These have to be considered, but are not within the scope of this paper. The aim of dividing between specific material/construction-type-related and overall design-related options is to provide guidance for environmental performance optimization of the building and its components. The proposed workflow is exemplified by means of a case study.

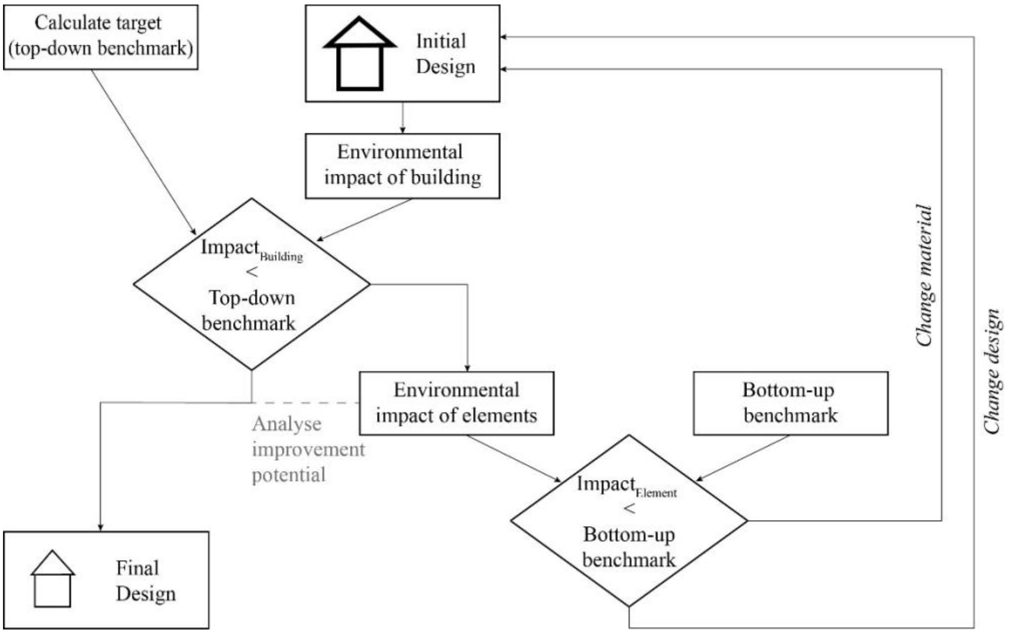

Figure 1. Flow chart of applying the dual benchmark approach in the design process

3. Case Study

To show the application of the benchmarks and validate the applicability of the proposed method, an existing building in Hamburg, Germany, called "Woodcube" is used as a case study. The reference study period is 60 years. The focus lies on analysing the embodied and the overall life cycle-related GWP and a comparison with the benchmarks. The operational GWP is calculated to provide the value in relation to the embodied part. Some small modifications to the geometry of the original building were made for simplification [15]. All material properties are taken from a published LCA report [16]. The quantities of the individual building components, respectively the areas of the building elements are taken off from a simplified 3D model, see Figure 2.

Figure 2. Left Woodcube (photo Hollberg), right simplified 3D model of the building

The assessment of the embodied impact for buildings in Switzerland is regulated in the standard SIA 2032 [17], which is currently revised and updated. The standard defines which building elements have to be included in the assessment. It refers to the elements defined in the Swiss standard for building cost regulation SN 506 500 [18] "Baukostenplan Hochbau" (BKP-H). In Switzerland, a building component catalogue [19] provides GWP factors for typical building components. It is based on the national Swiss database *KBOB Ökobilanzen im Baubereich* [20]. The building elements with the respective areas and related building components from the building component catalogue are listed in

Table 3. The GWP factors are provided including manufacturing (life cycle modules A1-A3 according to EN 15978 [21]) and end-of-life (modules C3 and C4). The values are provided per year taking the reference service life of the component declared in SIA 2032 [17] into account. When the values are multiplied with the reference study period of 60 years for residential buildings in Switzerland, the replacement (module B4) is implicitly considered.

Table 3. GWP factors per year and per m² of element area from the building component catalogue organized along Swiss BKP-H structure

Building element	Area [m²]	Component according to BKP-H	Code / ID	Component name according to catalogue	GWP [kg CO_2-e/(m^2·a)]
1. Foundation	228.0	C1 Base slab, foundation	C1 003	Flat foundation 5 or 6 storeys, Steel content 90 kg/m3, 35 cm	1.679
		G2 Floor covering	-	none	0.000
2. Exterior walls under ground	183.0	C2.1A Exterior wall under ground	C2.1A 029	Reinforced concrete wall, 20cm, Steel content 90 kg/m3	1.318
		E1 Exterior wall finishing under ground	-	none	0.000
3. Exterior walls above ground	723.5	C2.1B Exterior wall above ground	C2.1B 058	Timber frame construction	0.782
		E2 Exterior wall finishing above ground	-	Integrated in C2.1B	0.000
		G3 Interior wall finishing	G3 126	Timber cladding, painted	0.073
4. Window	200.7	E3 Window	E3 072	Double glazing, 10% timber frame	1.486
5. Interior walls	391.4	C2.2 Interior wall	C2.2 082	Reinforced concrete wall, Steel content 105 kg/m3	1.559
		G3 Interior wall finishing	-	none	0.000
6. Partition walls	643.0	G1 Partition wall	G1 107	Timber frame construction with insulation	0.541
		G3 Interior wall finishing	G3 127	Gypsum panel	0.170
7. Columns	0.0	C3 Column	-	none	0.000
8. Ceilings	1140.0	C4.1 Ceiling	C4.1 011	Timber frame ceiling	0.472
		G2 Floor covering	G2.2 108a	Sound insulation, anhydrite screed	0.321
		G4 Interior finishing	-	none	0.000
9. Balconies	90.0	C4.3 Balcony	C4.1 011	Timber frame ceiling	0.472
10. Roof	228.0	C4.4 Roof	C4.1 011	Timber frame ceiling	0.472
		F1 Roof covering	F1 017a	Foil sealing, EPS insulation	1.887
		G4 Interior finishing	-	none	0.000
11. Technical equipment	1099.0*	D1 Electric equipment	34.001	Electric installation, low requirements	0.310
		D5.2 Heat generation	31.002	Heat generation, power 30 W/m²	0.080
		D5.3 / D5.4 Heat distribution / delivery	31.024	Floor heating	0.290
		D7 Ventilation	32.003	Ventilation in kitchens and bathrooms	0.150
		D8 Sanitary equipment	33.003	Sanitary equipment	0.510

* The technical equipment is provided per floor area of energy reference area (A_E), which corresponds to the gross floor area of the heated building zones.

To define a GWP budget as the target value for the building, the top-down benchmarks in Table 1 are multiplied with the number of residents. In the design phase, an assumption for the number of residents is needed. The number of rooms in each apartment are analysed based on the architects' floor plans [16] and three scenarios are defined with the following assumptions: A) 24 residents; two persons for each master bedroom and one for each child and guest room; B) 18 residents; some master bedrooms are occupied by two, some by one person and not all guest rooms are continuously occupied; and C) 14 residents; one or two persons for each master bedroom depending on the size of the apartment and one person for each two child/guest rooms. In scenario B, the average living space of the residents is 45.8 m^2, which is close to the Swiss average value of 45.0 m^2 [22] and close to the German average of 46.5 m^2 in the years 2016 and 2017 [23]. Therefore, scenario B is assumed to be most realistic and employed for this paper. The influence of the floor area per resident on the top-down target is discussed later. The resulting benchmarks for the building are shown in Table 4.

Table 4. Top-down benchmarks for the case study building in GWP

	GWP [kg CO_2-e/a]
Embodied (including manufacturing, replacement and end of life)	4860
Operation (building-related part)	1620
Total	6480

4. LCA results of the case study building and discussion

Multiplying the areas of the eleven elements with the GWP factors for the components provides the results per building element shown in Table 5. The column *Actual value* shows the results for the selected materials as built. In addition, the other columns show the statistical values for minimum and target value based on the 0.05 quantile according to the bottom-up benchmark approach. These values are needed for the comparison later.

Table 5. Results for the embodied GWP of the building case study

Building element	GWP [kg CO_2-e/a]		
	Target (0.05)	Minimum	Actual value
1. Base slab	426	301	383
2. Exterior walls underground	613	644	241
3. Exterior walls aboveground	991	593	619
4. Windows	371	299	298
5. Interior wall	321	231	610
6. Partition walls	534	373	457
7. Columns	0	0	0
8. Ceilings	1562	752	857
9. Balconies	102	108	43
10. Roof	529	180	538
11. Technical equipment*	1297*	1297	1381
Total building	**6746**	**4779**	**5518**

* Due to a small number of solutions in the building component catalogue, no benchmark is calculated, but the minimum is used.

The building has a final energy demand for heating and hot water supply of 39674 kWh/a and an electricity demand (including auxiliary energy, ventilation, lighting and equipment) of 20212 kWh/a. The heating is provided though a wood chip boiler and the electricity by photovoltaic (PV) modules on the roof. The electricity demand can be fully covered by the building integrated PV on annual average. The factors for GWP are taken from the Swiss database *KBOB Ökobilanzen im Baubereich* [20]. The factors for the electricity from PV are based on a simplified approach of averaging all emissions within the life cycle such as production and disposal of the cells, but also the inverter and other parts of the system into one annual value per kWh. Excess energy exported into the grid is not considered to simplify the calculation. The benefit of exporting energy to the grid is highly dependent on the short-term variation of the electricity mix but also the long-term development in the next years. To assess the excess energy correctly, a dynamic approach considering the dynamic GWP factors for the Swiss grid would be needed [24], [25]. As this is not the focus of the paper, the calculation is simplified. The results are provided in Table 6.

Table 6. Results for GWP caused by operation of the case study building

	Final energy [kWh/a]	Final energy [kWh/(m^2_{AE}·a)]	Energy source	GWP Factor	GWP [kg CO_2-e/a]
Heating	39674	36.1	Wood chip boiler	0.027	436
Electricity	20212	18.4	PV on flat roof	0.081	1637
Total					**2073**

The total life cycle GWP of 7591 kg CO_2-e/a is 14.6 % higher than the top down target value of 6480 kg CO_2-e/a. Comparing the embodied and operational part separately shows that both parts are higher than the top-down benchmarks. Reductions of 11.9% for the embodied part and reductions of 21.8 % for the operational part are needed to meet the top-down benchmarks. As both parts do not meet the target values there is no opportunity to compensate one aspect with the other. Further alternatives to improve the building and reduce the environmental impacts are needed to make it compliant with the 1 t CO_2-e per capita and year approach.

Strategies to reduce the operational GHG emissions can be divided into approaches that influence the embodied impact e.g. increasing the insulation thickness and approaches that do not, such as choosing an alternative energy carrier. Here, it is assumed that approaches without influence on the embodied impact are followed. These could also include considering benefits from generating electricity onsite that is exported to others. As mentioned above, this raises further questions for example regarding system boundaries and allocation that cannot be discussed in detail is this paper. Furthermore, there are approaches that are beneficial for both operational and embodied impacts for example following a sufficiency strategy. This aspect is discussed later.

In the following, the case study focusses on the embodied impacts. To analyse how the embodied GHG emissions can be reduced best, the results for the building elements are compared to the bottom-up benchmarks. The results for the specific solutions are shown in the graph of the variability of the elements, see Figure 3, to indicate the improvement potential of each element. The points indicate the values for the specific solutions.

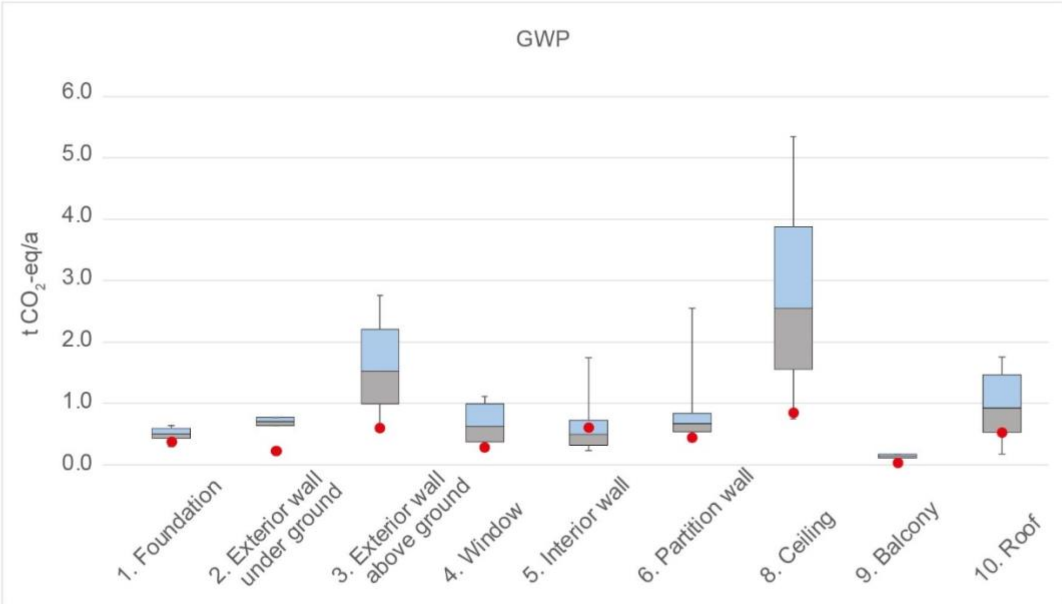

Figure 3. Benchmarks for the individual elements considering the surface areas of the building (points indicate the value for the specific material chosen in the case study)

For the *balconies* and the *exterior walls underground,* the specific values are smaller than the minimum values from the component catalogue. The specific balcony is made of wood, but only concrete is included in the component catalogue. For the *exterior walls underground*, the minimum is calculated including an exterior cladding and insulation for the wall. In the case study, the basement is not heated and therefore no insulation is included. As all selected solutions are close to the minimum, only the interior walls and the roof show a potential for improvement. Assuming the material of the internal walls could be exchanged to meet the benchmark this would save 289 kg CO_2-e/a. Doing the same for the roof would save another 9 kg CO_2-e/a. This means that the optimization of the material could save 298 kg CO_2-e. It is close, but not enough to reach the top-down target for the embodied part. Only, if the solutions with the minimum values are selected, the case study building achieves an embodied GWP of 4779 kg CO_2-e/a and the top-down benchmark is met. However, it is not clear whether this is technically feasible. Therefore, savings other than material optimization are needed. In this case study, the optimization potential of the building's shape is limited, because the building is very compact. One way to meet the top-down benchmarks is following a sufficiency strategy. If the floor area per resident can be reduced by 15% in this case study, for example through a higher efficiency of the floor plan, shared spaces or other design options, the top-down benchmark can be met.

Target values provided by certification systems and current national standards are usually based on the floor area (either the net floor area or the energy reference area). SIA 2040 currently provides targets for the so-called intermediate goal for the year 2050 which corresponds to total GHG emissions of 2 t CO_2-e/(c·a). Adapting these values to the goal of 1 t CO_2-e/(c·a) results in a target value of 6 kg CO_2-e/(m^2·a) for the sum of embodied and operational GWP. The DGNB target value for embodied GWP only is already 6.6 kg CO_2-e/(m^2·a) for residential buildings. The target value for the operational GWP in the DGNB-system is based on a reference building and is dynamic. Nevertheless, this shows that the current target values are too high to meet the "below 2 degree target" assuming a 1 t CO_2-e/c society. The case study building shows an embodied GWP of 5.0 kg CO_2-e/(m^2·a) and a total GWP of 6.9 kg CO_2-e/(m^2·a). A reduction of 15% is needed to meet the adapted SIA 2040 target. As such, the outcome of using the target values per floor area is similar in this case. However, the target per floor area does not allow to consider sufficiency strategies such as reducing the amount of floor area per resident. Therefore, a benchmark per capita is recommended here in addition

Finally, a building is more than a sum of its building components. As such, there are interdependencies between different components, for example load-bearing exterior or interior walls. Next to the embodied impact, the choice of materials and construction types influence many other building performance criteria. The presented approach is therefore an estimation in early design stages to provide guidance based on the currently available data.

5. Conclusion and outlook

As LCA is more commonly applied to assess the environmental performance of buildings, different actors have a need for LCA-based benchmarks. Investors, building owners and public funding institutions need them to define environmental performance targets and architects need them for design guidance. This paper shows how top-down and bottom-up benchmarks can be combined to provide design guidance. The top-down benchmark is based on the overall target of limiting GHG emissions to 1 t CO2-e per capita and year. The bottom-up benchmarks are statistically derived from typical building components for new residential buildings in Switzerland and the market share of different building materials following a best-in-class approach. A method for using this dual benchmark approach in the design process is proposed. The workflow suggests to first calculate the environmental performance target for the building based on the top-down benchmarks. Then the environmental impact of the building is calculated and it is checked whether the top-down benchmark can be met. If not, the impact of the individual building elements is calculated and compared to bottom-up benchmarks to indicate the material-related optimization potential. Depending on the result, decisions to change the material or the design parameters are taken. Differentiating between material and design-related options provides guidance on how to optimize the environmental performance of the building and its components efficiently. Of course, the approach can also be applied to reduce the impact, if the global target is met by the initial design. The method of using the dual benchmark approach in a case study of a multi-family house showed that the method is applicable. As such, the proposed approach can facilitate using LCA as a design-supporting method in design practice and promote environmental performance optimization of buildings.

Here, the method was applied for new residential buildings. The same method can be adapted to non-residential buildings as well as retrofit projects. The benchmarks should be regularly updated with the latest data. Furthermore, the benchmarks should be implemented into LCA tools applied during design to provide direct feedback on the optimization potential to decision makers. The proposed approach should be developed further including multi-criteria design decisions. In this paper, a top-down target for lifecycle-related GHG emissions has been used. In the future, the approach could be extended to include other environmental impacts besides climate change. The planetary boundary framework [26] could provide a basis for deriving additional target values for buildings. This will lead to a system of benchmarks. Furthermore, the dual benchmark approach could be linked to concepts such as “absolute sustainability” based on the carrying capacity of the ecosystem [27]. This would make sure that measures to lower the GHG emissions due not cause higher impacts in other categories. In the future, the method can also be transferred to other countries to derive national benchmarks for material-related environmental impacts as long as a building component catalogue and market share data are available.

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Dynamic Benchmarking of Building Strategies for a Circular Economy

Eberhardt L [1], Birgisdottir H[1], Birkved M[2]

[1] Danish Building Research Institute, Department of Energy Efficiency, Indoor Climate and Sustainability, Aalborg University, A. C. Meyers Vænge 15, 2450 Copenhagen SW, Denmark
[2] SDU Life Cycle Engineering, Department of Chemical Engineering, Biotechnology and Environmental Technology, University of Southern Denmark, Campusvej 55, 5230 Odense-M, Denmark

lcl@sbi.aau.dk

Abstract. Increasing building demands from a growing world population puts enormous pressure on natural resources. Management of resource consumption and environmental impacts is therefore vital to secure contemporary and future well-being and progress. Circular Economy (CE) is perceived as an industrial economy model potentially minimizing resource consumption, waste production and environmental impacts by the means of increased material circularity e.g. reuse. In order to promote CE in buildings, there is a need for benchmarks to support building designers in choosing environmentally viable solutions. Although life cycle assessment (LCA) help policy makers and building practitioners to define such benchmarks, benchmark studies often rely on static LCA approaches. Hence, uncertain and unknown dynamic changes during a buildings' long service life influencing the performance of long term sustainable building design principles are not accounted for. Through a literature review the paper at hand identified dynamic technological progress such as resource and energy consumption, energy grid mix, waste management, design and innovation and production efficiency as potentially essential to include when defining realistic CE building strategy benchmarks. How these dynamic factors may affect LCA results were demonstrated through a case study of a concrete column based on a range of possible scenarios. This included estimated future projections and the uncertainty relating to prospective assessments resulting in an output in the form of a span of possible future developments and environmental impacts instead of a single output. Based on the literature review and case study, main challenges of incorporating dynamism within building LCA benchmarking were identified.

1. Introduction

Circular economy (CE) is an industrial economy where the resource flows are managed within a restoring and regenerating capacity by extending resource life thereby avoiding depletion and reducing environmental burdens induced by these resource flows [1]. Thus, CE is of interest to minimize the construction industry's significant contribution to environmental impacts, resource consumption and waste production and both political and industrial initiatives are beginning to form at a greater extent [3–5]. For that reason it is increasingly important to be able to show the designers and decision makers where/how large the environmental benefits of CE are. One way is to establish benchmarks which are essential for comparing performances and establishing future mitigation goals to support building designers choose environmentally viable solutions. Life cycle assessment (LCA) can help establish such benchmarks [2] and is increasingly used by the construction sector and in some recently published CE studies [3,4]. LCA is used in certification schemes such as DGNB that have established benchmarks for LCA using reference buildings i.e. representative buildings for the establishment of benchmarks [2]. LCA benchmark values may also become part of the new Danish voluntary sustainability class in the building regulations [5]. However, the problem is that LCA is a well-developed tool for assessing products with a short service lives and/or have no ongoing inputs and outputs that change in magnitude and origin over time [6] whereas buildings sometimes have a very long service life with ongoing inputs and outputs that change in magnitude and origin over the course of many years or decades. Hence, benchmark studies often rely on static LCA approaches i.e. dynamic factors that can affect the environmental impacts of buildings and building components are not considered clearly limiting the validity of the LCA results [7]. In terms of CE this poses a problem as CE is about prolonging resource life thus designing also for systems operating in the future, not only today. For that reason a forecasting perspective is important for assessing and quantifying the benefits of CE to help guide design decisions today. Although, comparison of LCA results are important in order to develop benchmarks, in terms of CE comparing buildings such as done in e.g. DGNB will not be enough to establish reliable benchmarks. Instead LCA results should be compared against realistic future points of reference to provide a level of confidence when basing the adoption of CE building design strategies on LCA results. Dynamic life cycle assessment (DLCA) is an LCA approach enabling incorporation of dynamic process modelling in the context of temporal and spatial variations in the surrounding society as well as industrial and environmental systems [8]. Hence, the use of DLCA can potentially more realistically predict buildings' environmental performance by acknowledging potentially significant dynamic factors and thus offer a better basis for benchmarks to guide design decisions. However, DLCA research is at its infancy and predominantly applied in other industries and cannot be directly applied to buildings due to their complexity and long service life resulting in dynamic factors having a much longer and more complicated influence on building LCA results [7].

Focusing on the embodied environmental impacts related to the buildings' material resource flow in line with the CE, the paper at hand does not attempt to develop benchmarks for CE building strategies sector but rather explore the difference between using traditional building LCA and forecasting principle from DLCA when developing benchmarks. The paper at hand aims at: 1) through a literature review to create an understanding of the DLCA approach in the context of buildings and DLCA's potential importance to developing relevant benchmarks by identifying which elements of a building LCA can be addressed dynamically as well as which dynamic factors are assumed to be of significant importance to the environmental impacts of buildings' material resource flows and 2) based on the findings of the literature review, conduct a case study of a CE designed concrete column demonstrating how significant dynamic factors may affect LCA results. Furthermore, challenges of incorporating dynamic modelling principles within building LCA benchmarks are discussed.

2. Literature review

The literature review is not intended as an exhaustive study but a summarising representation of the state of art by covering the most recently published and relevant literature on the subject of DLCA focusing on quantifying the environmental burdens from buildings' energy and material flows. The literature review indicates that although DLCA studies within buildings exist dynamism is not incorporated in LCA benchmarks. Additionally, DLCA publications addressing temporal properties in building related LCAs is rapidly increasing, however, DLCAs are performed in various ways resulting in inconsistency and risk of undermining method validity and provide misleading results [6] and DLCA is still in its infancy [7]. Previous studies have found that DLCA results varied greatly when compared equivalent to static results[8]. Furthermore, changes during a buildings service life can in some cases influence the LCA result greatly compared to the production and construction phases [8]. From the literature two perspectives on dynamism are found i.e. dynamism related to the LCA framework and dynamism related to building life cycle stage specific processes such as production, operation and end-of-life. The LCA framework oriented DLCA approaches identified suggest that it is possible to treat any one or multiple of the four ISO 14040 LCA phases dynamically: 1) Goal and scope definition, 2) Inventory analysis, 3) Impact assessment and 4) Interpretation using different modelling methods: a) dynamic process inventories where future potential developments are incorporated into single unit processes, b) dynamic systems where future potential changes in terms of components of systems are accounted for by changing between unit processes, c) dynamic characterisation factors applied in the impact assessment to reflect impact potential change over time, d) dynamic scope and e) and dynamic weighting [6–9]. However, c) and e) have weak links to construction and insufficient research basis [7,8]. A full DLCA i.e. that covers dynamic aspects in all applicable phases and parts of the LCA for all unit processes are in most cases not feasible [6–8]. This is due to excessive data demands compared to conventional LCA, lack of adequate data, increased model complexity, lack of an established methodology, challenges in terms of incorporating dynamic aspect in existing LCA (static) software, or high uncertainty of dynamic process or system properties that is better omitted [6–8]. DLCA that does not exhibit dynamism in all phases or parts of an LCA results in a partially dynamic life cycle assessment (PDLCA) but can however still in many cases provide better/more realistic decision support compared to static LCA [6]. However, appropriate measures must be taken to ensure that use of PDLCA does not bias the results [6]. To avoid potential bias of results by applying PDLCA, system dynamics can be accounted for via the sensitivity analysis i.e. by exploring the effects of dynamisms on the system via sensitivity analysis facilitating illumination of potential issues i.e. temporal dependencies of the result [6]. The other DLCA approach accounts for building life cycle related processes that occurs during production, use, end-of-life and next product system. As previous LCA studies have consistently found that the operational energy consumption dominates most environmental impact categories DLCA in buildings has also mainly focused on buildings' operational energy consumption [10]. E.g. the Danish LCA software LCAbyg calculates both a static and dynamic energy consumption for operation based on a future Danish grid mix scenario for 2050 [11]. However, as some new low-energy buildings have radically reduced energy consumption the operational energy consumption is no longer considered to be the most important contributor to building-related environmental impacts [10,12]. This shifts focus to the buildings' embodied energy and environmental impacts [10,12] which is also in line with the CEs focus on resources. From the literature the dynamic factors related to specific temporal process developments in the building life cycle that are identified to be of significance for the embodied impacts as well as extraordinary relevance to CE are the technological progress related to: resource and energy consumption, compositional changes in energy structures and grid mix where the share of renewable energy is expected to increase in the future, waste management in terms of recovery and renewable rate of resources, design and innovation production efficiency [7,9]. Additionally, dynamic factors such as variation in occupancy behaviour, emissions/resources, environmental systems are also mentioned [5], [8]. Common for all of these dynamic factors are that they are related to (large) uncertainties, mainly related to future technological and political developments yielding many plausible futures. One way to handle future uncertainties is to build scenarios (i.e. scenario exploration) based on possible future trends or even likely trends based on predictive/prospective policies or historic trends (i.e. prospective scenario development based on back-casting) indicating realistic future developments with high probabilities that might have an influence on the environmental performance [6,8]. In addition, several scenarios that encompass a best or worst case scenario could be presented yielding a result span in which future environmental performance are expected to take place [6].

Another issue with building benchmarks is that they can be misguiding as different buildings may show similar results on the overall building level but for different reasons. This is because each building materials' and components' embodied environmental impacts are dependent on different factors such as different service lives, life cycles, dimensions, weight, functions etc. [13]. A systematic decomposition of buildings into their separate functions facilitating the identification of how the relationship of the embodied environmental impacts building elements relate to different building attributes may help predict and may greatly benefit the effort of reducing the embodied environmental impact of buildings even in the early design phase [13]. Ideally benchmarks could be established based on the specific conditions for every building element e.g. the embodied environmental impacts of a foundation is among others dependant on the weight it has to carry [13]. However, an adequate pool/sample of representative buildings are needed to base statistics on and standardize embodied environmental impacts to develop representative and specific benchmarks for e.g. building elements, functions, typologies, geographies, etc. in order relate to other building projects.

3. Case study method

Several studies show that concrete structures generally account for a large share of buildings' embodied impacts [14]. Hence, based on the findings of the literature review the use of dynamic process inventories and dynamic systems within DLCA focusing on energy grid mix, waste management, design changes and production efficiency are explored in a case study of a concrete column, building on an existing static LCA study where two scenarios sT and sD were modelled [15]. sT is a traditional design where the concrete column is casted together with the other concrete making it impossible to separate the column into its constituents for reuse without damage e.g. crushing of the column into concrete gravel for use as road filling and recycling the reinforcement steel to new steel products after a service life of 80 years. sD is where the column is designed for disassembly using large bolted mechanical steel connections from the Finnish company, Peikko, enabling reuse in a new future building after 80 years thereby prolonging the elements' service life and avoiding environmentally burdensome production of new concrete elements based on already existing marketed solutions [16]. Both sT and sD are modelled using a contemporary energy grid mix in all processes. The Danish 2050 energy grid mix scenarios forecast increased shares of waste incineration and renewable energy from wind i.e. the thermal energy will come from: 7% biomass and 93% waste, and electricity will come from: 10% biomass, 7% waste, 3% biogas, 1% natural gas, 76% wind and 3% solar [11,17]. New developments in cement production suggests a future reduction of up to 30% of its current embodied greenhouse gas emission (GHG) [18]. In addition, research on recycling of concrete into new concrete is currently ongoing [19]. Furthermore, future reductions in construction waste are expected as a result of the Danish government's CE strategy [5]. Additionally, with the increase of wind power it is expected that electricity will play an important role in future transport technology [17]. Adding these likely technological progresses to sT and sD resulted in two dynamic scenarios, dT and dD, modelled in accordance with the PDLCA approach. dT is similar to sT however assuming application of the 2050 energy grid in future life cycle processes, 30% less embodied GHG from cement production and higher quality recycling rates in year 80 which further increases in year 160. dD is similar to sD however assuming 2050 energy grid mix for future life cycle processes and 50% lower embodied GHG from transportation in year 80 and similar high quality recycling rates in year 160 as for dT. In year 1 sT and sD are modelled the same as is sD and dD using present grid mix. In year 80 for dT and year 160 for dT and dD, it is assumed that recycling of concrete substitutes a certain amount of virgin concrete that otherwise would have been produced using cement with 30% decreased embodied GHG. For D, the transportation distance is set to the longest possible transportation distance in Denmark of approximately 480 km. Table 1 and 2 provides an overview of how different processes within each life cycle phase are modelled for year 1, 80 and 160 for each scenario. The embodied GHG obtained from the dynamic models, d, are compared to the static models, s, where d reflects a best case scenario and s reflects a worst case scenario where we proceed as we do today. This provides a span in which the future embodied GHG can be expected to take place. All four scenarios were modelled following the LCA methodology stated in the standard EN 15978 using the openLCA v1.4 software and baseline characterization factors from the Centre for Environmental Studies (CML) baseline 2001.

Table 1. Traditional column scenario

		1st life cycle			2nd life cycle		
Life cycle phase		**P 1**	**E 80**	**N 80**	**P 80**	**E 160**	**N 160**
sT[4]	Grid mix	Present	Present	Present	Present	Present	Present
	Reinforce-ment steel	76 kg	99% recycling, 1 % landfill	-	76 kg	99% recycling, 1 % landfill	-
	Concrete 35MPa	1489 kg	90% recycling, 10% landfill	90% virgin gravel substitution	1489 kg	90% recycling, 10% landfill	90% recycling substituting virgin gravel
dT	Grid mix	Present	2050[1]	2050[1]	2050[1]	2050[1]	2050[1]
	Reinforce-ment steel	76 kg	99% recycling, 1 % landfill	-	76 kg	99% recycling, 1 % landfill	-
	Concrete 35MPa	1489 kg	100% recycling	25% / 75% virgin concrete/ gravel substituting[3]	1489 kg with 30% improved cement production technology[2]	100% recycling	50% / 50% virgin concrete/ gravel substituting[3]

Abbreviations: s =static, d= dynamic, T = traditional, D = design for disassembly, - = no substitution, P = Production, U = Use, T = Transport, E = End-of-life, N = Next product system, Present = Ecoinvent dataset energy grid mix. Sources: [1][11,17], [2][18], [3][5] and [4][15].

Table 2. Design for disassembly column scenario

		1st life cycle	2nd life cycle		
Life cycle phase		**P 1**	**T 80**	**E 160**	**N 160**
sD[4]	Grid mix	Present	480 km lorry transport	Present	Present
	Reinforcement steel	76 kg		99% recycling, 1 % landfill	-
	Steel connections	26 kg			
	Concrete 35MPa	1489 kg		90% recycling, 10% landfill	90% recycling substituting virgin gravel
dD	Grid mix	Present	480 km lorry transport with 50% improved transportation technology[3]	2050[1]	2050[1]
	Reinforcement steel	76 kg		99% recycling, 1 % landfill	-
	Steel connections	26 kg			
	Concrete 35MPa	1489 kg		100% recycling	50% / 50% virgin concrete/ gravel substituting[2]

Abbreviations: s =static, d= dynamic, T = traditional, D = design for disassembly, - = no substitution, P = Production, U = Use, T = Transport, E = End-of-life, N = Next product system, Present = Ecoinvent dataset energy grid mix. Sources: [1][11,17], [2][18], [3][17] and [4][15].

As CE focus on resource life extension the functional unit was set to provide the function/service of the column across two component life cycles (i.e. 2 times 80 years). The life cycle inventory (LCI) of the background system was based on the Ecoinvent 3.2 database using system processes to obtain aggregated results, however, switching between unit processes were used to model the dynamic aspects. The foreground system was compiled using the manufacturers' product specifications. The system boundaries include production, waste recovery for reuse, recycling or incineration and disposal by landfilling at end-of-life, and credits for potential reuse, energy recovery and recycling of materials and components in a next product system. Allocation of environmental impacts and credits are modelled following the 100:0 (cut-off) approach of EN 15978. As steel is assumed produced using scrap steel, no environmental crediting is achieved when recycled again [20]. To address uncertainties of the dynamic scenarios dT and dD a sensitivity analysis evaluates the influence of possible sensitive material and energy source input parameters resulting from a 10% input value increase [21].

4. Case study results

Figure 1 shows the life cycle embodied GHG and material flows resulting from the static LCA represented by sT and sD and the PDLCA represented by dT and dD where the size of the arrows approximately represents the amount of the material inputs and output flows. The highest material embodied GHG originates from production of concrete in year 1 for both T and D. However, the embodied GHG of producing column D in year 1 is slightly higher compared to column T due to the use of extra steel for the connections to allow assembly and disassembly. Considering sT, where column T is not suitable for reuse at the first use cycles' end-of-life, supplying a second use cycle with the same kind of column requires production of a new column. Hence, the embodied GHG of column sT originates from production in year 1, and at end-of-life in year 80 treatment of 90% concrete substituting virgin gravel resulting in negative embodied GHG, furthermore 99% reinforcement steel for recycling and 10% concrete and 1% reinforcement steel for landfilling at . During the second use cycle this is repeated. The similar processes are repeated for dT, however, differing as the dynamic aspects stated in Table 1 have been added. Hence, the embodied GHG of column dT comes from production in year 1, and at end-of-life in year 80 treatment of 100% concrete for recycling, where 25% and 75% substitutes virgin concrete and gravel respectively resulting in negative embodied GHG, 99% reinforcement steel for recycling and 1% reinforcement steel for landfilling. In the second use cycle the embodied GHG in year 80 comes from the production of a new concrete column however with 30% less GHG from the production of cement. And at the end-of life in year 160 the embodied GHG comes from treatment of 100% concrete, where 50% substitutes virgin concrete and 50% substitutes gravel resulting in negative embodied GHG, 99% reinforcement steel for recycling and 1% reinforcement ending up in landfills. For sD, the embodied GHG originates from production in year 1, transportation to a subsequent building in year 80 and end-of-life in year 160 from treatment of 90% concrete substituting virgin gravel resulting in negative embodied GHG, 99% reinforcement steel for recycling, 10% concrete and 1% reinforcement steel being. The similar processes are repeated for dD, however, differing as the dynamic aspects stated in Table 2 have been added. Hence, the embodied GHG comes from production in year 1 and transportation to a subsequent building at end-of-life in year 80, however, with 50% less GHG. At the final end-of-life in year 160 the GHG comes from treatment of 100% concrete for recycling, where 50% substitutes virgin concrete and 50% substitutes gravel resulting in negative embodied GHG, 99% reinforcement steel for recycling and 1% reinforcement deposited in landfills. From the accumulated embodied GHG it is seen that the scenario exhibiting the highest embodied GHG is sT with 488 kg CO_2 eq. and the scenario with the lowest embodied GHG is dD with 257 kg CO_2 eq. The accumulated graphs for the static scenarios clearly reveals that that reuse of the column sD to supply two life cycles is less burdensome compared to producing two column sT to supply the same two life cycles. However, when simultaneously looking at the accumulated graphs for the dynamic scenarios, this is no longer the case as the technological progress over time results in dT and dD exhibiting close to a similar performance with 297 kg CO_2 eq. and 257 kg CO_2 eq. respectively.

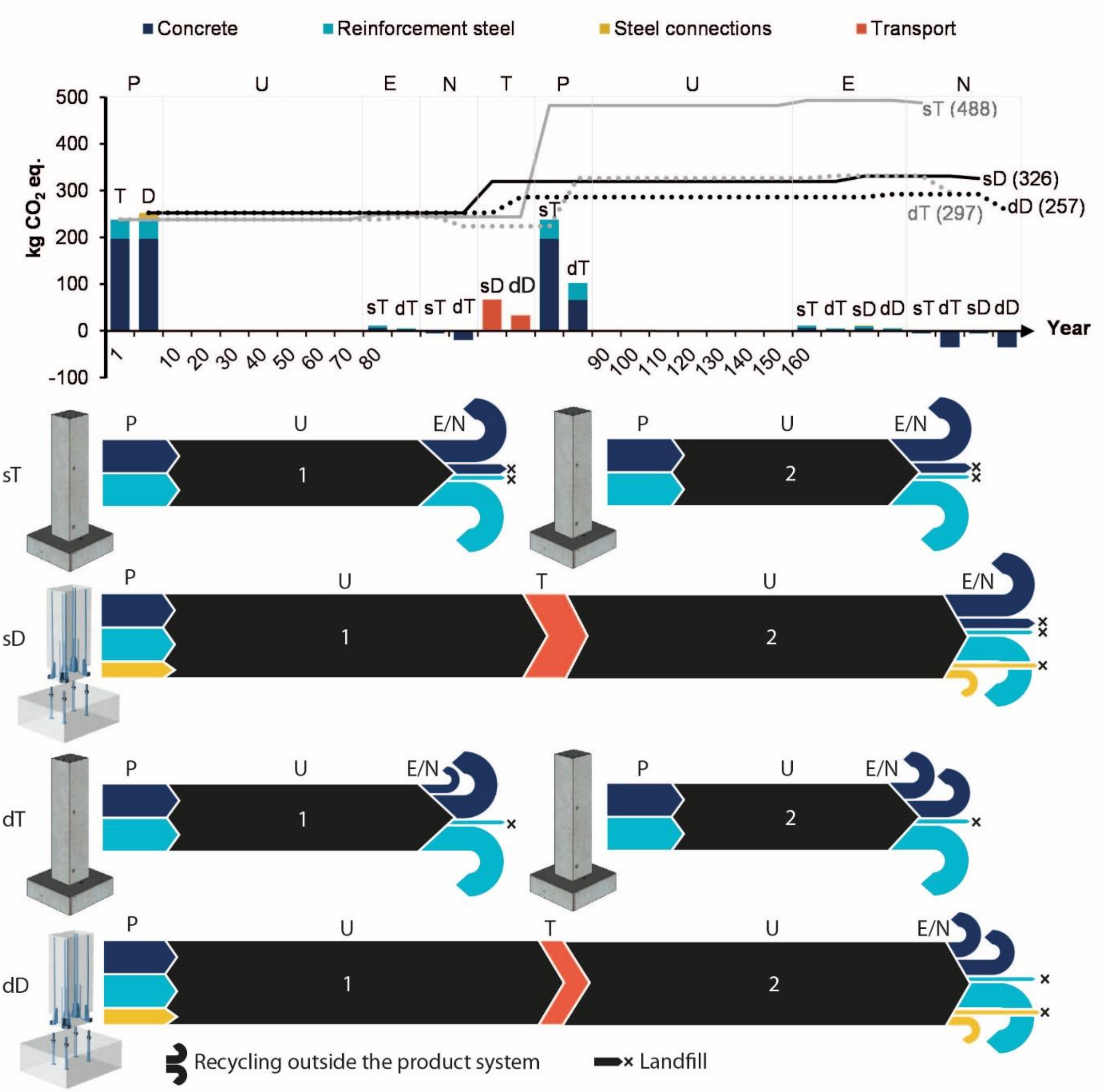

Figure 1. Comparison of life cycle embodied GHG and material flows of the modelled scenarios. Abbreviations: P = Production, U = Use, T = Transport, E = End-of-life, N = Next product system, 1 = first use cycle, 2 = second use cycle, s=static, d=dynamic, T=traditional, D= design for disassembly.

5. Discussion and conclusion

From the example of the concrete column provided here taking into account several life cycles, the static LCA results supports the CE idea that design for disassembly for reuse of building component is environmentally preferable over production of new components. However, when incorporating the technological progress in the dynamic LCA, results show that the environmental performance of a newly manufactured column performs close to the same as reusing an old column, but reuse of the column still performs slightly better. For CE design concepts such as design for disassembly, this could potentially mean that complete neglection of dynamic aspects when developing CE benchmarks can evidently provide false guidance on which design strategies to use on component level and how to best meet future mitigation goals. From the sensitivity analysis it was tested to which extent the output parameters of dT and dD were sensitive towards any of the material and energy source input parameters i.e. if a small change of a 10% increase in the input parameter value would result in a large change in the model results. Table 3 shows that, although the energy source input parameters related to electricity and thermal energy can be qualitatively associated with a high uncertainty, the model output is insensitive to these parameter as the sensitivity coefficients are below 10%, hence, the uncertainty of them will not affect the overall results. However, the output parameters of both dT and dD were found to be very sensitive to a 10% increase in the material input parameters, especially concrete which exhibited a sensitivity coefficient of 75% and 78% for dT and dD respectively. This could be due to the fact that for the column scenario the dynamic technological progresses explored mostly affects the concrete e.g. changes in waste management and production efficiency. For that reason the uncertainty of other technological progresses may influence the results even more compared to the future energy grid mix.

Table 3. Parameter sensitivity coefficient of dynamic scenarios dT and dD

Material parameters	**Scenario**	**Concrete**		**Reinforcement steel**		**Steel connections**	
	dT	74%		30%		-	
	dD	78%		19%		7%	
Electricity parameters	**Scenario**	**Biogas**	**Biomass**	**Natural gas**	**Solar**	**Waste**	**Wind**
	dT	0.004%	0.019%	0.019%	0.011%	0.115%	0.045%
	dD	0.000%	-0.021%	0.021%	0.013%	0.146%	0.056%
Thermal energy parameters	**Scenario**	**Biomass**				**Waste**	
	dT	0.04%				9.96%	
	dD	0.01%				2.13%	

However, the study at hand is limited in its scope as it only explores the influence of incorporating dynamism in an LCA of a concrete column focusing only on embodied GHG and may obviously overlook other potentially important aspects of incorporating dynamic aspects in CE benchmarks. E.g. in terms of CE, dynamic LCA does not show how the column performs in terms of resource scarcity. Furthermore, this study includes technological progress relevant in a Danish perspective for the particular column in question; however, influencing dynamic factors may differ greatly depending on the geography. Other developments relevant for the concrete column may also have been overlooked. The technological development and influence of dynamism on the environmental impacts of another CE designed building component may also differ greatly from that of the column making it difficult to define general benchmarks both on building and component level. Thus, CE benchmarks could, as a starting point, focus on where the largest environmental and resource burden improvement potentials lies and in this way facilitate the progression to a more sustainable development of buildings. In addition, the study only considers embodied GHGs, however, the performance of the column may differ when considering another environmental impact category. However, it is difficult to develop benchmarks on the basis of the majority of impact categories due to burden shifting between the impact categories. Although, some LCA software tools include dynamic factors for buildings such as the Danish LCAbyg software which includes forecasted Danish energy grid mixes for 2050 for the operational energy consumption of the building, implementing the dynamic factors' influencing the embodied environmental impacts of each building component is a (much) larger challenge as it requires many alterations to a vast number of (inventory) datasets. However, as a starting point datasets could be designed in a more modular way to also implement dynamic energy grid mix(es) influencing the embodied energy and environmental impacts and thus allow for easier exchange of energy processes. The study at hand also shows that CE requires a different way of conducting LCA in order to quantify future benefits of CE for long-lived building components i.e. accounting for several component life cycles instead of just the first. Despite the limitations of the study, basing benchmarks *on* a more dynamic LCA approach i.e. a range of possible scenarios including estimated future projections and the uncertainty relating to prospective assessments results in an output in the form of a range of possible future developments and hence a range of environmental impacts as demonstrated herein. Such a probabilistic set of results is likely to provide a more meaningful, realistic and accurate decision basis supporting a sustainable development in the building sector.

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Carbon Heroes Benchmark Program – whole building embodied carbon profiling

Pasanen P[1], Castro R[2]

[1] CEO Bionova Ltd. , Helsinki, Finland
[2] Senior LCA Expert, Bionova Ltd., Helsinki, Finland

panu.pasanen@bionova.fi

Abstract. Reducing the embodied carbon of the building stock requires a better understanding of the life cycle impacts of the materials used in those buildings. However, the characteristics of the building stock vary significantly by geography and building type. The "Carbon heroes benchmark program" is a cooperative initiative for carbon profiling by building type across different countries. The program's aim is to create uniform, full life-cycle of materials benchmarks for common building types. The benchmark program is on track to achieve 1000 fully completed and verified buildings by end of 2019, and contains data breakdowns for over 100 different material types and essential structural parts of a building. All data used in the program is rigorously anonymized and statistically small sets of data are also not used to protect data anonymity. The program implements the EN 15978/ISO 21930 standards as the basis of measurement, and includes life-cycle stages A1-A3, A4, B4-B5, and C1-C4. This presentation will share the preliminary findings of this project. 659 verified buildings (February 2019 cut-off), with substantial datasets for many European countries for some of the most common building types. The benchmark is generated using One Click LCA.

1. Introduction

Embodied carbon in the built environment is not well understood, and designers and project teams lack reference points to analyze their project performance. When a subject is at the same time new, and it does not have a clearly established reference point, it's easy to get lost and the issue of embodied carbon remains unaddressed.

Among the findings of the Embodied Carbon Review [1], five (5) methodologies were identified that help deal with embodied carbon in the building sector. These methodologies are carbon reporting, carbon comparison (in design), carbon rating, carbon caps, and decarbonization. With the exception of the first method, all share the need to develop a benchmark or baseline to measure or compare against to drive carbon reductions. Thus, carbon benchmarks can become instrumental for policy-making as they serve to set actionable targets.

The present study shares the preliminary results of the Carbon Heroes Benchmark program developed with anonymized building data. The article will describe the design of the data collection procedure, the assumptions in the organization of data, and the challenges found to this date in the program.

2. Developing embodied carbon benchmarks for buildings

The role of embodied carbon benchmarks for buildings is recognized as an important instrument for policy makers to help reduce the impacts of the building stock. However, a single benchmark cannot be applied across the all buildings as the normalization of embodied carbon per unit area ignores the impact

of building type on its carbon footprint [2]. Moreover, previous attempts at establishing carbon benchmarks, several challenges have been identified in their creation. Some of these challenges include the use of different life cycle inventory (LCI) databases, variability in the reported LCA methodologies used and variability in the material scopes of existing studies, inconsistent meta data to properly classify the data, and the reduced sample size to make significant statements [3,4]. Another study for multi-unit residential buildings done in Canada also highlighted the limitations of sample size and the impact of regionalization in the development of the benchmarks [5].
In order to address these issues, the Carbon Heroes Benchmark program is capable of leveraging the use of a single LCA software platform, One Click LCA, to guarantee consistency in the input of data and the calculation of its impacts.

2.1. Pre-requisites for the quality of embodied carbon benchmarks for buildings
As previous experiences have shown, ensuring consistency of embodied carbon benchmarks is all but easy. Carbon Heroes Benchmark Program is designed to ensure high quality control and robustness of the results. These include:

2.1.1. Consistent building information meta data. Each project includes information on building type (refer to Table 1), LCA scope reported according to EN-15978 standard, and gross internal floor area.

2.1.2. Relevant material classification. The materials included are classified by types and sub-types. For example, metals as a type is sub-divided into reinforcement steel, structural steel, aluminium, copper, etc.

2.1.3. Automated material feedback. An internal algorithm checks the quantities of materials per building element and the ratio between material sub-types to guarantee that the quantities reported are plausible and/or fall within expected ranges. This information is provided to the users so they may review the data introduced and make necessary corrections. For example, ratio of concrete mix to steel reinforcement.

2.1.4. Anonymized data. All identifiable information is removed before generating the dataset for statistical analysis. This is to ensure privacy and avoid bias in the analysis. Only the country location of the building is reported for the development of national and regional benchmarks.

2.1.5. Expert verification and removal of incomplete datapoints. An LCA expert reviews the scope of materials and results. Some potential sources of errors include incomplete scope for calculation, unusual quantities by building area, or suspected values. If errors or incomplete data cannot be resolved, the building is withdrawn from the sample.

2.2. Scope of benchmark program
The aim of this program is to create uniform, life-cycle embodied carbon benchmarks for common building types. The benchmark program is on track to achieve 1000 anonymized, verified buildings by end of 2019, and contains data breakdowns for over 100 different material subtypes and essential structural parts of a building. The benchmarks are generated and updated approximately every six months.
This program is operated in cooperation with Green Building Council Ireland, Green Building Council Italia, Green Building Council Hungary, Dutch Green Building Council, Romanian Green Building Council and Norwegian government real estate organization Statsbygg. Also, Chile Green Building Council has joined the program, but no verified datapoints from Chile are available. The synthetized results of the program are made available to the participating partners and software users.
The benchmark is developed by building type through a standardized life cycle model. Results are regionalized and communicated in a clear way to the non-expert public.

2.2.1. Building typologies. Currently, the program is collecting data for 18 building types. These typologies are listed in Table 1.

Table 1. Building typologies in Carbon Heroes Benchmark program

Building group	Building Type
Residential	Apartment buildings
	Attached or row houses
	One-dwelling buildings
	Social welfare buildings
Educational / Institutional	Cultural buildings
	Day care centres for children
	Educational buildings
	Historic or protected monuments
	Hospitals and healthcare centers
	Schools (primary education)
	Sports halls
Commercial	Hotels and similar buildings
	Industrial production buildings
	Office buildings
	Retail and wholesale buildings
	Transport buildings
	Warehouses
	Other buildings

2.2.2. Standardised life cycle model. The scope of the analysis follows the EN-15978 / ISO-21930 standard as the basis of measurement. The system boundary and essential methodology of the benchmark calculations is standardized. All calculations included in the program are uniform and cover life-cycle stages A1-A3, A4, B4-B5, and C1-C4; it excludes the module D. In other words, this covers the impacts from material production, the replacement and/or refurbishment due to the end of the material service life, and the end of life stage. Figure 1 includes the information modules described in the EN-15978 standard.

Participants in the program pursue specific requirements in green building certifications such as BREEAM [6] and LEED [7], that require a whole building life cycle assessment to measure the environmental impacts of the materials used to build and operate the building. As a requirement of these certifications, the period of study is 60 years. Also, the certifications require the report of embodied carbon as Global Warming Potential (GWP) 100 years in Kg CO_2-eq. Other environmental categories differ between the certifications. As a consequence, this benchmark was developed with GWP as a common denominator and easy to understand indicator associated with climate change.

Moreover, the benefits of biogenic carbon are not included in the benchmark. This is a result of the uncertainty associated with the disposal method or end of life scenario. For example, the incineration of vegetated products releases the stored carbon back to the atmosphere and results in a zero sum for the purposes of the analysis. Consequently, the assumed carbon storage benefits reported in module A1 are added back in module C. Nevertheless, biogenic carbon is calculated and reported as a separate indicator in One Click LCA.

Product Stage			Construction Process Stage		Use Stage							End-of-Life Stage				Benefits and loads beyond the system boundary		
Raw material supply	Transport	Manufacturing	Transport to building site	Installation into building	Use/application	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction/demolition	Transport	Waste processing	Disposal	Reuse	Recovery	Recycling
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D	D	D

Figure 1. Life cycle stages according to EN-15978

2.2.3. Regionalized samples. The sample is classified by countries at the moment with the aim at grouping buildings with similar construction techniques. Table 2 shows the breakdown of countries for the sample of European projects. Additional data is available for North America, Middle East, and Asia.

Table 2. Countries by region, Europe

Region	Countries
Northern Europe	Denmark, Finland, Iceland, Norway, Sweden
Eastern Europe	Croatia, Czech Rep., Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Serbia, Slovak Rep., Slovenia, Ukraine
Southern Europe	Italy, Portugal, Spain
Western Europe	Austria, Belgium, France, Germany, Luxembourg, Netherlands, Switzerland
British Isles	Ireland, United Kingdom

2.2.4. Facilitate the consistent input of building data. The collection of building information for the development of these benchmarks are the result of material quantity inputs made by users of One Click LCA. To assist the users in the correct input of information, the software includes two tools: Model Checker and LCA Checker. The Model Checker reviews the quality of the geometric information found in the Building Information Models (BIM) during the import process into One Click LCA. And, LCA Checker reviews that the material quantities are plausible using a set of proprietary algorithms and automated verifications.

2.2.5. Sample size. Currently, there are 659 buildings included in the program. The aim of the Carbon Heroes Benchmark Program is to reach 1000 buildings by the end of 2019, at which point the analysis is repeated. The results included in section 3 show the preliminary findings of this study for a limited number of building types: multi-family apartment, office, and warehouse/industrial. Also, this analysis will include only buildings in Eastern Europe Another review/update is expected at the end of 2019 and it will determine which building types will be reported based on their statistical significance.

2.3. Communicating results

Results are reported in two graphical forms that are easy to read. First, in a Boxplot with whiskers showing the median and range, including outliers. And, second as a performance metric as shown in Figure 2. The performance metric includes the range of results at two standard deviations of the mean for the building type. The range is divided into 7 (seven) bands equally distributed. The mean of the results falls within band "D" and the lower and upper extremes of the range are in bands "A" and "G" respectively.

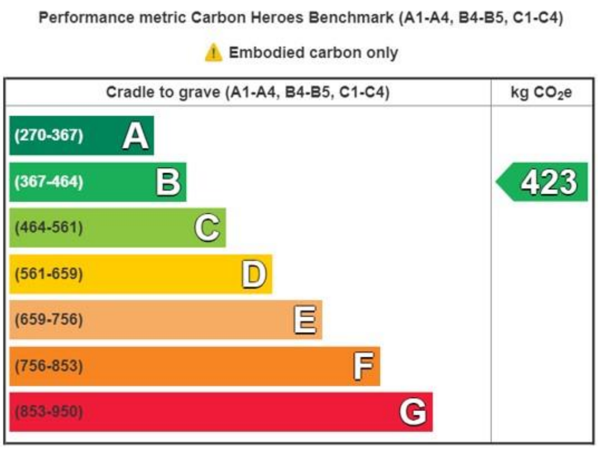

Figure 2. Performance metric Carbon Heroes Benchmark, example

3. Results & Discussion

For this article, three building types for Eastern Europe are presented here as an example of our data analysis process. In Table A1, the descriptive statistics for the sample of office buildings is included. The high values of Kurtosis and Skewness show the possibility that this dataset is not normally distributed. The histogram for the same dataset presented in Figure 3, seems to corroborate this assumption. The data shows positive skewness and a long tail to the left.

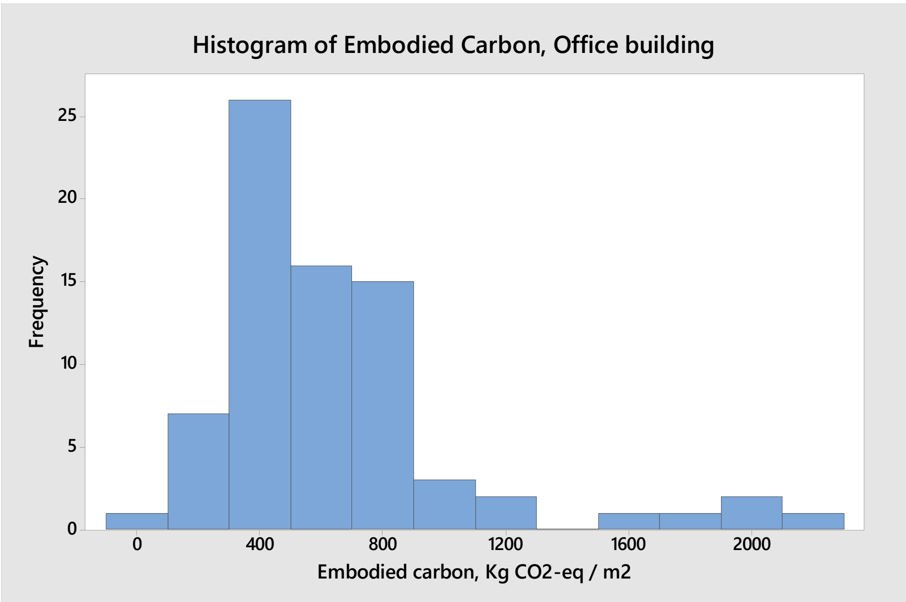

Figure 3. Histogram of office building, Eastern Europe

As a consequence, a 1-sample sign non-parametric test was applied to check if the median is a better test of central tendency for this dataset. The results of the test are included in Table 4, with similar test results for two other building types: "apartment buildings" and "warehouse/industrial facilities".

Overall, the median shows to be on target in its central tendency, and the resulting range (lower and upper values) captures with 95% confidence the values of the dataset.

Table 3. Median embodied carbon results per building type

Building type	Median embodied carbon, Kg-CO2-eq/m2	Confidence Interval, 95%
Apartment buildings	444	285, 886
Office	531	410, 591
Industrial & warehouses	609	357, 1115

Alternatively, additional building information can shed insights into the skewness of the distribution. This will be tested as the sample grows. Meanwhile, using the histogram of the office building subset, the outliers to the left were extracted from the sample, and a set of descriptive statistics were calculated. With a reduced sample (n=70), the mean and median were closer to each other, and the results are more normally distributed (M=538; SD=238) and range (63,1013) p=0.05. Figure 4 shows boxplot of the sample. Table A2 shows the descriptive statistics of this sub-sample.

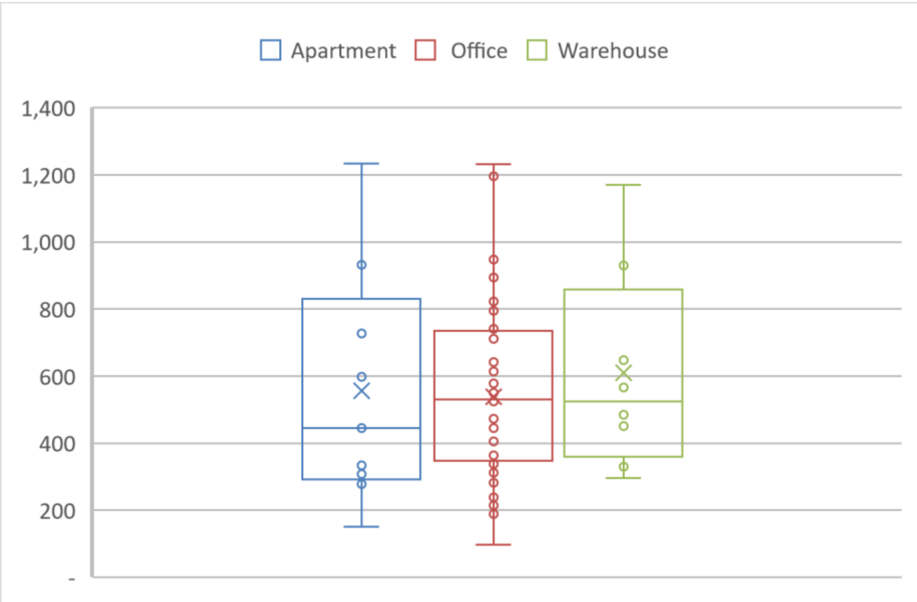

Figure 4. Boxplot of mean/median embodied carbon, Eastern Europe

In addition, global warming potential (GWP) is reported by information module as a percentage of overall embodied carbon (Kg CO_2-e) in Figure 5. It is not surprising that the largest share of GWP takes place during the construction phase. However, a study we conducted about modelling the impact of retrofit on accumulated impacts has shown that the impacts of module B4-B5 might be underrepresented [8]. At the moment, the results in B4-B5 represent changes in materials due to the technical service life of materials and do not consider changes in building renovations or retrofit scenarios. This can lead to a review of the scope of the analysis for module B.

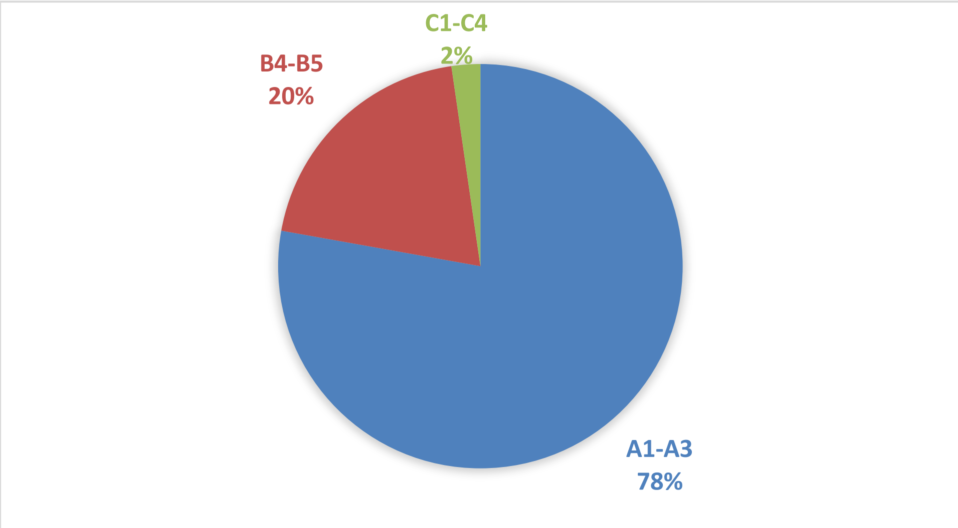

Figure 5. Distribution of %GWP, office buildings, Eastern Europe

Closing remarks

Finally, it is expected that as the sample grows the dataset will tend towards a normal distribution. This will facilitate its use in the performance metric shown in Figure 2. However, it is also possible that underlying effects are responsible for the spread in the dataset. This will be subject of future analysis and could lead to explain what other factors are correlated with the embodied carbon in buildings, and help improve its representation in the Carbon Heroes Benchmark.

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Appendix

Table A1. Descriptive statistics, office buildings Eastern Europe (Kg CO_2-e/m^2)

Mean	630
Standard Error	48
Median	550
Mode	#N/A
Standard Deviation	417
Sample Variance	173,702
Kurtosis	4
Skewness	2
Range	2,010
Minimum	97
Maximum	2,107
Sum	47,214
Count	75
Confidence Level (95.0%)	96

Table A2. Descriptive statistics, sub-sample office buildings Eastern Europe (Kg CO_2-e/m^2)

Mean	538
Standard Error	28
Median	531
Mode	#N/A
Standard Deviation	237
Sample Variance	56,402
Kurtosis	0
Skewness	1
Range	1,136
Minimum	97
Maximum	1,232
Sum	37,641
Count	70
Confidence Level (95.0%)	57

Inventory of the existing residential building stock for the purpose of environmental benchmarking

Verellen E, Allacker K

KU Leuven, Faculty of Engineering Science, Department of Architecture, Kasteelpark Arenberg 1 – box 2431, 3001 Leuven, Belgium

evelien.verellen@kuleuven.be

Abstract. The current renovation rate in Belgium is less than 1% and should be increased to 2,5% to reach the European targets to reduce the GHG emissions by 2050. There is a need to rapidly increase the renovation rate and at the same time guarantee that these renovations reduce the environmental impact on our planet. In order to define environmental benchmarks for existing buildings and their renovation targets, a better understanding of the existing building stock is needed. In this paper, the approach used to model the existing building stock is presented for the specific case of Leuven. The methodological steps, challenges and data gaps are presented in detail. The proposed building stock model uses GIS data in order to gain insights in the geospatial distribution of the impacts of the stock. These spatial maps moreover allow to clearly visualise the impacts which can improve communication and contribute to policy actions.

1. Introduction

The construction sector is responsible for 30% of the resources used in Europe as well as for 40% of the energy used and 36% of greenhouse gas (GHG) emissions.[1] According to the European Commission, cities are responsible for the largest share of most environmental impacts, but provide also major opportunities for improvement.[2] Cities hence play a crucial role in the aim to move towards a more sustainable built environment.[3] The European Union targets to reduce the GHG emissions by 2050 with 80% to 95% compared to 1990.[4] Likewise, Flanders wants to evolve to low carbon, sustainable, reliable and affordable energy sources to achieve this European target.[5] The building sector has in many aspects already moved forward to a sustainable transition path as innovative products and new skills have been developed and the energy performance of new buildings has improved to a great extent. Nevertheless, the existing building stock in Europe, and likewise in Flanders, is still using a lot of energy and the refurbishment rate is too low to be able to reach the GHG emission reduction goals. Belgium aims at increasing the current (2016) annual renovation rate of less than 1% to 2,5%[6] through the 'Renovatiepact'. The Renovatiepact consists of various actions: increasing the renovation level of each building, gathering energy related information of each building and formulating renovation recommendations for each building. It is clear that a building-specific approach needs to be followed, mostly because of the highly privatized and hence very diverse building stock of Belgium.

This paper presents a methodology for a part of the inventory of the existing residential building stock in order to model its environmental impacts. The inventory focuses both on the geometry and energy performance of the buildings in order to have insights in the operational energy use of the buildings and to have all data required for a life cycle assessment of the buildings and renovation interventions. This forms the base of defining environmental benchmarks for the renovation of residential buildings in future research.

Building stock modelling typically uses either a top-down or bottom-up approach. In top-down methods the complete building stock is described at an aggregated level based on input-output modelling (urban metabolism). Bottom-up methods start with a set of individual stock components, buildings or building elements for example, and upscale these components to the complete stock level.[7] In this research the bottom-up approach will be used because this approach allows to identify the root causes of phenomena at stock level. So, this inventory consists of a detailed inventory at the individual building level which is then scaled up to the city level.

The methodology is elaborated for the city of Leuven which is selected as a case study due to its experience in carbon footprinting[8] and hence there is a relatively good data availability.[2] Leuven moreover has its own ambitious target to renovate 1000 buildings each year by 2030.[9] Which makes it an interesting case study. Finally, the carbon footprint of Leuven was previously calculated through a top-down approach[8] which will allow to (partially) validate our proposed bottom-up model. Although the research focuses on Leuven, the method is also applicable to other cities.

2. Methodology

2.1. Bottom-up approach

Two building stock aggregation models can be used in bottom-up approaches: the archetype and the building-by-building approach. The archetype approach uses reference buildings according to the characteristics of the building stock and represents the full stock based on these reference buildings. The building-by-building approach consists of modelling each building of the stock or a sample of the building stock in case of large building stocks (e.g. national level).[7]

For the goals of our study, the inventory of the existing building stock should be as detailed as possible in order to define an accurate environmental benchmark for the renovation of existing buildings. For this reason, the building-by-building approach is preferred over the archetype approach. Nevertheless, lacking building-by-building data are filled with proxy data from archetypes.

For the inventory of the building stock, data about the geometry, the location, the function and the energy performance are needed. The search for this data for each building of the building stock of the city of Leuven revealed that most of the data is directly available or can be derived in a sufficiently accurate way. Publically available Geographic Information System (GIS) data from Flanders[10] include the following information required for the stock model: ground floor area of each building, perimeter of each building and ridge hedge of each building. In addition, for the specific case of Leuven, more extended GIS data are available: construction year, building type, roof type, function of the building, number of floors and number of residential units. Energy consumption data (electricity and gas) are available from the energy distribution network operator (Fluvius) at street level together with the number of gas connection points per street. An overview of the available data is provided in table 1, indicating also which data are not directly available but can be derived from the other data. An important data gap for each of the buildings in the building stock is the thermal insulation level of the building envelope. For this data gap, proxies from the archetypes will be used in a next step of the research. The archetypes are defined based on the reference buildings of the IEE-Tabula project. In the subsequent sections the inventory of the various data is described in more detail.

Table 1 Overview of the sources of the data inventory.

Data	Available?	Data Source	Discussed in section
Geospatial Information	yes	dataset Leuven/Flanders	2.2
Ground floor surface	yes	dataset Flanders	2.3
Perimeter	yes	dataset Flanders	2.3
Wall surfaces	can be derived	dataset Flanders	2.3
Window surfaces	no	-	-
Ridge height	yes	dataset Flanders	2.3
Roof type	partial	dataset Leuven	2.7.1
Building typology	can be derived	dataset Leuven	2.5
Construction year	partial	dataset Leuven	2.7.2
Energy consumption (at street level)	yes	Fluvius (energy network operator)	2.4
Function	yes	dataset Leuven	2.3
Number of floors	yes	dataset Leuven	2.3
Number of residential units	yes	dataset Leuven	2.3
U-values	no	IEE-Tabula project	3

2.2. GIS
The building stock model developed for the city of Leuven is based on GIS data in order to gain insight in the geospatial distribution of the buildings and their current energy performance and environmental impact. Such geospatial inventory data have various benefits: these allow to identify priority neighbourhoods for renovation, allow to define archetypes for environmental benchmarking of existing buildings, allow to visualise results in a clear way and allow to model effects of future scenarios.[7] Mapping the energy consumption or life cycle environmental impact of buildings results in clear visualisations can be very helpful for public administrators regarding their policy plans[11] and to improve the communication and strengthen their decisions according to their policy.

The building-by-building data in our GIS stock model are a result of the combination of the GIS data from Flanders and the GIS data from Leuven. The building datasets of Flanders include the address and geometry data while the building datasets of Leuven contain the construction year, roof type and building function(s). The combination of these data are presented in the sections 2.3 to 2.7.

2.3. Data collection
The geometric data needed for each building in the stock model is partly provided by the open data of the Flemish region, and partly by the city of Leuven (not publicly available). The datasets from Leuven and the Flemish region are GIS data. With these data the building stock can be modelled regarding the area of the ground floor, the perimeter of the building, the building height, address, the number of floors, the number of residential units, the construction year, the building function and the roof type. These data is mostly available for 96,7% to 100% of the buildings, except for the number of residential units where the data availability is only 22% and for the construction year with an availability of 60%. This means that for 13.619 buildings the construction year is lacking. In section 2.7 it is described how these lacking data are filled. The area of the walls are unknown, but based on the perimeter of the building, the roof type and the building height, estimations can be made. In future, the assumptions can be replaced by real data when these become available in the GIS datasets of the city or region, or may be filled with real building-by-building data based on measurements of specific projects.

2.4. Energy consumption at street level
With the Fluvius data regarding gas consumption per street and number of gas connections per street, the gas consumption of each building in the stock can be estimated. A first estimate of the average gas consumption per square meter floor area of the residential building stock in 2017 is calculated and presented in figure 1. This average is calculated by dividing the total gas energy consumption of a street by the total area of the buildings of that street. This calculation does not take the energy performance of the buildings into account, so these values are street averages, not building specific values. In future the

allocation per building can be improved when the insulation of the buildings is known. This first estimate however already reveals where the largest energy consumers are located and hence allows to identify the energy problematic neighbourhoods of a city.

Figure 1 Overview of the average gross gas energy consumption of the residential buildings of each street per square meter in 2017 in Leuven (kWh/(m².year))

2.5. Building typology

The GIS data obtained from Leuven do not provide information about the building type. It is hence not clear if a building is a detached building, terraced building, semi-detached building or apartment. This information is however important to calculate the surface of the building envelope and the related energy transmission losses, since the energy transfer is different for separating walls and exterior walls.

To define the building type for each of the buildings in the stock model, the following approach is used. For each GIS dataset (building), the GIS software allows to define if the building (polygon) is attached to one or more neighbouring buildings (polygons). These results are combined with the available information regarding the building function (apartments and single-family houses) and the information in the dataset regarding the fact if it is a main building or an annex building. Annex buildings (e.g. garages) have been excluded from the datasets in order to ensure that two buildings with two garages in between (figure 2) are considered as detached instead of terraced buildings.

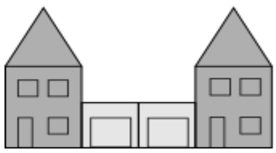

Figure 2 By excluding annex buildings (e.g. garages) from the GIS data, the main buildings (dark grey) are classified as detached houses.

The distribution of derived building types for Leuven is visualised in figure 3. By visualising buildings with similar properties, it becomes clear that the majority of the residential buildings are terraced buildings (13.521 (42,3%)), and the minority are apartment buildings (2.142 (6,7%)). The detached and semi-detached buildings are respectively 7.564 (23,7%) and 8.743 (27,3%) buildings. Further, in the visualisation it becomes clear that almost half of the terraced houses and apartment buildings are situated inside the city centre of Leuven, for the (semi)-detached houses only 20% are situated inside the city centre. So the distributions inside and outside the city centre are clearly different.

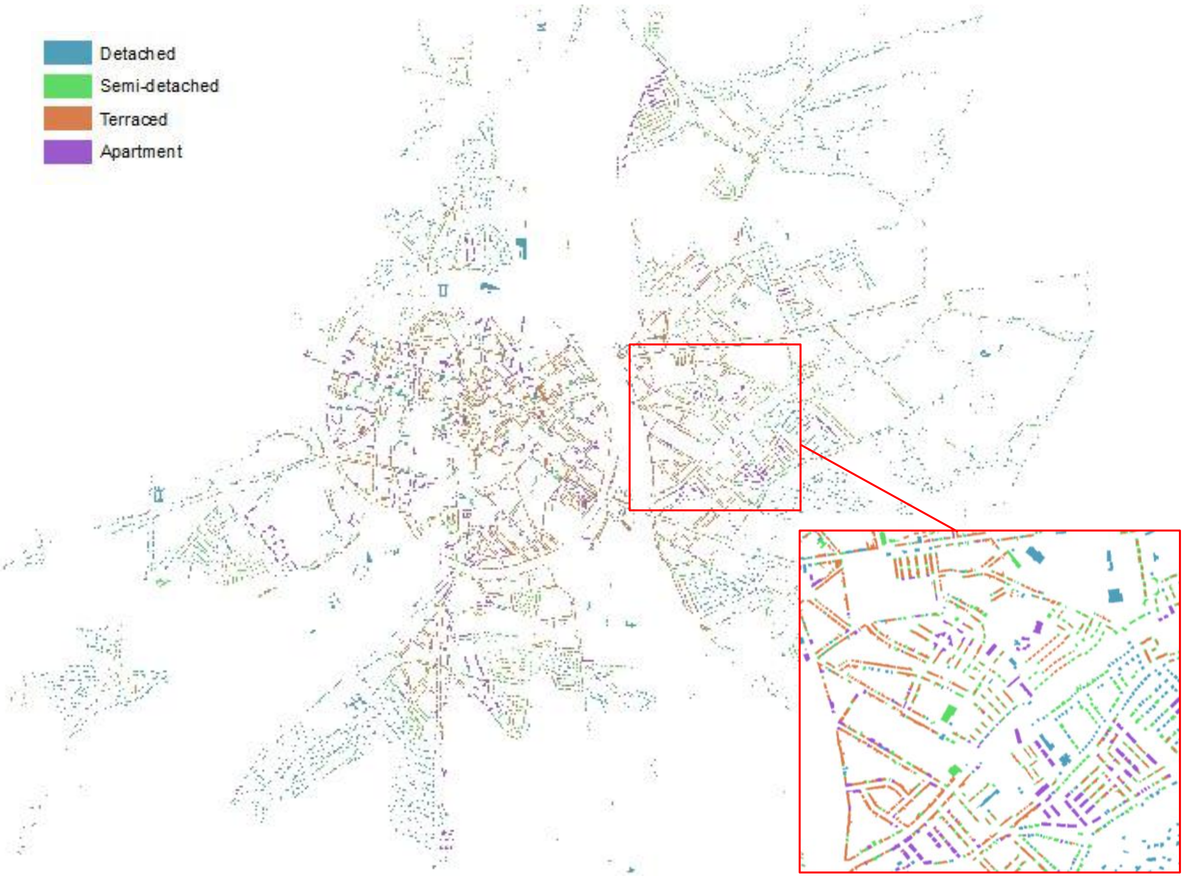

Figure 3 Overview of the building typologies of the residential buildings in the city of Leuven.

2.6. Coupling of GIS datasets from different sources

The datasets provided by Leuven and by Flanders were not compatible. The FME (Feature Manipulation Engine) software is a platform for data integration specialised in spatial data and has been used to couple both GIS datasets in our study. The following matching procedure is used (figure 4): for each polygon the coordinates of a central point are defined. In the FME software, the coordinates of the central points of both datasets are matched and the datasets are combined based on these matching coordinates.

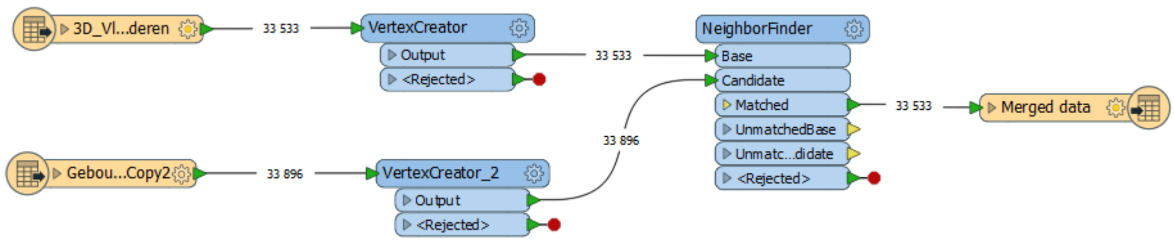

Figure 4 Matching procedure of the two datasets in FME.

2.7. Data gaps

As mentioned in section 2.3, for some buildings the roof type and/or construction year is lacking in the GIS data from of Leuven. These data had to be filled in to make a complete building stock model. The data gaps are filled in based on statistical data regarding construction years and roof types of buildings in Leuven for which these data are known.

2.7.1. Roof types Firstly, the buildings with undefined roof types are identified. Secondly, for each building type, the percentage of flat roofs and pitched roofs is calculated based on the dataset of Leuven. Thirdly, each building with an unknown roof type is assigned a roof type according to the percentages calculated. The unknown data of roof types are geospatially randomly allocated to the buildings belonging to the specific category.

Table 2 Distribution of the roof types and construction years of the detached buildings in Leuven.

detached							
<1945			% total known	% distribution of known		distribution of unknown	
flat roof	pitched roof	% flat		flat roof	pitched roof	flat roof	pitched roof
67	473	12,41%	10%	10%	10%	39	183
1946-1970			% total known	1946-1970			
flat roof	pitched roof	% flat		flat roof	pitched roof	flat roof	pitched roof
248	1720	12,60%	36,76%	37%	37%	145	667
1971-1990			% total known	1971-1990			
flat roof	pitched roof	% flat		flat roof	pitched roof	flat roof	pitched roof
214	1501	12,48%	32,03%	32%	32%	125	582
1991-2005			% total known	1991-2005			
flat roof	pitched roof	% flat		flat roof	pitched roof	flat roof	pitched roof
65	886	6,83%	17,76%	10%	19%	38	343
2006-2011			% total known	2006-2011			
flat roof	pitched roof	% flat		flat roof	pitched roof	flat roof	pitched roof
28	29	49,12%	1,06%	4%	1%	16	11
>2012			% total known	>2012			
flat roof	pitched roof	% flat		flat roof	pitched roof	flat roof	pitched roof
57	66	46,34%	2,30%	8%	1%	33	26
unknown			total known		total	396	1812
flat roof	pitched roof	% flat					
398	1812	18,01%	5354				
			total unknown				
			2210				

2.7.2. Construction years. Using a similar approach, the unknown construction years are defined. Of the 7.564 detached buildings, the construction year is unknown for 2.210 buildings (41%) (see table 2 for the detached houses). Firstly, the buildings with an unknown construction year are identified (2.210). Secondly, table 2 is set up for each of the building types, in this table all the buildings with a known construction year (5.354) are counted according to their construction year and roof type. For example, of all the 7.564 detached houses, 67 have flat roofs and are built before 1945. This means that for the period before 1945, only 12,41% of the detached houses have flat roofs. In a next step is defined how many detached houses are constructed in each construction period, for instance 10% of the detached houses is built before 1945. With these numbers, the distribution of the known construction years can be calculated according to their roof type. For example, 19% of the detached houses with pitched roofs are built in 1991-2005. When these percentages are multiplied with the number of buildings with an unknown construction year, the number of buildings for each construction period are known. So, table 2 shows that 183 buildings with an unknown construction year and a pitched roof have been assigned the construction period 'before 1945'. This allocation of construction years is done in a geospatial random way. These construction periods are in accordance with the construction period of the IEE-Tabula project: before 1945, 1946-1970, 1971-1990, 1991-2005, 2006-2011 and after 2012.[12]

3. Conclusions and future outlook

The building stock model developed in our study combines a building-by-building and an archetype approach to make a model that includes all data needed to model the energy performance, material amounts and environmental impact of the buildings, with information on their geospatial location. The geometric data of all buildings in the stock is mainly based on building-by-building data, either directly retrieved from GIS datasets from the city or the region or calculated based on other data from the GIS datasets. For the buildings where geometric information is lacking, statistical data were used to fill the data gaps. The FME software is used to couple the various GIS data sources.

Although the research focuses on the city of Leuven, the used approach to model building stocks is also applicable to other cities. The method proposed can however only be used if GIS data of (part of) a city are available. GIS data of building stocks are available for a growing number of Flemish cities and it is expected that in the near future the majority of the cities will have such GIS model.[13] In Flanders these data are combined in the GRB-tool (Grootschalig Referentie Bestand) and are publically available. The European Commission furthermore aims to create a European spatial data infrastructure with the tool INSPIRE (Infrastructure for Spatial Information in the European Community) to provide public sector data in a practical way.[14,15]

In a next step of the research, the geometry characteristics will be combined with energy performance characteristics. When the U-values of the construction elements are known, the energy losses of the buildings can be estimated, environmental benchmarks defined and renovation strategies proposed. Furthermore, this will allow to identify the main drivers of the total energy consumption of the building stock and consequently efficiently reduce the energy use of the building stock. The collection of the U-values is less obvious because of privacy issues. These data are not available for the various buildings in the stock and hence a building-by-building approach is not possible. The archetype approach will be used differentiating in U-value for the various elements of the building envelope per construction period, roof type and building type. Based on the statistical distribution of the building types and construction periods of each building in the stock, the representative values of the archetypes can be linked to the buildings in the stock. And based on these proposed U-values, the energy consumption can be calculated at the level of a building or for the whole building stock. Further investigation is needed on how renovations in the past can be included in the model. Potentially, the gas consumption at street level and at municipality level might be used to validate the estimated U-values and to correct these based on statistical data on renovation measures have already been done in the past. For the U-values of representative buildings, the IEE-Tabula project might be helpful. In the Tabula project, U-values are defined for different construction periods and building types.[12] Combining the U-values and the corresponding energy consumption with the geometric building stock model, will result in a complete building stock model including spatial data (SBSM – Spatial Building Stock Modelling)[16] where hotspots and improvement potentials can be defined for each neighbourhood of the model.[7]

The building stock model that is under development will allow to identify how future renovation measures will allow to reduce the energy consumption of the stock and its implications regarding the life cycle environmental impact of each building in the stock as well as for the stock as a whole. As the geometry of the building stock and the construction period of the buildings are collected, an inventory of the materials in the building stock can also be made and consequently the environmental impact of the stock can be assessed. In Europe, life cycle assessment (LCA) is more and more integrated in building practice to reduce the environmental impact of buildings.[17,18] As LCA is mostly used in comparative studies, benchmarks should be defined so that targets can be set to support policy making and tracking of the achievement of policy goals. In order to allow for defining such environmental benchmarks for existing buildings and their renovation, this paper presents how an inventory of the current building stock can be made that will allow to gain insight in their environmental impact.

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Life-Cycle Assessment as a decision-support tool for early phases of urban planning: evaluating applicability through a comparative approach

Slavkovic K[1], **Nault E**[1], **Jusselme T**[1], **Andersen M**[1, 2]

[1]Building 2050 Research Group, Ecole polytechnique fédérale de Lausanne (EPFL), Fribourg, Switzerland
[2]Laboratory of Integrated Performance In Design (LIPID), Ecole polytechnique fédérale de Lausanne (EPFL), Lausanne, Switzerland

katarina.slavkovic@epfl.ch

Abstract. While ambitious environmental objectives are being set for new constructions in Switzerland, the assessment of urban-scale projects and comparison of their performance to national targets are made possible by a growing number of life-cycle assessment (LCA) tools. However, previous research emphasizes the lack of existing tools to support the decision-making process at the early design stage, characterized by a low level of project details. This paper presents a comparison between three LCA tools. The first, stemming from a research and development project (SETUP), is an exploration tool relying on a database of urban-level scenarios and their environmental performance, able to convert district targets (e.g. 2000-Watt society objectives) into specific sub-targets at the building or component levels. The other two are online LCA tools currently available to practitioners (Sméo and Calculation tool for 2000-Watt-society-sites RH II), that allow assessing the project and verifying its compliance with a given target. Each tool was applied to a low-carbon case study, the blueFactory district in Fribourg (Switzerland), in two hypothetical contexts corresponding to the schematic and detailed project development phases, characterized by different levels of details. When used for the assessment of a project at a more advanced development stage with a high resolution of detail, findings indicate that Smeo and RH II provide similar environmental performance results. However, in early planning stages, SETUP shows better abilities to support decision-making by providing ranges of results and highlighting uncertainties and the influence of design parameters that have not yet been fixed.

1. Introduction

On the global level, the building sector has a major impact on the environment, being responsible for approximately 32% of final energy consumption and 19% of related CO2 emissions [1]. In the context of climate change mitigation reinforced by the Paris Agreement [2], countries have been developing, implementing and strengthening national plans and targets for decreasing the environmental impact of the built environment. Switzerland introduced the 2000-Watt Society vision, that sets the pathway to limiting the total primary energy use to 2000 Watts per person and greenhouse gas emissions to 1 ton per person by the year 2100 [3], with intermediate goals for the year 2050 [4]. Accordingly, the Swiss

Society of Engineers and Architects (SIA) defined targets for the building sector, with non-renewable cumulative energy demand (CEDnr) and global warming potential (GWP) as the main assessment metrics [4].

Life-cycle assessment (LCA) is a well-recognized method for estimation of the environmental impacts from the product phases, over the construction process and use, and up to the end-of-life [5]. Even though LCA is widely used for benchmarking the finalized construction project to environmental targets, its application is essential for guiding the practitioners during the design process at early planning stages. As notably stated by the SIA, "*important decisions for the achievement of the target values are made in the early planning phases (strategic planning, preliminary studies and preliminary project)"* [4]. Moreover, the application of LCA is extending beyond the scale of individual buildings (building labels such as Minergie-ECO [6] or new concepts such as Life Cycle-Zero Energy Building LC-ZEB [7]), to considerations at larger scales such as neighborhoods and cities [1,8–10].

LCA-based tools for urban level projects need to fulfill numerous requirements [11], and their application at early design stages faces several challenges [12]. Tools are needed for exploration of interrelations between specific design choices and their influence on the project performance as early as the beginning of the project, in the context of high uncertainty, lack of information and low resolution of project details. The objective of this study is to assess the ability of LCA tools to support the decision-making process for urban–level projects, and to better understand the type of results they are able to provide.

Testing LCA tools is hardly possible by referring to empirical evidence from the real life context (e.g. analysis of energy bills within Building Energy Simulation Test (BESTEST) [13]), due to the system, spatial and temporal boundaries for life-cycle impact assessment of urban-level constructions. Therefore, the study compares LCA-based tools that are currently available to practitioners in Switzerland.

2. LCA-based tools

Three LCA-based urban-level tools developed for the Swiss built environment context are identified: SETUP, which stands for Specific Environmentally-conscious Targets for Urban Planning, Smeo Red thread for sustainable construction (Fr. Sméo Fil rouge pour la construction durable) [14], and Tool for 2000-Watt-Society-sites (Ger. Rechenhilfe II für 2000-Watt-Areale, RH II) [15]. The comparisons are possible because the environmental evaluation relies on national databases of life-cycle impact values and SIA standards and norms. The three tools are characterized and compared according to eight categories identified by Bach and Hildebrand [16]. Most important features of the tools are presented in Table 1.

The main purpose of SETUP is to decompose environmental targets from district- to building-, domain- (construction, operation, mobility) and component (e.g., windows) levels, and to facilitate exploration of databases of project alternatives and relating environmental impacts of individual plots within the district at early-planning phases [17]. A proof-of-concept was developed for the blueFactory district in Fribourg, which aims to be low carbon (Figure 1). Project alternatives for each plot were created by varying 17 building parameters (e.g. building shape, depth, height etc.), and assessing operational, embodied impacts and building-induced mobility. The database thus generated includes a large number of project alternatives, sampled through the Sobol low discrepancy method (for more information see: [17]). An Excel-based VBA prototype tool allows exploring these pre-simulated databases. Input-data comprises values for construction areas per plot and building use, and the selection of a reference target for the whole site (from a certification system or building label). Outputs include: decomposed site-level performance targets (CEDtot, CEDnr and GWP) into differentiated sub-targets per plot, building program, domain and component, frequency (number of occurrences) of scenarios that are meeting different target values, influence of variable parameters (geometry, components, technical installations, etc.), and graphical presentation of (un)favorable options through a decision tree.

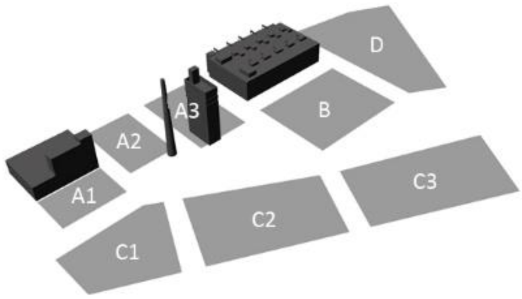


Figure 1. Existing buildings and plots on the blueFactory site, as defined for the SETUP tool.

Smeo assesses the sustainability of a project by addressing its environmental, economic and social domains and applying the Hermione method, which aggregates a number of quantitative and qualitative criteria [18]. Through a preliminary section of the internet platform, the project is characterized by selecting its scale (building or site), main program (residential, administration, etc.), type (new constructions, renovations, use, and transformation), phase (initiation, masterplan, district plan, realization, and use) and stakeholder. Accordingly, the suitable interface with input fields opens in the first out of several tool sections. For the purposes of this study, i.e. district-level new construction project at early and advanced planning phases, the interface offers three main sections. The General Data section is the same for both phases and it comprises input fields regarding urban-level parameters, embodied, operational impacts, mobility, etc. Beside dropdown lists with predefined data, required inputs often include aggregated parameter values, for all buildings within the studied district (e.g. floor space index, land use index, total footprint of assessed buildings, etc.), as well as adaptable default values. After entering the number of buildings within the district, the tool hypothesizes that all buildings have identical characteristics, thus not allowing the comparison of building alternatives and related impacts. The Detailed Results section is identically structured for both studied planning phases, and provides site-level results of the qualitative social and economic sustainability criteria, and the quantitative evaluation of environmental impacts (CEDnr, GWP and ecological scarcity points UBP for the entire site and per domain, illustrated in charts).

The main purpose of the third tool, RH II, is benchmarking the site-level project to 2000-Watt-Society targets. The data input begins with specifying the main project features, e.g. project type (new constructions, renovations, buildings in use), reference year for norms and targeted impacts (2030, 2050), project phase (according to SIA 112) and other data which determines the format of the user interface, requested input, software workflow, etc. Data is entered separately for each building. For the preliminary study phase, input is simple and intuitive with a lot of adaptable default values and dropdown lists, which requires only general knowledge from the user. In contrast, the module for the project execution phase requires more detailed input of numerical values for embodied and operational impacts, transferred from independent software, which might require expert skills. In this case, boundaries of LCA depend on the external software. The type of data outputs for both project phases is identical: on site and building scales, numeric values per impact category (CED, CEDnr and GWP) per domain and in total, with corresponding graphs for the site level indicating compliance or not with the 2000-Watt-Society targets.

Table 1. Comparison of three LCA-based tools according to [16].

	SETUP (prototype)	**Smeo**	**RH II**
Origin	EPFL Fribourg, Switzerland, 2019	City of Lausanne and Canton of Vaud, Switzerland (www.smeo.ch), 2009	Federal office of Energy OFEN, Zurich, Switzerland (www.local-energy.swiss), 2018

Data source	CEN EN 15978, KBOB 2009/1:2016, SIA 380/1:2016, etc.	SIA 112, KBOB 2009/1:2012, SIA 380/1:2009, etc.	SIA 112, KBOB 2009/1:2014, etc.
Required user's knowledge	No prior knowledge	Basic knowledge	Expert knowledge
Accessibility	Conditional access (project stakeholders)	Free access (registration needed)	Free access (registration needed)
Entry format	Spreadsheet	Input fields and dropdown lists	Input fields and dropdown lists
Level (scale)	District-, plot- and component-levels	District-level	District- and building-levels
Default settings	Default settings	Default settings partly available	Default settings partly available
Life cycle phases	According to CEN EN 15978: Product (A1-3), Use (B6), End-of-life (C1-4)	According to SIA 112 project phase; project planning construction and use phases	According to SIA 112 project phase, but also dependant of system boundaries of external software

3. Comparability of the tools

In order to better understand differences among workflows and discrepancies between impact assessment results, the tools are applied to the urban-level project in the advanced stage, characterized by a high resolution of project detail. The comparison is focused on embodied and operational impacts, without considerations of building-induced mobility, because these impacts do not influence the design process. The case study is the hypothetical project illustrated in Figure 2 for the blueFactory site introduced earlier.

Impact assessment of the blueFactory site focuses on ten administrative buildings, three of which also have residential use (plots C1 and C2, see Figure 1), with total area of approx. 126 000 m^2. Buildings have rectangular floorplans and north-south orientation of the longer facades. Buildings' depth is 18-30m and height 3-15 floors. Window-to-wall ratio on all facades is 0.65 for the office buildings and 0.5 for the apartment buildings. Triple glazed windows (U-value: 0.5 W/m^2K) have wooden frames (U-value: 1.3 W/m^2K), and the thermal transmittance of external walls and roof is of 0.1 W/m^2K. Construction of roof, interior floors and external walls are defined according to the Swiss construction catalogue (concrete slab [E0 B01] and wall [W W04]) [19]. Thermal insulation is polystyrene, covering slab material linoleum and covering material of external walls is cement panels. 90% of the total roof surface is covered with PV systems. The HVAC system is a heat pump, with coefficient of performance COP=2.43.

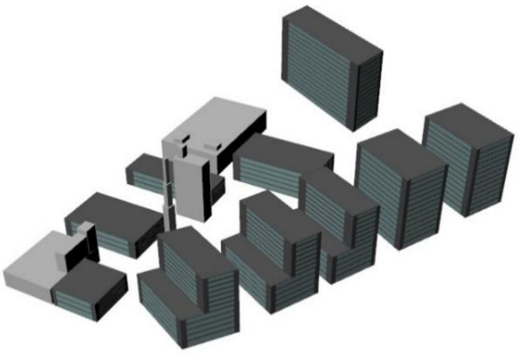
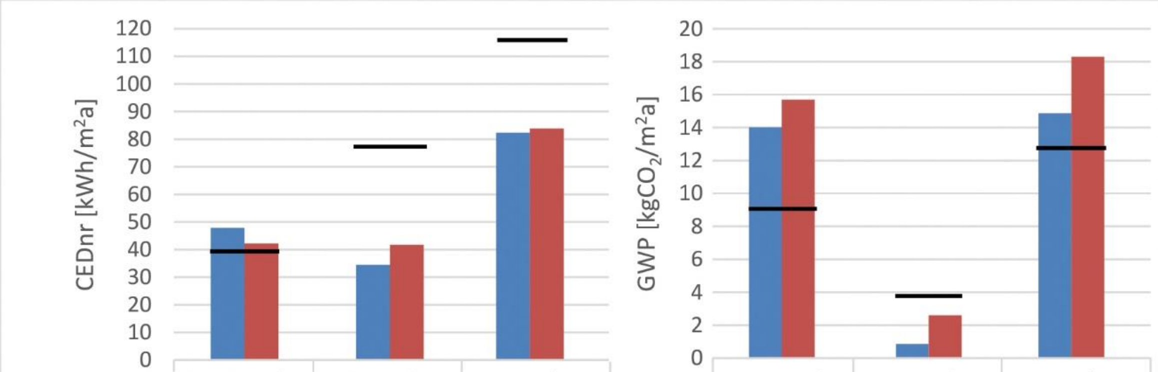


Figure 2. Urban massing volumes of the hypothetical project (blueFactory site case study) in the advanced planning phase.

The assessment of the environmental impacts of the hypothetical project in its advanced planning stage is performed in SETUP and Smeo, and the results are shown in Figure 3. RH II is excluded from this first experiment, as it requires inputs deriving from external simulation software.



	CEDnr Construction	CEDnr Operation	CEDnr Total	GWP Construction	GWP Operation	GWP Total
SETUP	47.84	34.50	82.34	14.01	0.86	14.87
Smeo	42.22	41.67	83.89	15.70	2.60	18.30
Impact target	38.69	77.37	116.06	9.00	3.74	12.74

Figure 3. Results in terms of CEDnr (left) and GWP (right) impacts computed with SETUP and Smeo, compared to environmental targets defined by SIA [4].

The construction CEDnr impacts computed with Smeo is 5.6 kWh/m^{2}a lower than the value obtained with SETUP, which corresponds to a relative change of 11.7% (compared to SETUP). In terms of GWP impacts, the Smeo result is higher by 1.7 kgCO_2/m^{2}a, which is equivalent to a relative change of 12% compared to the SETUP result. Discrepancy of embodied impacts of construction might be explained by the mismatch between component options offered in Smeo (e.g. external walls, floor slabs, roof, etc.) and those set for the case study, which were based on options available in SETUP. Therefore, the selection in Smeo was done to match the desired components as close as possible, in terms of types and thermal properties of materials.

Compared to SETUP, absolute increase of CEDnr operational impacts computed with Smeo is 7.2 kWh/m^{2}a, which is in terms of relative change 20.8%. Considering GWP impacts, the 1.74 kgCO_2/m^{2}a difference represents as much as a 202% increase from the Smeo to the SETUP result. This gap might be explained by different energy conversion coefficients derived from distinct versions of KBOB databases (data sources, see Figure 1), and different boundaries for the impact assessment of the electricity produced by the PV systems. Indeed, Smeo does not take into account positive impacts of electricity exported to the grid, in comparison to SETUP where the calculation is based on [20], which states that this positive impact should be accounted for.

Environmental impact assessment of the project in its advanced phase is possible, despite methodological differences and heterogeneous inputs and outputs between SETUP and Smeo. It should also be noted that impact results in SETUP are obtained by identifying a specific project alternative from the database of pre-simulated projects (see: [17]). However, due to the extent of the database (limited sample size), it is not always possible to identify the desired project alternative, because this particular scenario might not exist in the database.

4. Application of tools in early planning phase

At the beginning of the planning process, urbanists need to make decisions regarding the design parameters on building scales, and understand the implications of their design choices on the environmental performance of the site in later phases of its life cycle. The ability of the LCA tools SETUP, Smeo and RH II to facilitate the decision-making process is tested by answering a design question, formulated according the findings of a survey on the current use of LCA tools in building design [21]. More than 80% of survey respondents (out of 263 practitioners) are considering building shape and orientation as design parameters during the early project phase. Accordingly, our design question is: “Which design choices relating to building shape and orientation would increase the feasibility of the construction project and contribute to meeting environmental targets?” Tested variable parameters include bar-shaped buildings with north-south orientation of longer facades (I N-S), same shape with east-west orientation of longer façades (I E-W), “L” shape (L), “U” shape (U) and atrium shape (O).

To be able to answer the design question, the assessment in Smeo and RH II must be performed through an iterative process, in which only the tested parameter is changed while all other parameters are kept constant. Therefore, the hypothetical project for the blueFactory site in its early planning phase is defined by a set of assumptions. Impact assessment of the site level project comprises administrative buildings, with varying area according to the building shape. Other hypotheses correspond to those set for the project in the advanced design stage, excluding the PV systems, as the calculation of operational impacts between SETUP and Smeo significantly differs (see Section 3). Relating parameters are adapted according to the input format of each tool (e.g. Smeo requires inputs such as floor space index, length of buildings perimeters, etc., while RH II needs data regarding each building such as building footprint and thermal envelope factor). On the other hand, SETUP relies on the database of project alternatives (Section 2) and requires input of building program and area for each plot, which is in total 104 000 m^2.

5. Answer to the design question

The illustration of the impacts of masterplan alternatives with equally shaped buildings (Figure 4), shows an incoherence between selecting a building shape according to the mean and median (SETUP) and minimum (RH II and Smeo) impacts. Indeed, the shape with the lowest GWP differs according to the tool: it is I E-W for RH II, and I N-S for Smeo and SETUP (although there is an overlap with other distributions such as I E-W). A more detailed illustration of impacts related to project alternatives on individual plots (Figure 5) indicates more consistency among the three tools. Mean and median (SETUP) and minimum impact results (RH II and Smeo), presented in Table 2, indicate that the bar shape is most favorable for accomplishing compliance with the impact target. However, there is a mismatch in terms of selecting the building orientation (except on plots A2 and D).

Mean and median impacts are calculated in SETUP based on a high number of project alternatives, which are taking into consideration effects of the variation of other not yet defined design choices, and thus capturing the uncertainty aspect in early design. In contrast, the impacts computed with traditional tools derive from more definite range of results obtained from a manual iterative process in which only one parameter is varied. Therefore, higher reliability of making a decision on most favorable building shape and orientation according to SETUP results is argued by the representativeness of a distribution range of results.

SETUP indicates increase in feasibility indices from I N-S shape (FI = 8.1%) to O shape (FI = 10.1%) on the site level, and from plot A1 (FI = 4%) to plot D (FI = 64%) on the plot level (see Table 2). The compliant part of the distribution range of results includes variability of uncertain design parameters, and thus indicates a high number of feasible project alternatives. On the other hand, RH II results demonstrate that none of the considered project alternatives is feasible, while Smeo assumes uniformity between the buildings and demonstrates compliance in one project alternative with I N-S shape.

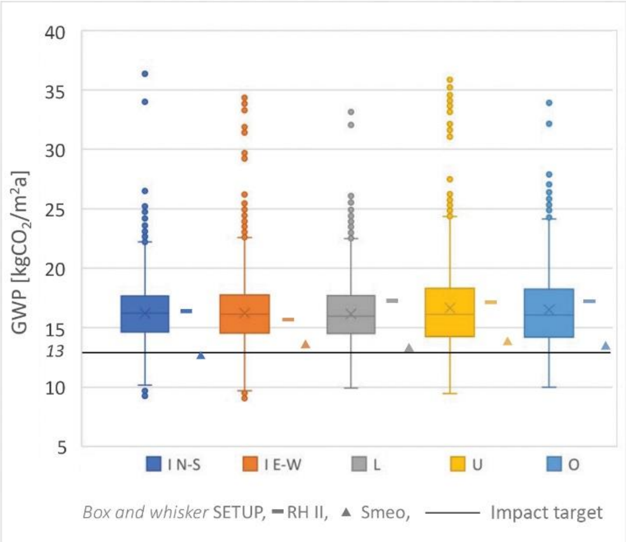


Figure 4. Site-level GWP impacts of master plan alternatives composed of buildings with uniform shape, compared to environmental targets defined by SIA [4].

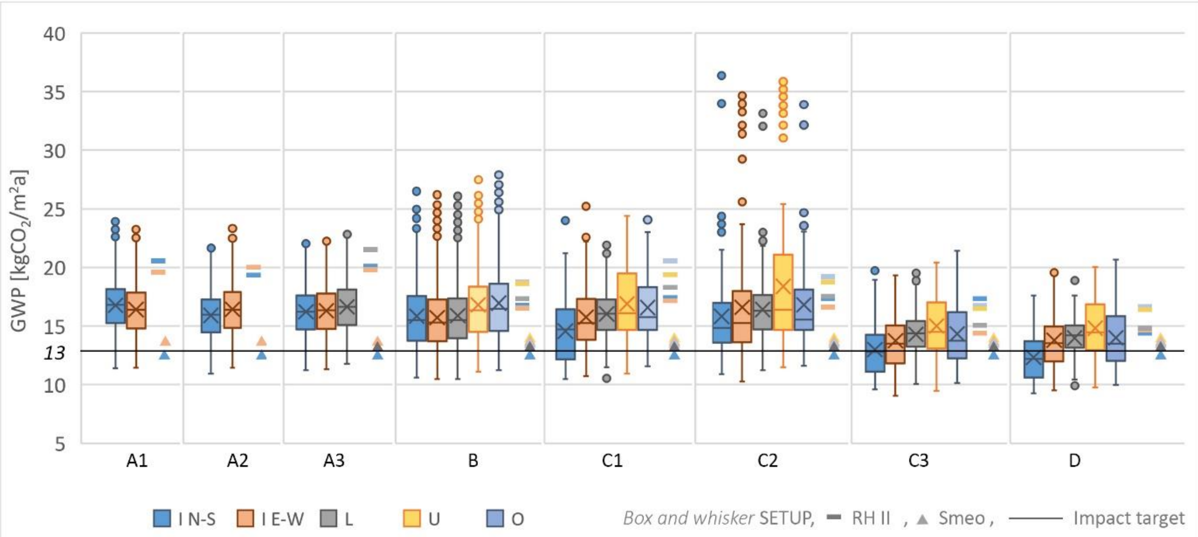


Figure 5. Plot-level GWP impacts of project alternatives with variable shapes.

Table 2. Building shapes and orientations, GWP impacts and feasibility indices for individual plots.

		A1	A2	A3	B	C1	C2	C3	D
Setup	Shape and orientation	I E-W	I N-S	I N-S	I E-W	I N-S	I N-S	I N-S	I N-S
	Mean GWP [$kgCO_2/m^2a$]	16.44	15.99	16.21	15.90	14.71	15.85	13.24	12.64
	Median GWP [$kgCO_2/m^2a$]	16.41	15.98	16.23	15.31	14.71	14.88	12.82	12.18
	Feasibility index [%]	3.95	8.11	5.46	18.49	36.65	20.37	54.32	64.20
RH II	Building shape	I E-W	I N-S	I E-W	I E-W	I E-W	I E-W	I E-W	I N-S
	Lowest GWP [$kgCO_2/m^2a$]	19.80	19.30	19.80	16.70	17.30	16.70	14.50	14.50
Smeo	Building shape	I N-S	I N-S	I N-S	I N-S	I N-S	I N-S	I N-S	I N-S
	Lowest GWP [$kgCO_2/m^2a$]	12.70	12.70	12.70	12.70	12.70	12.70	12.70	12.70

6. Discussion. Decision-support and ability to lead the design process

Difference between lowest (L) and highest (I N-S) median GWP values is 0.26 $kgCO2/m^2a$, and between lowest (L) and highest (U) mean GWP values is 0.5 $kgCO2/m^2a$. As SETUP results are more representative, they can be used for demonstrating the low sensitivity of building shape to GWP impacts, which can direct the attention of practitioners to another parameter in following steps of design process.

Increase in feasibility indices from simple bar shape to more complex atrium shape relating to the site level, and from smaller plot A1 to larger plot D, relating to the plot level, can be explained by embodied impacts normalized by m^2 which are disproportionate to size and complexity of constructible volumes. For instance, smaller plot A1 cannot facilitate construction of L, U and O shaped, but only bar buildings with maximum 5 floors, while larger plot D is suitable for all building shapes, with maximum height of 18 floors. SETUP reveals a wider approach to assessing the project compliance by exploring a series of project alternatives that are incorporating unknown design parameters. This uncertainty is opening the possibility for exploration of scenarios and identification of design parameter values that all feasible scenarios have in common.

Ranking of impacts calculated with traditional tools is matching the ranking of mean and median values within distribution range, however they do not fall into the interquartile range, for most of the alternatives. Limited insight to slightly differentiated or totally uncompliant project alternatives, might direct the design process to incorrectly defined assumptions regarding yet unknown parameters, and also point to the differences among contextual characteristics of plots (e.g. shading effects across the site).

Graphical representation of impact results with box and whisker plots illustrates a probabilistic approach in early design and reveals the richness of considering uncertainty. Compared to the limited number of results computed with traditional tools according to one variable parameter, mean and median, maximum and minimum impacts and interquartile range are integrating the effects of the design choices that have to be made in the following steps of the design process. Outliers theoretically represent false results that should be removed from the database. If we however assume that outliers here correspond to scenarios that are valid and not erroneous, this emphasizes that we might be misled by the initial assumptions about the project.

7. Conclusion. Importance of uncertainty in decision-support

LCA at early planning stages exposes several challenges. It is difficult for urbanists to fully anticipate the links between their design decisions and the later project performance when the resolution of project detail is low and the scale extends beyond a single building. In order to perform life cycle assessment, they need to define a high number of hypotheses regarding the unknown parameters. Even with project assumptions, it is not yet possible to demonstrate the robustness of impact results on life cycle scale, as the reference for validation of LCA method is missing (e.g. BESTTEST). Therefore, three methods developed to provide decision support in early stages (among other purposes) are tested in this study.

Traditional LCA-based tools used in Switzerland are applicable for the impact assessment of the urban-level project at advanced stages of design, with the main purpose to benchmark the project against environmental targets. In early design stages, testing the comparativeness of outputs reveals the value of distribution range of results and the importance of integrating the uncertainty aspect. Since we are unable to confirm that LCA results are absolutely correct, it is still challenging at this point to compare the project with the target. SETUP provides a broader view on project compliance with ranges of results representative of many design choices. The risk of making incorrect conclusions is decreased, as we are able to explore common design choices within feasible project alternatives. Wide space for exploration of the project is available precisely due to the presence of uncertainty linked to the project. In contrast, results from traditional tools are straightforward, as they derive from an iterative process that mainly focuses on the adaptation of input parameters in relation to the outputs (one-step at the time method which defines only several points in the planning process). Results may vary from totally compliant to totally uncompliant, therefore it might be premature to take decisions based on LCA at early design stages. Without the uncertainty aspect, traditional tools might be referred to as compliance or confirmation tools, rather than decision-support tools.

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Critical analysis of environmental benchmarks for buildings

Trigaux D[1,2,3], Allacker K[2], Debacker W[1,3]

[1] EnergyVille, Thor Park 8310, 3600 Genk, Belgium
[2] KU Leuven, Department of Architecture, Kasteelpark Arenberg 1/2431, 3001 Leuven, Belgium
[3] VITO, Unit Smart Energy & Built Environment, Boeretang 200, 2400 Mol, Belgium

damien.trigaux@kuleuven.be

Abstract. To reduce the environmental impact of the building sector, environmental targets should be defined considering the full life cycle of buildings. In recent years various benchmarks based on Life Cycle Assessment (LCA) have been developed as part of regulations, labelling systems and sustainability rating tools. This paper presents the results of a critical analysis of six existing benchmarking systems. An overview is given of the different benchmark approaches, scope, applications and communication. The strengths and weaknesses of the various systems are highlighted. Based on the analysis, recommendations are formulated for the development of future LCA benchmarks for the building sector.

1. Introduction

The building sector has a major impact on the environment. In Europe, this sector is responsible for about 50% of the use of natural resources, 40% of the energy use and 16% of the water use [1]. Buildings are furthermore responsible for 36% of the total CO2 emissions in the EU [2].

As recommended by the European standard EN 15978 [3], Life Cycle Assessment (LCA) is an appropriate method to assess and optimize the environmental impacts of buildings over their entire life cycle. In Belgium, where this research was conducted, several steps have been taken to mainstream the use of LCA in building practice, including the development of a national LCA method, a database of Environmental Product Declarations (EPDs) and a web-based calculation tool for architects [4].

In a next step, reference values or benchmarks should be defined to support policy makers in the definition of environmental targets for buildings. These LCA benchmarks would allow architects and building stakeholders to position themselves in the market and consequently to further push the construction sector in reducing its environmental impacts.

In contrast to energy performance benchmarks which are well established in building practice, the development and implementation of LCA benchmarks is still in its early stages [5]. Since 2018, the life cycle environmental impact of new buildings in the Netherlands is restricted to a maximum value per m² floor area per year [6] and classes of environmental performance of residential buildings have been defined [7]. LCA benchmarks are furthermore used in a number of labelling systems such as the French initiative "E+/C-" [8, 9] and integrated in sustainability rating tools such as BREEAM [10].

The aim of this paper is to critically analyse existing benchmarking systems, focusing mainly on methodological aspects but also on their applications and how these are communicated. The strengths and the weaknesses of the various approaches and methods are highlighted. Based on this analysis, recommendations are formulated for the development of future LCA benchmarks.

2. Evaluation aspects

In order to critically analyse benchmarking systems and identify the main approaches and methods, a list of evaluation aspects is defined based on existing methodological reports and literature reviews on LCA benchmarks [11–13]. Four main aspects, including various sub-aspects are investigated:

- Definition of benchmark values: comparative base, benchmark approach, benchmark typology and sources for benchmark;
- Benchmark scope: life cycle stages and environmental indicators covered;
- Benchmark applications: building types, new construction and/or refurbishment projects;
- Benchmark communication.

3. Selected benchmarking systems

Six representative benchmarking systems are selected for a critical analysis. These include benchmarks from regulations, labelling systems and sustainability ratings tools. As regulatory tool, the legal requirements on the environmental performance of buildings in the Netherlands ("MilieuPrestatie Gebouwen" (MPG)) are evaluated [6, 7]. Two labelling systems are selected: the French initiative "E+/C-" [8, 9] and the Swiss SIA Energy Efficiency Path (SIA 2040) [14, 15]. Finally, LCA benchmarks implemented as part of three well-known sustainability rating tools are analysed: BREEAM Home Quality Mark (version 2018) [10], DGNB for new buildings (version 2018) [16] and LEED for Building Design and Construction (version 2019) [17].

The selection is based on existing review studies [11, 12] and aims at providing a wide overview of possible approaches and methods. It does not reflect any a priori preference between the benchmarking systems. Next to the implementation of benchmarks in regulations, labels and rating tools, various research studies focus on defining environmental benchmarks for buildings [18–26]. These studies are excluded from the critical review as benchmarks implemented in building practice were focused on.

4. Evaluation of the selected benchmarks

In this section the results of the critical analysis are presented, subdivided according to the four main aspects defined in section 2. For each aspect, the strengths and weaknesses of the different approaches are described and recommendations are formulated.

4.1. Definition of benchmark values

An overview of the approaches followed to define benchmark values is given in Table 1. Concerning the applied comparative base, the benchmarking systems can be classified in two groups: external and internal benchmarks [11]. External benchmarks are representative values for the environmental impact of a category of buildings within the building stock and serve as comparative base for buildings from that category. In case of internal benchmarks, an internal comparison is done based on a baseline building with geometrical and context features similar to the project. The majority of the analysed benchmarking systems are external benchmarks; only LEED falls into the second group.

Compared to internal benchmarks, two main advantages of external benchmarks are identified [12]. First, external benchmarks allow for a comparison between the environmental performance of the project and the building stock and hence a positioning within the market. Second, the impact of the full design in terms of building geometry, material choices and energy performance can be assessed while internal benchmarks are limited to the influence of material choices. Therefore internal benchmarks should only be preferred when there is a lack of data to model the impact of the building stock and derive representative external benchmark values.

In order to define external benchmark values, two approaches can be followed which are closely related to the data sources [13]. The first and most widespread one is a bottom-up approach consisting of values derived from a statistical analysis of the building stock. This can be done by analyzing a set of representative real buildings, as in E+/C- and DGNB, or by defining virtual (generic) buildings or archetypes, as in MPG. The second is a top-down approach which defines benchmarks based on global environmental goals or policy targets translated to the building sector. This approach is used in a number of research studies [18, 19], which are not analysed in this critical analysis. More rarely, a combined top-down and bottom-up approach is followed, such as in SIA 2040.

Both the bottom-up and top-down approaches have their strengths and weaknesses. The main strength of the bottom-up approach lies in the derivation of feasible benchmark values based on currently available construction methods and technologies. This approach however requires sufficient data to define representative reference buildings and market variations. The main advantage of the top-down approach is that it allows to derive long term target values to fulfill environmental goals and policy targets. The main drawback is that it implies the availability of global targets for the assessed impact indicators and an appropriate procedure to allocate part of these overall goals to the building sector. As both approaches provide complementary insights, a combined top-down and bottom-up approach is seen as the best way forward. Such hybrid approach allows to define long term target values (top-down) and to investigate their practical feasibility based on a statistical analysis of the building stock (bottom-up).

Table 1. Definition of benchmark values

	Comparative base	Benchmark approach	Benchmark typology	Sources for benchmark
MPG	External	Bottom-up	Limit value	Statistical analysis of 5 virtual residential buildings and 1200 virtual variations (dimensions, material and technical choices)
E+/C-	External	Bottom-up	- Reference value (Carbon level 1) - Best practice value (Carbon level 2)	Statistical analysis of 115 real buildings including various functions, climatic zones, construction types and energy performances
SIA 2040	External	Top-down and bottom-up	- Target value (whole life cycle) - Reference values (embodied impacts, energy use and user transport)	- 2000W Society goals for 2050 (top-down) - Scenario analysis (bottom-up)
BREEAM	External	Bottom-up	Benchmark scale for score allocation	Statistical analysis of a sample of buildings
DGNB	External	Bottom-up	- Limit value - Reference value - 2 target values (standard and over fulfilment)	- Statistical analysis of real buildings [27] - Results of DGNB certifications - Long-term DGNB objectives
LEED	Internal	Not applicable	Not applicable	Comparison with baseline building (building with comparable size, function, orientation and energy performance)

Concerning the benchmark typology, the majority of the analysed benchmarking systems combines different types of benchmark values. In general, these values can be classified in four types [13]:

- limit value: lowest value of an assessment scale (minimum acceptable performance);
- reference value: present state of the art (average or median value);
- best practice value: value reached in experimental or demonstration projects;
- target value: upper value of the assessment scale (highest theoretically possible level).

Limit and reference values can be characterized as short term values. Their strengths are to exclude buildings with high environmental impacts while addressing all stakeholders (level-playing field). However, it is expected that these values will not lead to major environmental improvement and will therefore require a regular update towards more severe benchmarks [12]. On the other hand, best practice and target values are characterized as medium- or long term values. These values allow to steer towards an improved environmental performance and policy target. Their main drawback is that they might not be feasible for all buildings due to a lack of knowledge or technology [12]. The use of a combination of at least two benchmark values to cover both short and long term objectives is therefore recommended. In addition, a stepwise implementation approach should be defined to gradually evolve from the current-state reference values towards more ambitious values in future.

4.2. Benchmark scope

The life cycle stages and environmental impacts covered by the six benchmarking systems being studied are described in Table 2.

Table 2. Benchmark scope

	Life cycle stages	Environmental indicators
MPG	Embodied impacts	Aggregated indicator expressed in environmental cost - based on 11 impact categories: global warming, ozone depletion, photochemical ozone formation, acidification, eutrophication, resource depletion (fossil and non-fossil), human toxicity, ecotoxicity (fresh water, marine and terrestrial)
E+/C-	- Whole life cycle - Embodied impacts	Global Warming
SIA 2040	- Whole life cycle including user transport (target value) - Whole life cycle excluding user transport (additional requirement) - Indicative values for embodied impacts, energy use and user transport (reference values)	Global warming and primary energy non renewable
BREEAM	Embodied impacts	Aggregated indicator expressed in Ecopoints - based on 11 indicators: global warming, ozone depletion, photochemical ozone formation, acidification, eutrophication, resource depletion (fossil and non-fossil), net use of fresh water, hazardous waste disposed, non-hazardous waste disposed, radioactive waste disposed
DGNB	- Whole life cycle - Indicative values for embodied impacts and energy use	- 5 impact indicators: global warming, ozone depletion, photochemical ozone formation, acidification, eutrophication - 3 LCI indicators: primary energy non-renewable and total, proportion of renewable primary energy
LEED	Whole life cycle	At least three of the following impact indicators: global warming, ozone depletion, photochemical ozone formation, acidification, eutrophication and depletion of non-renewable energy resources

When considering the life cycle stages (Figure 1 – left), the scope can be either limited to embodied impacts such as in MPG and BREEAM or cover the whole building life cycle (i.e. embodied and operational impacts), such as in E+/C-, SIA 2040, DGNB and LEED. Whole life cycle benchmarks are often combined with sub-benchmarks or indicative values for embodied impacts and energy use.

While embodied impacts benchmarks only focus on the impact of material use, whole life cycle benchmarks allow for a global optimization of the environmental performance considering the trade-offs between embodied and operational impacts. For example, the improvement of the building insulation level results in an increase of embodied impacts from insulation materials and a decrease of operational impacts for energy use. Whole life cycle benchmarks furthermore give more flexibility to architects to decide how to optimize their building design. We therefore recommend to define whole life cycle benchmarks. These benchmarks could be combined with indicative values for embodied and operational impact (e.g. energy use, water use) to guide designers towards lower environmental impacts throughout the various life cycle stages.

Concerning the environmental indicators (Figure 1 – right), the benchmarking systems can either define benchmark values per individual indicator, such as in E+/C-, SIA 2040, DGNB and LEED or rely on an aggregated indicator calculated based on a set of individual indicators, such as in MPG and BREEAM.

Compared to individual indicators, an aggregated indicator is easier to understand and communicate to a non-scientific audience. A huge set of individual indicators such as in DGNB can be difficult to handle. On the other hand, benchmarks per individual indicator allow to focus on specific issues which require urgent action such as for example global warming. If the LCA method includes the calculation of an aggregated score expressed in environmental costs (as is for example the case for the Belgian LCA method [28]), we recommend to use this single score indicator for benchmarking. This could be combined with sub-benchmarks or indicative values per individual indicator in order to fulfil international sustainability goals such as the greenhouse gas emission reduction targets.

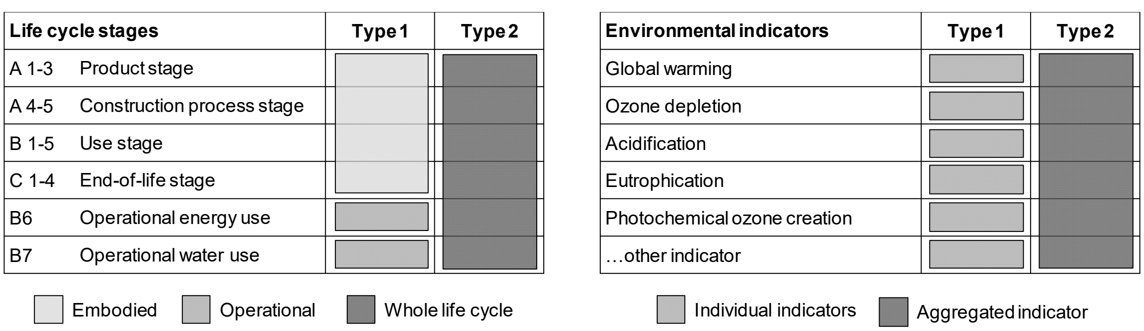

Figure 1. Benchmark scope in terms of life cycle stages (left) and environmental indicators (right)

4.3. Benchmark applications

The benchmarking systems can cover various building types and types of construction work (new construction versus refurbishment) (see Table 3). The benchmarking systems MPG and BREEAM are limited to one or two building typologies while the others are applicable to a wide range of typologies. Our recommendation for the development of future benchmarks is to use a stepwise approach starting with the most widespread typologies (i.e. residential and office buildings) which are then extended to other building types in subsequent steps.

The majority of the analysed benchmarking systems are limited to new construction. Only SIA 2040 includes benchmark values for both new construction and refurbishment. The latter should be preferred as the refurbishment of the existing building stock is seen as a policy priority for the coming years [29].

Table 3. Benchmark applications

	Building types	New construction and/or refurbishment?
MPG	Residential and office buildings	New construction
E+/C-	Single family houses, multi-family houses, office buildings and other buildings which are subject to the energy regulation	New construction
SIA 2040	Residential, administration, school, specialised store, food store and restaurant	New construction and refurbishment
BREEAM	Residential buildings	New construction
DGNB	Residential, office, education, hotel, consumer markets, shopping centres, business premises, logistics and production	New construction
LEED	Commercial, institutional, high-rise residential, schools, retail, data centers, warehouses and distribution centers, hospitality healthcare	New construction

4.4. Benchmark communication

Among existing benchmarking systems, three options can be distinguished for benchmark communication (see Table 4). The first option is to directly communicate benchmark values (e.g. kg CO_2 eq.). The second option is to use performance classes (e.g. label A to E). The third option, which is applied in sustainability rating tools, is to calculate a total score based on the benchmark values.

While benchmark values are more transparent in a scientific perspective, performance classes and scores are easier to communicate. Therefore we recommend a combination of both as applied in MPG.

Table 4. Benchmark communication

MPG	- Benchmark value - 5 performance classes (from A to E)
E+/C-	2 performance classes (Carbon level 1 and Carbon level 2)
SIA 2040	Benchmark values
BREEAM	Score based on benchmark scale
DGNB	Weighted score based on score per impact indicator
LEED	Score based on minimum impact reduction compared to baseline

5. Conclusions and further research

In this study six benchmarking systems were critically analysed considering the benchmark approach, scope, applications and communication. Based on this analysis, five main recommendations for the development of future benchmarks have been formulated. First, a combined top-down and bottom-up approach for defining benchmarks is recommended to ensure that benchmark values are in line with long term policy targets but still feasible based on currently available construction methods and technologies. Second, the benchmark system should include different performance levels (from limit to target values) to cover both short term and long term objectives. Third, the benchmark scope should be flexible in terms of life cycle stages and environmental indicators. This means a combination of whole life cycle benchmarks and indicative values for embodied and operational impacts but also a combination of aggregated indicator and indicative values for individual impact indicators. Fourth, the benchmarks should in a first phase at least cover the most widespread building typologies and be applicable to both new construction and refurbishments. Finally, benchmarks should be communicated in a transparent and user-friendly way based on a combination of benchmark values and performance classes.

In further research, the literature review will be extended to research studies [18–26]. This will provide in particular more insight into top-down approaches which are underrepresented in existing benchmarking systems. Furthermore, the results of the literature review will be presented to Belgian policy makers and building stakeholders in order to validate the formulated recommendations and define a methodology for benchmarks adapted to the Belgian context. In this context alignment with the ongoing harmonization works of IEA EBC Annex 72 and ISO/TC 59/SC 17/WG 2 ("Sustainability indicators and benchmarking") will be aimed for [30, 31].

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Passive house-concept apartments: sustainability evaluation in a case study of Stockholm, Sweden

Khatibi M

PhD Candidate, Department of Architecture and Urban Studies, DAStU,
Politecnico di Milano, Piazza Leonardo da Vinci 26, Building 29, 20133 Milano, Italy.

maryam.khatibi@polimi.it

Abstract. The housing sector accounts for almost one-third of total energy use in Sweden; of this amount, the operation phase of a building is responsible for around 85% of its total energy use. The Swedish government aims to reduce the energy consumption in buildings by 50 % by the year 2050. One way to achieve this goal is the construction of the low-energy buildings. The purpose of the study has been to analyse the Blå Jungfrun passive house-concept, tenant occupied apartments in Stockholm, Sweden, through a blend of qualitative and quantitative research methodology. The Swedish energy-efficient buildings are considered as a platform for recommendations for improving the knowledge and practice of low-energy buildings grounded in sustainability science as the theoretical framework. The study has investigated the roles of the responsible architects and design features of the Blå Jungfrun. The economic viability of the apartments is calculated by the economic evaluation software OekoRat for a life span of 50 years. The annual energy requirements of the studied apartments are analysed in regard to their post-occupancy evaluations. The social inclusion of the Blå Jungfrun tenants is investigated considering the issue of their participation in planning stages of the apartments. The empirical findings of the study shows the inevitable correlations between the environmental, economic, and social dimensions of the passive house. The findings suggested that in order to achieve a successful sustainable system of the sustainable housing, a holistic approach in the low-energy buildings is necessary.

1. Introduction

Global warming, climate change, increasing energy costs, and decreasing resources availability are among the reasons, which have caused a focus on the building of environmentally friendly houses. The Swedish ratification of the Kyoto Protocol and the United Nations Framework Convention on Climate Change (UNFCCC) are applied as a basis for decision makings regarding the Swedish climate strategy [1]. The Swedish government agreed on 15 environmental goals in April 1999 and one additional goal was added in November 2005 [1]. The goals that are important for the building industry can be listed as *A Good Built Environment* and *Reduced Climate Impact*. In regard to the goals for the Swedish energy policy, which were provided in 1997 and consequently were confirmed in 2002 by the Swedish parliament; the Swedish energy supply should be effective and sustainable in both short and long term perspectives. In the directive for energy efficiency in the built environment, the European Union (EU) Commission declares that in order to decrease CO_2 emissions, the building sector must decrease its use of energy [2]. In June 2006, the Swedish government stated a goal, to reduce the energy consumption in buildings with 50% until the year 2050 [3]. One way to achieve this goal is the construction of the passive house-concept buildings.

1.1. Objective and methodology of the study

The analyses of the study is based on the case study of Blå Jungfrun passive house-concept project in Stockholm. The focus is on the design aspects, economic viability, and annual energy requirements of the project. The study also aims to explore the social inclusion of the users in the planning process of Blå Jungfrun in order to identify potential shortcomings.

To approach the challenge of this study, a blend of qualitative and quantitative data was needed. The qualitative data in regard to the social inclusion of the tenants of Blå Jungfrun apartments were collected through the interview sessions with the architects of the project and the environmental engineer of the construction company Skanska during years 2012-13. This qualitative data is coupled with quantitative data available from the post-occupancy evaluation of the project for the year 2011 (collected from Svenska Bostäder; the responsible housing company), the relevant statistical online databases, and Oeko-Rat software economic calculations. Hence, the sources of qualitative and quantitative data, analysis and discussion sections are not based on the marketing materials of Blå Jungfrun project but on the collected data from interviews, post-occupancy evaluations, statistical databases, and economic software calculations.

1.2. Swedish passive house definition and development

Forum för Energieffektiva Byggnader (FEBY) Passivhus defines passive houses as:
"Low energy buildings that aim to perform better than new built buildings regulated in BBR 16 (BFS 2008:20)" [4].

The earlier experiences of Swedish passive house projects were carried out in 1981 in Växjö and Färgelanda. Later, in the mid-80s, a German researcher Dr. Wolfgang Feist and a Swedish professor Dr. Bo Adamson developed the concept of present-day passive houses [1]. Ten years after the first positive experiences of passive house in Germany, the first modern passive house in Sweden was built in 2001 [1]. The Lindås project, which is a 20 terrace houses project in Göteborg (Lindås) as a part of CEPHEUS research project, became a milestone in the construction of Swedish low-energy buildings [5]. The experiences of Swedish modern passive house projects in 2001 demonstrated that this concept can be feasible in Scandinavian climate [5].

1.2.1. Energy demand of the passive house in Sweden

Space heating demand, domestic hot water, electricity for mechanical systems (fans and pumps), and general electricity utilized by the building such as common lighting and electricity used for elevators are included in the Swedish criteria regarding the energy consumption [6]. However, household electricity and the energy produced at the building from installed solar cells or panels are not included in the energy consumption demand of passive houses [6]. The Swedish criteria recommend a total energy consumption of maximum 45 kWh/m^{2}a for southern climate zone and a limit of 55 kWh/m^{2}a for northern climate zone of Sweden [7]. An additional 10 kWh/m^{2}a in both regions is allowed for detached houses with less than 200 m^2 [7].

This study aims to assess not only the specific energy requirements of the case study project, but also the energy consumption patterns of the tenants of the case study. This assessment should contribute to environmental and economic aspects of the passive house. That is because the very low energy demand of the passive house contributes to fulfil the economic and environmental components [8].

1.2.2. Economic efficiency of the passive house

The specific extra costs, which are related to passive houses compared to conventional buildings, can be divided into the categories such as costs for heating, ventilation, isolation, air tightness, ground works, differentiation in net floor surface and miscellaneous costs [9]. The extra costs of passive houses are invested in energy efficiency of these buildings and are supposed to be paid back through the annual energy savings, which is provided by this obtained energy efficiency [10].

1.2.3. Social sustainability and inclusion of the residents

The social issues linked to participation of a large range of actors such as occupants are considered as a component in the making of successful sustainable building [11]. Social sustainability need to include residents in the building processes [12]. Social sustainability is an important point in the development of passive houses. The social sustainability of passive houses deals not only with the protection of human health, well-being, and indoor thermal comfort, but also the behaviour of end-users of the passive house. To achieve the goal of social sustainability several issues should be taken into consideration [12]:

- The occupants of passive houses should get included during the planning and design stages of these buildings.
- Post-occupancy evaluations of these buildings should present data "both on what energy resources residents are using and why the pattern of use looked like that".
- Eventually, post-occupancy evaluations should yield "accurate and accessible" input to new developments.

The assessment of the social sustainability of the case study project, however, is limited. There were no studies carried out on the tenants of the case study apartments. Therefore, the effect of indoor air quality on the health and comfort of the tenants, and their views on energy consumption patterns have been not assessed.

2. Blå Jungfrun energy efficient apartment project in Stockholm

Blå Jungfrun is a pioneer passive house standard residential development with a total of 97 rental apartments, which was constructed by Skanska in 2010 first in Stockholm (see figure 1). It is located in the southeast part of Stockholm between Farsta and Hökarängen, which is about 10 km south of central Stockholm. The planning phase of the project started in October 2008 and tenants moved into the buildings during the second and final quarter of 2010 (see table 1).

Figure 1. Blå Jungfrun energy efficient apartment project in Stockholm.

Table 1. The project facts.

Project: Blå Jungfrun		
Client: Swedish housing association (Svenska Bostäder in Swedish)		
Construction company: Skanska		
Architect company: Reflex Architects		
Architects in charge: Kjell Mejhert and Pernilla Ivarsson		
Construction type: Prefabricated frame passive house		
Construction cost: (27000 SEK/m^2)* including value added tax (VAT)		
Year completed: 2010		
Location: Hökarängen, Stockholm; Sweden		
Development type: 4 blocks of 5 and 6-storeys high with 97 apartments		
Building type	Number	Area (Sqm)
2 Bedrooms apartment	21	53-55
3 Bedrooms apartment	36	73-85
4 Bedrooms apartment	20	88-105
5 Bedrooms apartment	20	111

*This amount is based on the data received from Svenska Bostäder (the responsible housing agency)

After the first year of the tenants' occupancy of the Blå Jungfrun apartments, the amount of energy consumption was calculated by Svenska Bostäder [13]. The calculations show that the energy consumption for heating has been reduced around 85% in comparison to the standard of BBR, legislation 2009 (see figure 2).

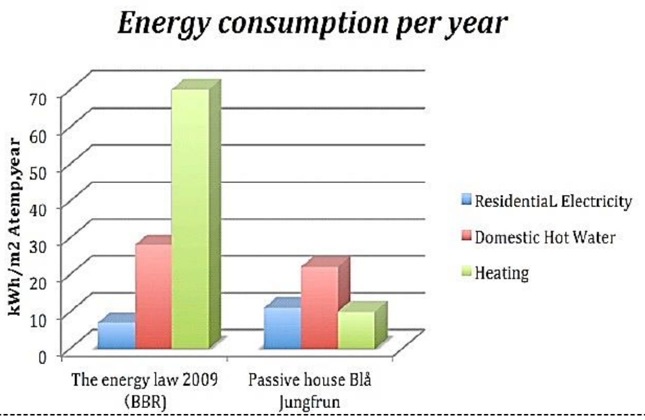

Figure 2. The comparison of energy consumption of the Blå Jungfrun with the requirements of the applicable BBR legislation 2009 [13].

3. Interview Study

From the start of the Blå Jungfrun project the architects team of the project have suggested Svenska Bostäder (the client) to develop an environmentally responsible building project. Further, Skanska as the developer and investor has entered the project and the financial comparison between conventional buildings and passive houses got calculated by Skanska. Eventually, the Blå Jungfrun project got to be constructed with passive house standards. Besides, the environmental development leader of Skanska, has explained that the driving forces for their customers of green houses have been lower energy costs during use, better in-door environment, higher value (financial benefits) of the building, and a green profile for the company.

3.1. Specific design aspects of Blå Jungfrun project

3.1.1. Architectural effect and form

Buildings have the southern orientation with most windows to the south, however, they are not the most compact buildings possible. The buildings were designed very simple in their form, while the architects could not add a lot of architectural effects to them. According to the architects, in spite of the fact that the focus of the first passive house designers has not been on architectural parts, rather on the technical parts, it is possible to design modern and attractive architectural forms for passive houses (Interview with architects).

3.1.2. Large south-facing balconies

The south-facing large balconies are designed to sunscreen the summer sun. According to architects, although, the large balconies and their connection to the buildings have been expensive to construct, they save costs in operation phase of the buildings (Interview with architects).

3.1.3. Placement of windows

There have been many calculations on the placement of windows. These buildings apply passive solar heating system through the windows for some part, thus it has been critical to decide to place the windows right in the façade (Interview with architects).

4. Economic evaluation of the Blå Jungfrun passive apartments

Construction costs of the passive house are more expensive than a conventional house, because of extra costs of a passive house such as: costs for ventilation, costs for insulation, costs for triple glazed windows and entry doors, costs for measuring air tightness, costs for ground works, etc. [10]. The additional costs of constructing passive houses are invested in energy-efficiency quality of these buildings. These extra costs are supposed to be paid back through the annual energy savings of passive house during its lifespan. The main factors that affect economic aspect of the passive house are considered as (see appendix 1) [14]:

- Initial investment costs
- Annual energy saving
- Energy costs
- Annual operation costs
- Considered period of time (Utilization of building)
- Interest rate
- General inflation rate
- Energy inflation rate

The economic efficiency of the passive house can be calculated regarding the payback time and internal interest rate of the investment [14]. The payback time of passive houses is directly dependent on the growth of the energy prices and inflation rate indirectly influences energy price and interest rate [10]. These factors are used in order to decide whether the construction of the Blå Jungfrun passive apartments is economically viable. As the first condition, the payback time must be shorter than the lifespan of the buildings [14]. Secondly, the internal interest rate, which depends on the lifespan of the buildings, has to be larger than or equal to the interest rate of the capital investment.

In order to evaluate the economic efficiency of the investment for Blå Jungfrun passive-house apartments, the software called Economic Evaluation (Oeko-Rat) is used. This software is specifically designed for economic calculations of energy savings and renewable energies and evaluates the economic efficiency of an investment in accordance with the capital value method [14].

The total cost difference of normal houses and the Blå Jungfrun passive apartments is used as initial investment costs. The annual energy saving is the annual difference of energy consumption of normal houses of Svenska Bostäder and the Blå Jungfrun passive apartments (see table 2; see appendix A for calculations). According to Nordic conditions, the basic lifespan of the buildings is considered to be 50 years and can be then renovated and used for another 50 years [15].

Table 2. Amount of factors used for economic evaluation of the Blå Jungfrun passive apartments

Factor	**Blå Jungfrun project passive house apartments**
Initial investment costs (SEK)	16065000 SEK= (160650 hSEK*)
Annual energy saving (kWh)	943500
Energy cost (Electricity) (SEK/ kWh)	1.6833= (0.016833 hSEK/kWh)
Annual operation costs (%)	2
Considered period of time (utilization) (Years)	50
Interest rate in 2011 (%)	1.625
Inflation rate in 2011 (general) (%)	3.0
Annual inflation rate of energy in 2011 (%)	6.1

*the unit h stands for Hecta (hundred) in calculations.

Sources of table 2:
Row 1: Based on data from Svenska Bostäder.
Row 2: Based on data from post-occupancy evaluations of Svenska Bostäder.
Row 3: Based on data from European statistics (Eurostat, 2012).
Row 4: [14].
Row 5: [15].
Row 6: Swedish central bank's interest rate (global-rates, 2012).
Rows 7 and 8: Based on data from Organization for Economic Co-operation and Development (see appendix B).

The economic evaluation with the energy price in Sweden shows that the investment for building the Blå Jungfrun passive apartments is economically viable, since the payback time for this investment is less than the lifespan (utilization time) of the houses. The internal interest rate of this investment is 14.4 %, which is more than the general interest rate in Sweden (see table 3).

Table 3. Factors of economic efficiency for the Blå Jungfrun passive apartments.

Considered period of time	Payback time	Interest rate	Internal interest rate of the investment	Result
50 years	**10.1 years**	1.65 %	**14.4 %**	**Economic**

The economic evaluation for all the 2 bedrooms apartments, 3 bedrooms apartments, 4 bedrooms apartments, and 5 bedrooms apartments of the Blå Jungfrun passive-house concept apartments has carried out, separately. The results for all calculations are the same with payback time of 10.1 years and internal interest rate of the investment, which is 14.4 %. This estimated payback period of 10.1 years could have been shorter, if the annual energy consumption of the project would have been lower than the measured requirement of 2011.

5. Energy requirements of the Blå Jungfrun passive apartments

According to the post-occupancy evaluation, which is carried out by Svenska Bostäder, the measured energy requirements of the Blå Jungfrun passive apartments for the year 2011 has been 59 kWh/m^2a for residential electricity, space heating and, hot water and 92 kWh/m^2a including tenant electricity (see table 4) (see appendix C).

Table 4. The measured energy requirement of Blå Jungfrun passive houses for 2011.

Residential electricity	9 kWh/m^2a
Heating ventilation and VVC (district heating) & Dehydration of concrete (electricity or district heating)	19 kWh/m^2a
The heating electric radiators	4 kWh/m^2a
The warm water (apartments and laundry)	27 kWh/m^2a
The household and laundry electricity	33 kWh/m^2a

Considering the Swedish criteria for energy consumption, the maximum amount of energy demand for passive apartments (excluding household electricity) is recommended not to exceed 45 kWh/m^2a in Southern climate zone of Sweden [7]. Therefore, the measured value of 59 kWh/m^2a for Blå Jungfrun in 2011 is not within the Swedish criteria of the passive houses.

On the other hand, it has been argued that the energy use, especially for space heating, can be higher during the first heating season in comparison to later during the continuous operation. Generally, this situation is caused by additional energy used for structural drying and also the phase when the occupants are learning how the system works might take more or less time [1].

6. Discussion

The vision of sustainability has been the driving force for constructing the Blå Jungfrun passive-concept apartments. The energy efficiency awareness of the residents is achieved by installing Smart box for each apartment unit in order to provide energy consumption feedback to tenants of the Blå Jungfrun passive apartments. However, the post-occupancy evaluations that have been carried out by Svenska Bostäder demonstrate that the tenants have not reduced their energy consumption patterns. In the Blå Jungfrun apartments, the rents are reduced and tenants have to pay for warm water and extra heating that they consume, separate from the rent amounts of the apartments. According to the architects of the project, when one reads about what tenants have answered to evaluation questions of the project, they have declared that they are more concerned now and they think more about environmental questions. However, when these answers and results are compared with the post occupancy energy statistics, it is seen that tenants have not reduced the energy consumption. Moreover, from interviews, it has been recognized that tenants of Blå Jungfrun apartments have received a lot of information about the buildings being passive house before signing their contracts. Since the tenants pay for their own use of hot and cold water, electricity and some of the heat, the hope has been that they would use less energy. One issue is that he residents of Blå Jungfrun project have got their apartments in Blå Jungfrun apartments through the regular Stockholm apartment queue. In this manner, Svenska Bostäder has no right to favour people who are environmentally interested and responsible and hence few of the tenants choose the apartments due to the house being passive.

According to Palm (2011), in low-energy buildings tenants and tenant/owners often identify actors other than themselves as responsible for energy efficiency [16]. For example, householders rely on the construction company regarding the energy efficiency issues [16]. The research by Pyrko and Darby on conditions of energy efficient behaviour identifies that citizens in Sweden trust their government and often expect that someone does something and that decisions are made for the society's best, thus people should be informed about the right and rational way to be effectively involved in the process [17]. Their research emphasizes the shortage of face-to-face advice in the home on the issue of energy efficiency, which is more effective but more expensive than normal procedures [17]. Likewise, Palm and Ellegård suggest “time diaries and visulaization tools” as useful tools for approaching inhabitants to target their energy behaviour [18].

The first modern passive house, which was built in 2001 in Sweden, was Lindås project. However, involving end-users was never an option in Lindås project [19]. Isaksson & Karlsson has conducted an interdisciplinary investigation on the thermal environment and space heating of low-energy terraced houses of Lindås project [20]. They have concluded that in developing the next generation of low-energy buildings, an interdisciplinary planning that takes the experiences of occupants as well as measurements into consideration is very important [20].

However, nine years after the completion of the Lindås project in south of Gothenburg in 2001, the Blå Jungfrun passive apartments are constructed in Stockholm in 2010 and still the residents are disconnected from the planning phase of the project. Moreover, the interview materials of this study revealed that Svenska Bostäder has compared the results of the post-occupancy evaluation forms of the tenants and the results of the energy statistics. The tenants have expressed their sustainability awareness intentions; however they have not acted in an environmentally sustainable manner. The reason for this disagreement can be that households want to answer for example survey questions in a way that is politically correct, but it may be difficult to translate that desire into practical action. One major problem with housing policies can be that the housing sector is dominated by a “techno-centric (top-down policy recommendations)” approach, while the “eco-centric (public participation and community involvement)” approach can result in more beneficial outcome [21].

7. Conclusion

The findings of this study show that the environmental, economic, and social aspects of the passive house are closely intertwined. The deficiency in each aspect affects the whole system of the passive house. Fifty percent energy consumption reductions in buildings to year 2050 in Sweden mean substantial changes in patterns of energy consumption in buildings with improvements in all environmental, economic, and social aspects of sustainable buildings. In order to achieve a sustainable system of the passive house, the government or public authorities at the national and local levels need to inform the public of such projects, mediate the involvement of the public, and provide support for the community involvement. The energy-saving behaviours of the passive house tenants can be facilitated by their early participation.

As the result of the increase in the world population from 7.0 billion to 9.3 billion by 2050, 70% of people will be living in urban areas [22]. Cities considered responsible for about 60-80% of global energy consumption and for 75% of global greenhouse gas emissions [22] are increasingly perceived as being crucial in addressing climate change and environmental problems. Accordingly, urban housing as a major component of the city has turned to the centre of attention with the potential to attain the essential strategies to achieve greater sustainability. Housing design that does not take into consideration the participation of its inhabitants, cannot be sustainable in long-term. The results of this study highlight that the of UN`s Agenda 2030 and Sustainable Development Goals (SDGs) [23] would not be achieved, when bottom-up approaches are not applied to urban housing development and planning.

An integrated approach can contribute to achieving the successful sustainable system of the passive house concept, which needs to be user-centred rather than just selling the technology. The purpose of this study has been to contribute to the development of knowledge regarding the best practices by which, a balanced sustainable system of the passive house can be achieved. Findings show that with the changes in both the housing company governance structure and community involvement, reductions in energy usage of the residents would be expected.

Appendix A

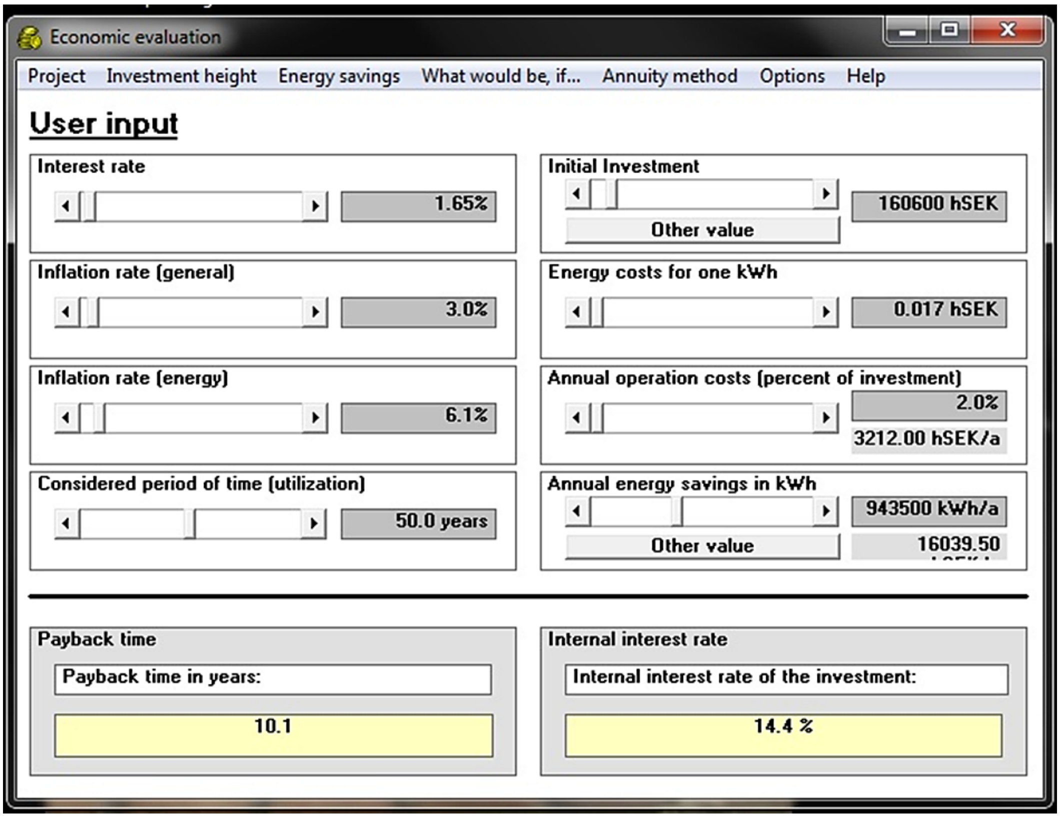

figure A1. The economic evaluation of Blå Jungfrun passive houses in software Oeko-Rat.

The input & output data and factors for the Blå Jungfrun passive apartments are summarized as below (see figure A 2):

Economic Evaluation

Input data

Interest rate:	1.65%
Inflation:	3.0%
Energy infaltion	6.1%
Period of using:	50.0 years
Costs of investment:	160600 hSEK
Costs of energy pro kWh:	0.017 hSEK
Savings of energy:	943500 kWh/a - 16039.50 hSEK/a
Operating costs per year:	2.0% - 3212.00 hSEK/a

Output data

Period of amortization:	10.1
Internal interest rate:	14.4 %

Figure A 2. the input & output data for economic evaluation of the Blå Jungfrun passive apartments [Oeko-Rat[1]]

1 Oeko-Rat. Economic Evaluation Software. Available at: http://nesa1.uni-siegen.de/index.htm?/projekte/OekoRat/Oeko-Rat.htm

The calculations procedure for economic evaluation of Blå Jungfrun passive houses:

In order to calculate the initial investment costs:
Construction cost of Blå Jungfrun passive houses including VAT = 27 000 SEK/m^2
This amount is 7 % more than construction costs of conventional buildings.
27 000 – 7 % = 25 110 SEK/m^2
Construction cost of conventional houses including VAT = 25 110 SEK/m^2
Living area of Blå Jungfrun passive houses = 8 500 m^2
27 000 SEK/m^2 - 25 110 SEK/m^2= 1890 SEK/m^2
1890 SEK/m^2 × 8500 m^2 = 16065000 SEK = 160650 hSEK = Initial investment costs

In order to calculate the annual energy saving:
The average energy requirements in conventional buildings of Svenska Bostäder (excluding household electricity) = 171 kWh/m^2.year
The measured energy requirements of Blå Jungfrun passive houses (excluding household electricity) = 60 kWh/m^2.year
171 KWh/m^2.year - 60 kWh/m^2.year = 111 KWh/m^2.year
111 KWh/m^2.year × 8500 m^2 = 943500 kWh/year = Annual energy saving

Energy costs:
0.204 Euro per kWh (in the year 2011) = 1.6833 SEK = 0.016833 hSEK ≈ 0.017 hSEK

Appendix B

figure B 1. General inflation rate in 2011 in Sweden

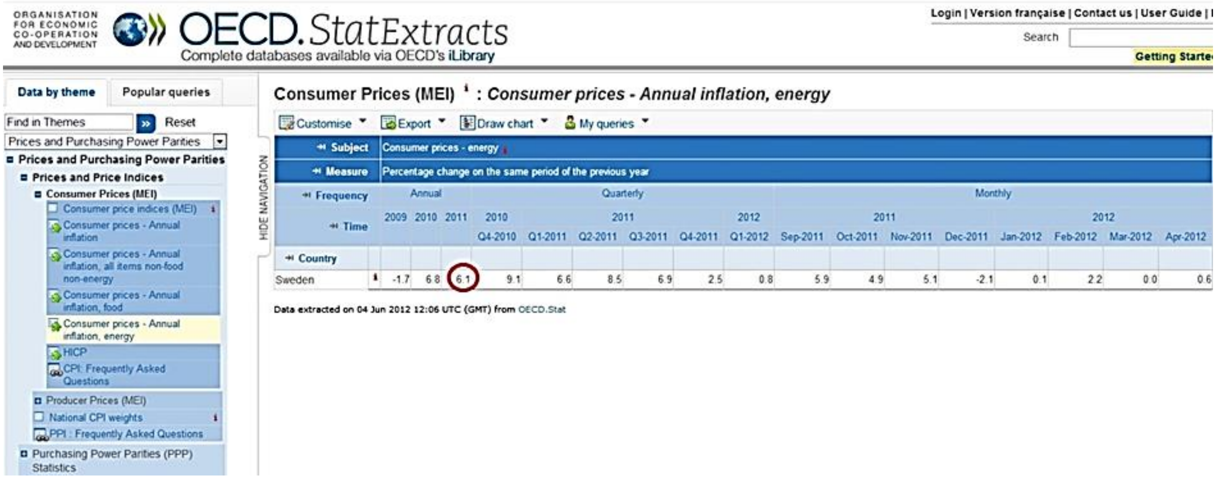

Figure B 2. Energy inflation rate in 2011 in Sweden

Appendix C

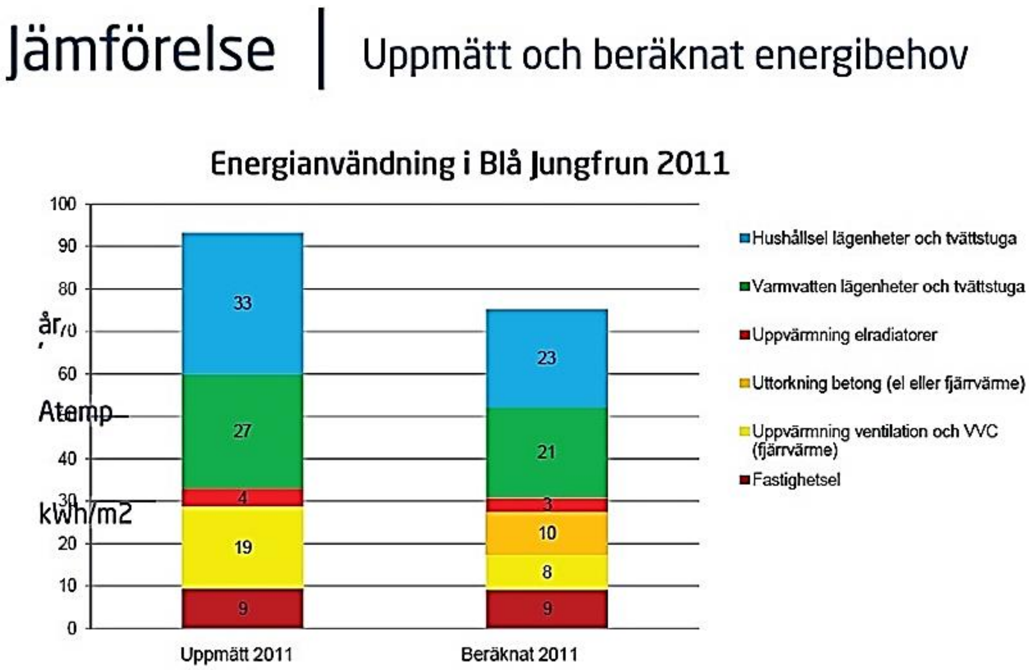

figure C 1. The comparison of the annual calculated energy requirement (right column) & annual measured energy requirement (left column) of Blå Jungfrun passive apartments in 2011 (data gather from Svenska Bostäder in 2012)

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The effect of insulation thickness on lifetime CO_2 emissions

Totland M, Kvande T and Bohne R A
Norwegian University of Science and Technology

marietot@stud.ntnu.no

Abstract. This paper assesses the total carbon emissions of a single-family home designed and built for Norwegian conditions, according to current standards (TEK 17), using an LCA approach. Various combinations of insulation thicknesses are assessed to identify which combination is most efficient in lowering the lifetime emissions as well as in which part of the building envelope additional insulation is most efficient in reducing the lifetime greenhouse gas emissions of the building. Overall, increased insulation resulted in lower lifetime emissions; the increased embodied emissions generally being outweighed by the energy savings resulting from the increased insulation thickness. The location of the insulation is the factor that was found to have the largest impact on the lifetime emissions. When increasing the insulation thickness from 100-500 mm, changing only one component at a time, the operational emissions were most sensitive to the insulation thickness in the walls, with a 26 % decrease compared to 7% and 3% for the roof and floor respectively. The most efficient cases tended to have little insulation in the floor (100 - 150 mm) and relatively high insulation thickness in the wall (350 mm). The most variable component was the roof, varying from 150 to 400 mm.

1. Introduction

According to the IPCC 19% of the global CO_2 emissions, and 32% of the final energy consumption in 2010 could be accounted to the building sector[1]. Due to the long lifetime of buildings, the efforts made to reduce these emissions can affect the world in decades to come. In recent years there has been an increasing focus on reducing the carbon footprint of buildings, which in colder climates like in Norway, focuses on reducing heat loss and thus lowering the operational energy consumption. Increasing the insulation thickness, ensuring airtightness and eliminating thermal bridges are steps taken to bring the use phase energy consumption down. These measures are indeed reducing the lifetime energy use and emissions, but at what cost? The solutions to reduce the carbon footprint of buildings are increasingly ”engineered”, relying on more materials to further reduce the emissions. Increasing the insulation thickness will potentially reach a limit where adding more material can not further decrease the energy use without it affecting the user-friendliness or increasing lifetime emissions.

The overall objective of the study is to investigate the effect of insulation thickness on lifetime greenhouse gas emissions. This is done through the case study of a single family home located in Norway. Life-cycle assessment (LCA) methodology is used to analyse the GHG emissions and to answer the following research questions:

(i) To what extent will increased insulation thickness reduce the lifetime GHG emissions?

(ii) In which part of the building envelope is additional insulation most efficient in reducing the lifetime GHG emissions of the building?

To assess the environmental impact of buildings, the embodied emissions; impacts that are ”built into” the building, are separated from those coming from the use phase of the building, also called the operational emissions. Traditionally, when the buildings were less insulated, the operation phase constituted between 70-90 % of the total environmental impact[2]. As the buildings have improved the operational energy consumption has been reduced, which increases the relative importance of the embodied emissions. For buildings of passive house standard the embodied emissions can constitute almost 50 % of the total emissions[3]. The impacts of the operational and embodied emissions are highly dependent. The choice of materials used in the construction can for instance decrease the heating requirements of the use phase, but increase the need for transportation or emissions related to the production of the materials[4].

2. Method

2.1. Case study

The case study for this project is a small, residential building designed by Norgeshus, called Trend 2. The house will, for the purpose of this analysis, be considered as a detached, single family house, but the design is also compatible as several adjacent units as a row house, and can therefore easily be scaled for further investigation.

The main part of the building has a rectangular shape with two stories and a flat roof. In addition there is a carport attached to the long side of the building, also serving as a terrace with access from the second floor.

The construction is placed on a concrete perimeter foundation, with timber frame walls insulated with mineral wool, and a flat, compact roof on glulam beams. The original house is built according to current Norwegian standards, TEK 17. The details and thermal properties of Trend 2 are presented in Table 1.

Table 1. Trend 2 building properties

Property	**Value**
U-value External wall [W/m^{2}K]	0.207
U-value Ground floor [W/m^{2}K]	0.092
U-value Roof [W/m^{2}K]	0.14
U-value Windows [W/m^{2}K]	0.81
Airtightness, n_{50} [1/h]	0.9
Heat recovery efficiency	85%

2.2. LCA methodology

Life-Cycle Assessment (LCA) is used to analyse the environmental impacts of a product or service during their entire lifetime [4]. The International Organization for Standardization (ISO) publishes standards for Principles and Framework - ISO 14040 [5] and Requirements and Guidelines - ISO 14044 [6] for life-cycle assessments, and the procedure for the LCA of this paper follows these standards.

The goal of this study is to investigate the effect of increased insulation on the lifetime GHG emissions and identify hot spots, components that contribute more than others to the life-cycle emissions. For this reason, only the impact category global warming potential (GWP) is assessed. According to NS-EN 15643 [7] the embodied emissions correspond to A1-A3 and the operational emissions to B1. The lifespan of the building is considered to be 60 years. Materials with a shorter lifespan than 60 years were multiplied with a lifetime factor to be included in the embodied emissions.

The functional unit is 1 m^2 heated floor area. A complete life-cycle inventory of Trend 2 as designed was performed based on a material list provided by Norgeshus, using a combination of EPDs from EPD

Norway and the Ecoinvent v3 database. The operational energy use was calculated using the energy calculation software SIMIEN. Trend 2 uses a combination of electric heating and biofuel (wood burning fireplace). The electricity mix is assumed to emit 132 g CO_2/kWh[8] and 22 g CO_2 eq/kWh for the biofuel [9].

Initially, two combination methods were used in the case study for the insulation thicknesses, hereafter called Case A and Case B. In Case A all insulation thicknesses were assumed to be identical, e.g. 100 mm insulation in the wall, the roof and the floor. Case B is a parameter study, where all values were kept as they were designed for Trend 2, and only one component was changed at a time. As the work progressed, it became apparent that other combinations of insulation thicknesses should be investigated, which became Case C. A total of 126 combinations were assessed with various combinations of insulation thicknesses, but for the purpose of this paper only the most efficient are presented in detail.

A sensitivity analysis was performed with regards to lifetime (± 30 years) and electricity mix (±30%).

3. Results

The life-cycle impact analysis of the building body of Trend 2 yielded an embodied emission of 25176 kg CO_2 eq, corresponding to 194,56 kg CO_2 eq/m^2.

The LCIA revealed that concrete was the greatest contributor to embodied GHG emissions despite the relatively small amount used in the construction. Concrete is used only in the perimeter foundation, yet constitutes almost 16 % of the total embodied emissions, emphasising the carbon intensity of the material. Insulation is the third most carbon intensive material in the construction.

The variations in embodied emissions for the case study was calculated for each case, and the difference is mainly due to the change in insulation quantity. Polystyrene insulation (EPS and XPS) is more carbon intensive than mineral wool. EPS provides a GWP of 2.2 kg CO_2 eq/m^2 for phases A1-A3, whereas Glava mineral wool provides 0.43 kg CO_2 eq/m^2. For Trend 2, insulation contributes 11 % of the total carbon emissions, including the mineral wool, XPS and EPS. For the most insulated case (A.500), the insulation accounts for 19 % of the total embodied emissions.

Table 2. Embodied and operational emissions

Insulation thickness [mm]	100	150	200	250	300	350	400	450	500
Case A: Same insulation thickness in all components									
Operational emissions [kg CO_2eq/m^{2}year]	18.7	15.7	14.2	13.2	12.5	12.1	11.8	11.6	11.4
Embodied emissions [kg CO_2eq/m^2]	184	188	191	194	198	201	204	208	211
Case B: Varying insulation thickness for single component, others unchanged									
Embodied emissions [kg CO_2eq/m^2]									
Wall	192	193	195	196	197	199	200	201	203
Roof	193	194	194	195	195	195	196	196	196
Floor	188	190	191	193	195	196	198	199	201
Operational emissions [kg CO_2eq/m^{2}year]									
Wall	17.0	14.9	13.9	13.2	12.7	12.4	12.2	12.0	11.5
Roof	14.8	14.3	14.1	13.9	13.7	13.7	13.6	13.5	13.5
Floor	14.5	14.2	14.1	13.9	13.9	13.8	13.8	13.8	13.8

The results for the embodied and operational emissions for cases A and B are presented in Table 2. For all insulation thicknesses in both cases the embodied emissions increase with the increased insulation, and the operational emissions decrease. The operational emissions were most sensitive to the insulation thickness in the walls. Thin walls (100 mm) resulted in lifetime emissions 15.2% higher than Trend 2 and when the walls had 500 mm insulation the lifetime emissions decreased with 14.9%. With the same insulation thicknesses in the roof and the floor the lifetime emissions varied from +5.1% to -1.5% and from +2.8% to -0.1% respectively. It is likely that this distribution is partly affected by the area difference, as the wall surface area is more than double those of the roof and floor and thus allows for more heat transmission.

Overall, the lifetime emissions decrease as the insulation amount increases, this applies for almost all case variants. Table 3 shows the results of Case A, displaying variations regarding lifespan and emission of the electricity mix. The baseline results, with a lifespan of 60 years, and 132 gCO_2 /kWh are shown in the middle. The difference between the least and most insulated cases increases as the electricity mix becomes more carbon intensive and as the lifetime increases. The size of the reduction of lifetime emissions as the insulation increases from 100 to 500 mm depends on the electricity mix (reduction of 25-38% for least and most carbon intensive electricity mix respectively) and expected lifetime (reduction of 26-31%).

Figure 1 shows the lifetime GHG emissions for Case B with a lifespan of 60 years. The insulation thickness in the wall has the greatest effect on the lifetime emissions. The lifetime emissions are less affected by the insulation thickness of the roof and floor, the greatest difference occurring when going from 100 to 150 mm in both components. The wall provides the most significant decrease in lifetime emissions per mm added insulation, with a 26 % decrease compared to 7% and 3% for the roof and floor respectively when the insulation is increased from 100 - 500 mm at a lifetime of 60 years.

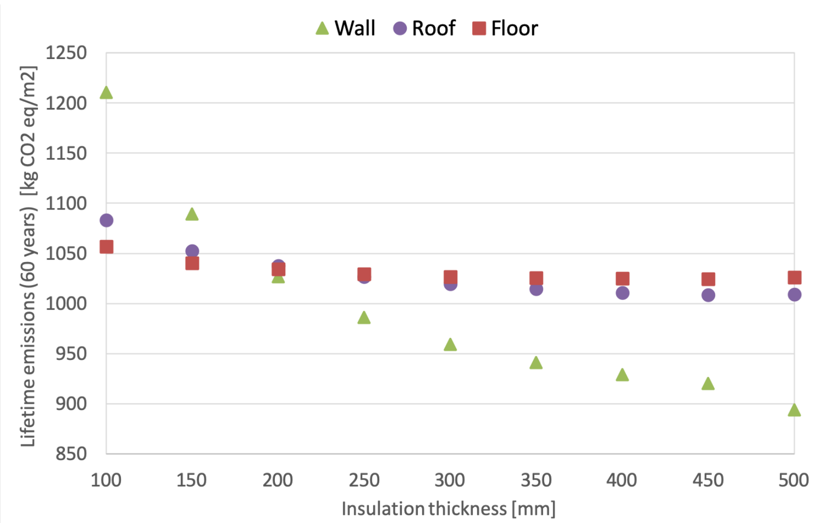
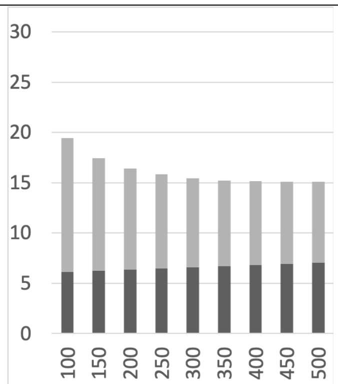
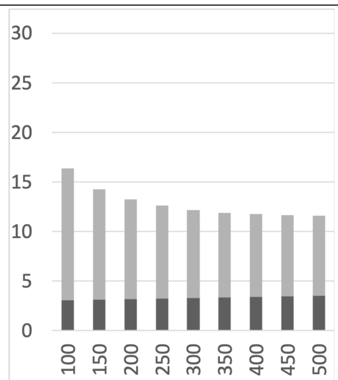
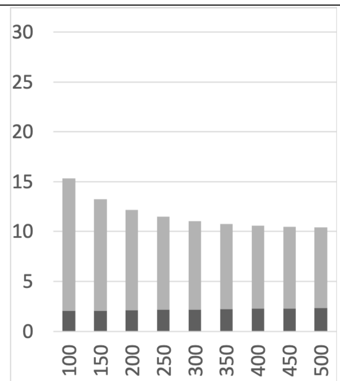
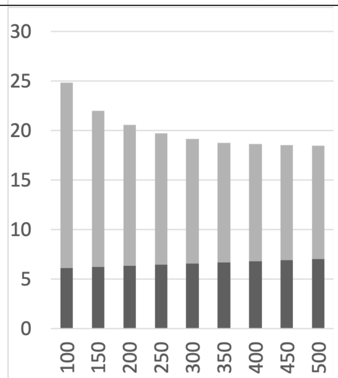
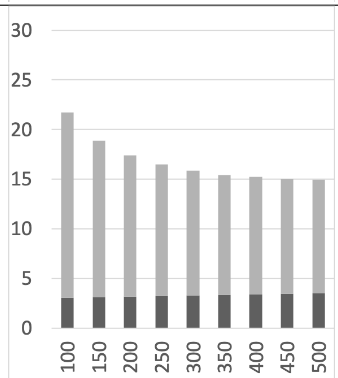
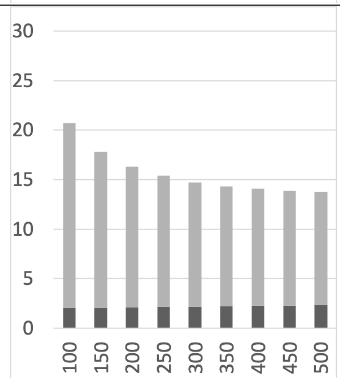
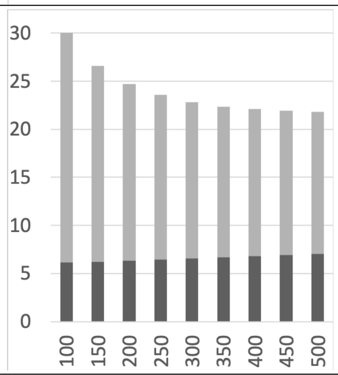
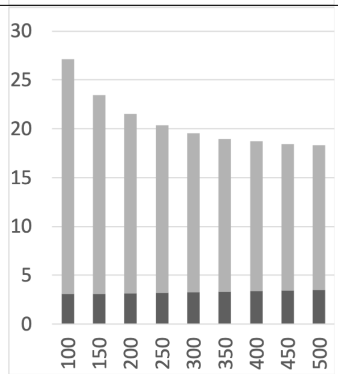
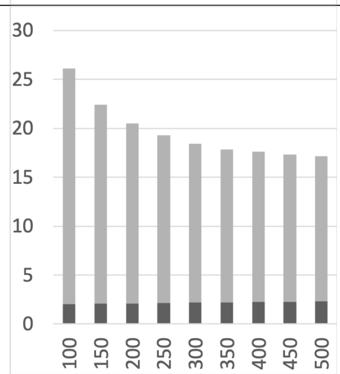


Figure 1. Case B Lifetime emissions (60 years) for the various insulation thicknesses changed in single component

Figure 2 shows the relationship between the lifetime embodied and operational GHG emissions with a life span of 60 years for all the assessed cases. The frontier along the leftmost data points in the figure is called the Pareto frontier. Pareto efficiency is a concept that stems from economics, describing an allocation that makes some individuals better off, and no individual worse off [10]. In the case of optimising insulation thickness, the Pareto frontier represents cases where the operational emission is as low as possible for a given embodied emission. Cases to the right of the frontier therefore have the same operational carbon emissions, but higher embodied emissions, and are thus less efficient than a case on the frontier. The simulations of Trend 2 and the three versions of the Norwegian building standards

Table 3. Annual CO_2 emissions for the Case A variants (insulation thickness in mm) as functions of different lifespans and electricity emissions

gCO_2 /kWh	Lifetime = 30 years	Lifetime = 60 years	Lifetime = 90 years
92			
132			
172			

■ Embodied [kg CO2 eq/year] ■ Operational [kg CO2 eq/year]

(TEK17, TEK07 and TEK 97)[1] all result in data points to the right of the Pareto frontier.

The insulation thicknesses and lifetime emissions of the cases on the Pareto front are presented in Table 4[2].

[1] TEK17 is the current standard, TEK07 and TEK97 are past standards, included to see the effect of the evolution of the insulation requirements

[2] The values are sorted alphabetically according to Case ID and the order does not represent Pareto efficiency

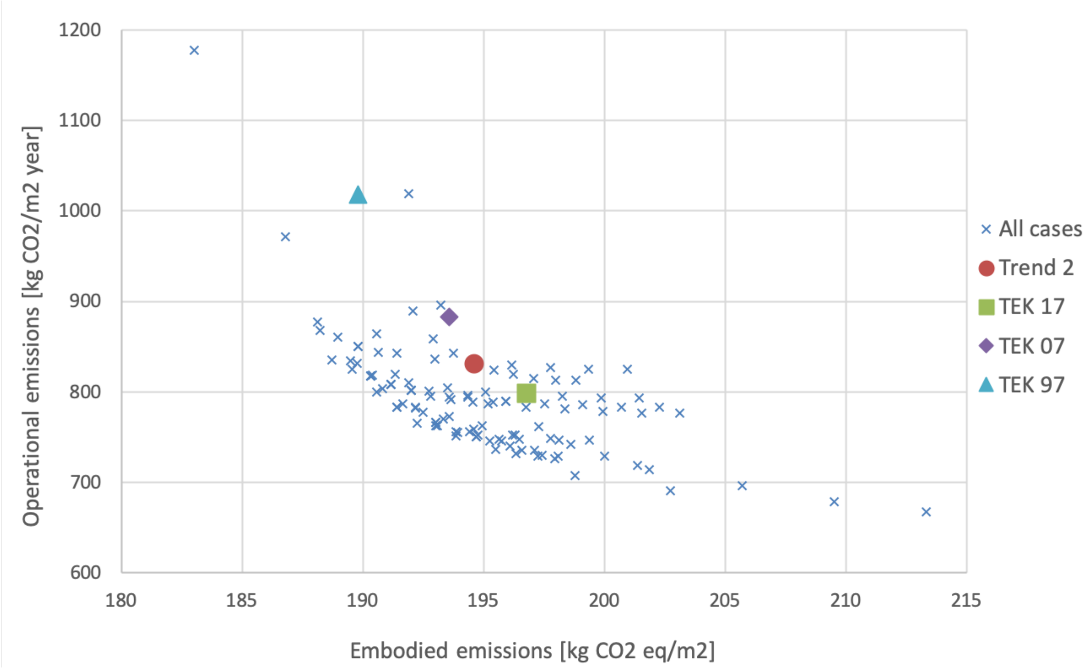


Figure 2. Relationship between embodied and operational carbon emissions

Table 4. Cases on the Pareto frontier with insulation thicknesses [mm] and lifetime emissions [$kgCO_2/m^2$]

Case ID	Insulation Roof	Insulation Wall	Insulation Floor	Operational	Embodied
All 100	100	100	100	1177,8	183,0
All 450	450	450	450	679,0	209,5
All 500	500	500	500	667,6	213,3
C.2.250	200	250	150	190	817,9
C.3.400	250	400	150	195,2	746,1
C.3.500	250	500	150	197,9	726,7
C.4.500	300	500	150	707,3	198,8
C.6.100	200	250	100	835,6	188,7
C.7.100	250	250	100	189,5	825,4
C.9.100	200	350	150	783,2	191,4
C.10.150	150	350	100	800,1	190,6
C.10.250	250	350	100	765,1	192,2
C.11.200	400	350	150	762,7	193,0
C.11.250	250	350	150	751,4	193,8
C.11.300	300	350	150	750,3	194,7
C.11.350	350	350	150	736,5	195,5
C.11.400	250	350	150	732,2	196,3
C.11.450	450	350	150	732,2	196,3

4. Discussion

The results are based on a theoretical framework, which can lead to discrepancies based on factors outside of the scope of this study. Some uncertainty is to be assumed as the study does not consider all phases of a life-cycle assessment. The sensitivity analysis with regards to lifespan in table 3 is especially uncertain as it is a purely theoretical analysis. When exceeding the original lifespan of 60 years no additional maintenance, repair or replacement is assumed, meaning that in reality the embodied emissions would increase as well as a possible change in operational emissions. Furthermore, the insulation thicknesses assessed in this study might exceed what is practical or economically feasible, however these aspects have not been considered for the purpose of this study.

The environmental impact of a building can vary greatly based on the geographical location, both as a result of the electricity mix used, both in use and for the material production, as well as transportation of the materials to the building site. As shown in Case A, the choice of electricity mix makes a significant impact on the lifetime emissions. The sensitivity ratio (SR) was calculated according following standard methodology [11], the results can be seen in Table 5. The results are clearly more sensitive to variations in lifespan and CO_2 factor, than the insulation variations studied, which corresponds to the findings in Table 3. The building sector might not be able to control the CO_2 factor from the grid, but it can affect the lifetime of the buildings. The findings show that no matter how optimally insulated the building is the annual CO_2 emissions will decrease for longer lifespans, so it is important to ensure that the building is robust enough to last for as long as possible.

Table 5. Sensitivity analysis

Parameter	**SR**
CO_2 factor	0.76-0.81
Lifespan	0.78-0.82
Insulation - roof	0 - 0.12
Insulation - wall	0.07 - 0.37
Insulation - floor	0 - 0.07

The results of this study are representative of a house built in Norway or the Nordic region, as most of the materials (and thus EPDs) considered are provided by Norwegian manufacturers.

Case B showed that the roof and the floor insulation did not contribute significantly to the decrease of lifetime emissions compared to that of the wall insulation. At around 200-250 mm, the slopes level out. Even though the lifetime emissions are decreasing after this point, the return on investment will be slight. If the electricity mix becomes less carbon intensive over time, this added insulation might even contribute to an increase in lifetime emissions. This study suggests that it is not given that the solution to reducing the carbon footprint of buildings can rely solely on adding more material. In passive houses it is not uncommon for the insulation thicknesses in the roof to exceed 400 mm and 300 mm in the floor. As Figure 1 shows, the slope of lifetime emissions has evened out long before reaching these thicknesses. It might therefore be beneficial to reconsider the amount of insulation used in these components.

The results of this study indicate that it is not necessarily beneficial to increase the insulation thickness uncritically and expect it to yield lower lifetime emissions. Trend 2 has 250 mm insulation in the roof, 200 mm in the walls and 300 mm in the floor. For this particular building, the results show that the insulation in the floor does not have a significant impact on the lifetime emissions, yet in the original building, the floor is the component with the most insulation. EPS insulation, which is used in the floor construction, is also more carbon intensive than mineral wool, used in the wall and the roof. For Trend 2 it would therefore be recommended to decrease the insulation in the floor construction, and increase it in the walls. Changing the insulation thicknesses to 150 mm in the roof, 350 mm in the walls and 100 mm in the floor leads to the same amount of delivered energy as a building with TEK 17 recommended insulation thicknesses, but with embodied emissions of 191 kg CO_2/m^2, 6 kg CO_2/m^2 less than the original. In total, this is actually less insulation than in the TEK 17 version. It is therefore possible to use less material, yet still achieve the same or even better energy performance.

5. Conclusion

The study concludes that overall, the calculated GHG emissions vary inverse proportionally with the material quantities - more insulation leads to lower operational emissions, and overall lower lifetime emissions. Although more insulation increases the embodied emissions, it generally does not outweigh the energy savings of the increased insulation.

The location of the insulation is the factor that was found to have the largest impact on the lifetime emissions. For this particular building, when changing only one component at a time, the operational emissions were most sensitive to the insulation thickness in the walls. Thin walls (100 mm) resulted in lifetime emissions 15.2% higher than Trend 2 and when the walls had 500 mm insulation the lifetime emissions decreased with 14.9%. With the same insulation thicknesses in the roof and the floor the lifetime emissions varied from +5.1% to -1.5% and from +2.8% to -0.1% respectively. It is likely that this distribution is partly affected by the area difference, as the wall surface area is more than double than those of the roof and floor and thus allows for more heat transmission.

While the increased embodied emissions generally is outweighed by the energy savings resulting from the increased insulation thickness, it is desirable to ensure that the embodied emissions are as low as possible for a given level of operational emissions. A Pareto distribution comparing the embodied to the operational emissions for each case was created to identify the most efficient combinations of insulation thickness. The most Pareto efficient cases tended to have little insulation in the floor (100 - 150 mm) and relatively high insulation thickness in the wall (350 mm), some cases having more and less. The most variable component was the roof, varying from 150 to 400 mm.

It is clear from the findings of this study, that increasing the insulation thickness uncritically does not necessarily yield an optimal solution for lowering the lifetime GHG emissions of a building. It can be enough to increase only one component (in this case the insulation in the wall) while keeping others constant or even decreasing them to lower the lifetime emissions.

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Surface-to-volume ratio: How building geometry impacts solar energy production and heat gain through envelopes

Araji M T

Environmental Design Program, Faculty of Architecture, University of Manitoba, 201 John A. Russell Building, Winnipeg, MB R3T 2N2 Canada

Mohamad.Araji@umanitoba.ca

Abstract. This paper explored the relationship between building geometry and renewable energy production of building-integrated photovoltaics (BIPV). Heat gain was incorporated as a conflicting constraint with respect to energy performance. The building façade was mathematically analyzed by taking into account heat transfer pertaining to site conditions along with different parameters that included shading, orientation, PV tilts (β) and surface-to-volume ratio (S/V) as a measure of building compactness. The study involved calculating the impact of each parameter on the convection, conduction and radiation components of the incoming solar energy. S/V was shown to be directly proportional to the amount of solar energy received by the façades and gained by the building in the form of heat. The positive correlation of heat gain with S/V was nearly linear with a slope of around 41.8 kWh/m^2/m^{-1} and a mean of approximately 3.4 times more. With the most suitable geometry in terms of net energy gain, S/V of 0.14 m^{-1} yielded the highest difference between energy production and heat gain. In terms of β, the results demonstrated negative slope of energy production with respect to the tilt at about 2.12 times higher than that displayed by heat gain. Accounting for inter-building effects, a shading reduction equal to d percent can be estimated to an increase of $1.37d$ degrees in β at a building consumption of 60 kWh/m^2.

List of Abbreviations

H	Shading factor
h	Building height
E	Illuminance
C	Building consumption
E_e	Irradiance
v	Human sensitivity
λ	wavelength
Λ	Range of wavelengths from 450 nm to 750 nm
w	Length of the East-West façade
l	Length of the North-South façade
S/V	Surface-area-to-volume ratio
β	PV tilt
F_s	View factor from sky to PV surface
F_g	View factor from PV surface to ground
A_{facade}	Total area of façade
E_{prod}	Production from building integrated renewable energy
Q_{facade}	Heat gain through the façade per unit area
Q_{solar}	Heat gain through solar irradiation
Q_{cond}	Heat gain through conduction
U	The surface U-value
T_{out}	Outside temperature
T_{in}	Inside temperature
$Q_{solar,b}$	Heat gain through E_B
$Q_{solar,d}$	Heat gain through E_{diff}
$Q_{solar,r}$	Heat gain through E_r
$SHGC_\beta$	Solar Heat Gain Coefficient, dependent on β
E_B	Beam component of solar irradiation
E_{diff}	Diffused component of solar irradiation
E_r	Reflected component of solar irradiation

1. Introduction

BIPV's influence on the heat transfer through the building's envelope has been significant. This is because solar cell surfaces affect the overall thermal resistance of the envelope. Comparisons of energy performance and building cooling and heating loads were performed in [1]. Non-ventilated air duct BIPV was shown to have highest power output and lowest heat transfer. Hot wire anemometry measurements, coupled with CFD computations were utilized to calculate heat transfer coefficients in a BIPV/T setting [2]. It was concluded that heat transfer characteristics of PV's internal surface play a critical role in the performance of the façade. The impact of climate on BIPV production was studied in [3]. It was concluded that output is maximized on cold, clear days. Also, snow was found to be a positive factor in production since it can reflect light on to the solar panel from other surfaces. Using a series of experiments, a non-linear stochastic differential equation was developed for the heat transfer of a BIPV component [4]. The method was shown to be useful in modelling nonlinear stochastic thermal phenomena in BIPV systems. The impact of surface temperature of BIPV was mathematically investigated in [5]. It was established that heat transfer increased with forced ventilation, and a high forced velocity in the air gap contributed to increased heat transfer from the BIPV unit. A simulation model aimed at predicting energy production, thermal behaviour and transient interaction with the building envelope was presented in [6]. The accuracy of the model regarding surface temperatures was close to 0.6^{o}C, while for air temperature at the outlet of the system, the accuracy was slightly less than 1^{o}C. Suitability of BIPV in terms of thermal performance was studied in [7]. The study was based on real-time data monitoring supported by computer-based building simulation model. It was concluded that PV as a roofing material caused significant thermal discomfort to the occupants. A fully coupled PV model, integrated in a building simulation code was used to predict the temperature field in the complex wall constituted by BIPV façade in [8]. It was concluded that the performance of the BIPV was greatly dependant on the radiative heat transfer within the semi-transparent layers and the convective heat transfer in the fluid layers.

In terms of building form utilizations, the associated optimum geometry and composition in the presence of BIPV is still limited. Bostancioglu [9] confirmed that the building form along with thermophysical features of the envelope are among the significant factors affecting a building's energy performance. Depecker et al. [10] studied the ratio of the external skin surface and inner volume of the building as a representation of building geometry. This ratio was found to be inversely proportional to building's energy consumption in cold and scarcely sunny winters. A one-dimensional transient model for a BIPV system resulted in an overall energy efficiency of 53.7% by applying the PV modules for a fixed building form [11]. Hemsath et al. [12] studied energy consumption with multiple building geometry variations and material considerations. The outcomes of their research stressed the significance of formal variations in the early design phase to inform decision-making for best building performance. Hwang et al. [13] showed an analytic optimization for PV modules inclinations with relevant spacing between them in building façades. A genetic algorithm was recently developed to help designers determine the optimal envelope geometries with BIPV while considering the net building energy performance with both consumption and generation as the evaluation criteria [14]. The study tested features such as building dimensions, window-to-wall-ratio, orientation, and PV alignment.

Overall, focusing on the specification of PV components in relation to the envelope is no longer sufficient. There is a need for computational methods to advance building form optimization while integrating renewables for zero energy targets. Energy generation and heat gain have been studied separately in terms of the building geometry. This paper aims to answer the novel question of how to seek the most optimal geometry that *jointly* optimizes the conflicting constraints of BIPV performance and heat gain through the façade. Since there is no closed-form relationship between a building's geometry and these constraints, numerical studies are presented to estimate this correlation. The analysis involves mathematical modeling of parameters specific to additional contextual boundary factors of building consumption with various programs and forms with their applicability and feasibility analysis.

2. Methodology

A mathematical model is extended in the following subsections to examine the energy performance as related to building design optimization and integrated PV. The work comprises of procedures for heat gain calculation and the influence of building geometry.

2.1. Heat Gain Calculation

Let the rate of heat gain through the façade per unit area be given by $\dot{Q}_{facade}$ (units: W/m^2). Then,

$$\dot{Q}_{facade} = \dot{Q}_{solar} + \dot{Q}_{cond}, \tag{1}$$

where Q_{solar} and Q_{cond} represent the heat gain through solar irradiation and conduction respectively, and the dot operator is used to represent the rate. $\dot{Q}_{cond}$ depends on the U-value of the surface and the temperature difference across it:

$$\dot{Q}_{cond} = U(T_{out} - T_{in}), \tag{2}$$

where U, T_{out} and T_{in} represent the surface U-value (units: W/m^{2}K), outside temperature(units: K) and inside temperature(units: K) respectively.

The heat gain through solar irradiation is a product of incident solar irradiation and the solar heat gain coefficient (SHGC) of the surface. In order to account for $\dot{Q}_{solar}$, components of irradiation (beam, diffused and reflected) should be separately accounted for. In other words, $\dot{Q}_{solar}$ can be written as

$$\dot{Q}_{solar} = \dot{Q}_{solar,b} + \dot{Q}_{solar,d} + \dot{Q}_{solar,r}, \tag{3}$$

where $Q_{solar,b}$, $Q_{solar,d}$ and $Q_{solar,r}$ represent the heat gain through the beam, diffused and reflected components of solar irradiation (denoted by E_B, E_{diff} and E_r respectively). Studies have shown that SHGC for $Q_{solar,b}$ depends on the tilt of the surface [15]. $Q_{solar,b}$ will also be affected by the shading coefficient H. Thus,

$$\dot{Q}_{solar,b} = SHGC_\beta \cdot E_B \cdot H, \tag{4}$$

where the subscript β with SHGC is there to show the former's dependence on the latter. H takes values between 0 and 1, where 0 implies complete shading and 1 implies no shading. $\dot{Q}_{solar,d}$ is given by

$$\dot{Q}_{solar,d} = SHGC \cdot E_{diff} \cdot F_s, \tag{5}$$

where F_s is the sky view factor given by $F_s = \frac{1+\cos\beta}{2}$. $Q_{solar,r}$ is given by

$$\dot{Q}_{solar,r} = SHGC \cdot E_r \cdot F_g = SHGC \cdot \rho_g E_B \cdot F_g, \tag{6}$$

where ρ_g is the reflection coefficient (typically set as 0.2), and F_g is the view factor from the ground given by $F_g = \frac{1-\cos\beta}{2}$. Plugging Eqs. (2), (3), (4), (5) and (6) in Eq. (1), the total heat gain per unit area through the façade can be summarized as:

$$\dot{Q}_{facade} = SHGC_\beta \cdot E_B \cdot H + SHGC \cdot E_{diff} \cdot F_s + SHGC \cdot \rho_g E_B \cdot F_g + U(T_{out} - T_{in}). \tag{7}$$

The convention to calculate $SHGC_\beta$ utilizes angle correction factors [16]. If the correction factor for a specific β is given by f_β, then $SHGC_\beta = f_\beta \cdot SHGC$.

In conjunction with the above analysis on irradiation, a similar analysis can be done on lighting by noting that illuminance is obtained by averaging irradiance over the sensitivity of human eye for the full spectrum of wavelengths [17]. In other words,

$$E = 683 \cdot H \int_{\lambda \in \Lambda} E_e(\lambda) v(\lambda) d\lambda. \tag{8}$$

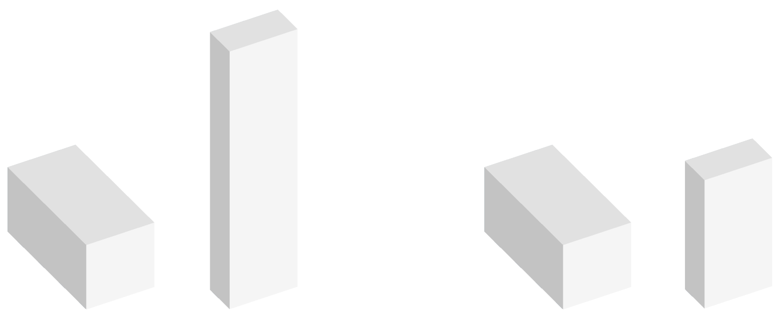
where E represents illuminance (units: lux), $E_e(\lambda)$ represents spectral irradiance (units: W/m^2), v represents human sensitivity, λ represents wavelength (units: m) and Λ represents the range of wavelengths from 450 nm to 700 nm, where spectral efficiency is prominent [17]. It is clear from Eq. (4) and Eq. (8) that the effect of shading on lighting will be similar to that on irradiance, i.e., shading factor H acts as a proportionality constant in both cases. This is in alignment with studies reported in the literature [18].

2.2. Influence of Building Geometry

It is noteworthy that $\dot{Q}_{facade}$ in Eq. (7) is represented per unit area. However, area of the façade alone does not provide the complete picture of a building performance in terms of its heat gain and energy production. Let E_{prod} (units: kWh/m^2) denote the energy production per unit area from the PV panels installed on the building's façade. Figure 1 shows two cases to demonstrate the influence of building's geometry. In the first case, two buildings with equal occupancy but unequal façade area (A_{facade}) are shown. In the second case, the reverse case is shown (unequal occupancy and equal A_{facade}). Both these cases allude to some correlation between a building's performance per capita and its compactness. A suitable measure of building's compactness is the surface-area-to-volume-ratio (S/V) which is defined as the ratio of A_{facade} to the volume of the building. For a rectangular building, this can be given by,

$$S/V = \frac{A_{facade}}{lwh} = \frac{2lh + 2wh}{lwh} = \frac{2}{w} + \frac{2}{l}. \tag{9}$$

A similar relationship between building shape and heat transfer through its façade is reported in [19], where the author used the term shape coefficient to represent the ratio of façade and roof surface area to its volume. In Figure 1, both cases yield a higher energy production and heat gain per capita when S/V is higher.



	Case 1		Case 2	
Width x Length x Height	1 x 2 x 1	1 x ½ x 4	1 x 2 x 1	1 x ½ x 2
Volume (cubic unit)	2	2	2	1
Façade Area (square unit)	8	12	6	6

Figure 1: Case 1: Equal volume but different façade areas. Case 2: Equal façade areas but different volume.

2.3. Assumptions and Input Parameters

To apply the mathematical model, some parameters need to be specified. For application purposes, the city of Chicago in the United States of America was considered with a latitude

41.87^{o}N and longitude 87.62^{o}W and a six-hour lag from Greenwich. The average solar irradiation on the PV modules was 2 to 3 kWh/m^2/day and the climate was classified as continental. Building orientation and PV tilt ranged from 0^o to 90^o and from site's latitude to vertical façade's application, respectively. T_{out} is taken to be 27^{o}C, which is the average temperature in Chicago for the month of August. T_{in} was chosen as 23^{o}C; typical indoor temperature. The U-value for a typical double glazed unit plus a transparent PV module was selected to be 1.2 kW/m^2 [20].

3. Result and Discussion

The positive correlation between a building's performance and its S/V value cannot be expressed in closed form analytically. However, numerical evaluation is conveniently done by changing l, w and h is equal proportions for E_{prod}, Q_{facade} and S/V. This trend is shown in Figure 2a, where the optimum number of occupants per square meter have been chosen to be 0.0286 [21]. The trend of Q_{facade} is fairly linear with a slope of 41.8. However, the behavior of E_{prod} can be divided into two separate (almost linear) regions. For $S/V < 0.13$, the slope of E_{prod} is steep with a value of 405, while for $S/V > 0.13$, slope decreases to about 30. Given that Q_{facade} contributes to the overall building consumption C, an optimum building geometry should be sought that maximizes the difference between E_{prod} and Q_{facade}. This difference is shown in Figure 2b. It can be observed that the relationship between S/V and $E_{prod} - Q_{facade}$ follows a convex path with a global maximum at some intermediate value (0.1407 in this case). It follows that the most optimal geometry for a building in terms of its energy performance and heat transfer will have S/V that maximizes $E_{prod} - Q_{facade}$. In order to achieve S/V values shown in Figure 2b, a range of values of h, l and w are $h \in [20,200]$(units: m), $lw = Area \in [400,2000]$ (units: m^2) and $AR = \frac{l}{w} \in [1,10]$ (unitless).

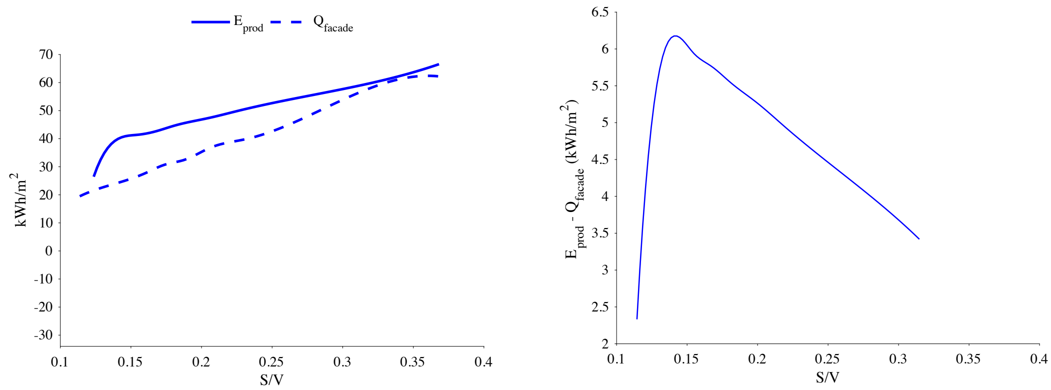


Figure 2: (a: Left) E_{prod} and Q_{facade} vs S/V (b: Right) S/V vs $E_{prod} - Q_{facade}$.

It is noteworthy from Eq. (9) that a specific value of S/V can be achieved by an infinite combinations of h, l and w. This flexibility is useful in case of any practical constraints that may limit a building's area or height. $E_{prod} - Q_{facade}$ starts from a minimum and increases linearly with a slope of about 8.45 before reaching its maximum of 98,700 kWh/person. Then, $E_{prod} - Q_{facade}$ begins to decrease in a non-linear fashion before reaching the minimum value at S/V of 0.28.

The dependence of β on Q_{facade} is evident from Eq. (7). Additionally, E_{prod} also depends on β since the incident angle of solar irradiation directly influences the amount of energy generated.

The quantification of this dependence is shown in Figure 3 for a south facing façade surface at a site location of latitude 41^o. E_b is calculated to be 23.93 kWh/m^2 through ASHRAE [22], and E_{diff} is taken to be 45% of E_b [23]. It is clear that $\beta = 40^o$ yields the highest energy production. This is in confirmation with the literature, that reports the site's latitude to be the most productive value of β [24]. The decrease in E_{prod} with β is observed to be almost linear. For every d unit increase in β, E_{prod} decreases by 28.3d units. With respect to Q_{facade}, the trend is constant till $\beta = 65^o$, after which it starts decreasing with a slope of 13.47 units.

In order to study the inter-building effects on BIPV production, Figure 4 displays the range of achievable energy thresholds as a function of β and H. These thresholds refer to the percentage of energy produced compared to the total consumption of 40 kWh/m^2 and 60 kWh/m^2. A threshold level of 100% or more would correspond to meeting the net-zero criterion. For each β, the lower and upper boundaries of the region correspond to full shading ($H = 0$) and no shading ($H = 1$) respectively. As β moves away from the site's latitude, shading level should decrease to stay at the same threshold level. For example, at 60% level and $C = 60$ kWh/m^2, $\beta = 40.6^o$ can allow for 59% shading, while $\beta = 89.9^o$ allows for only 15% shading. The net-zero region can be achieved for ($\beta < 49.49^o$, $H > 0.91$) for $C = 60$ kWh/m^2 and ($\beta < 90^o$, $H > 0.48$) for $C = 40$ kWh/m^2 as shown in the shaded region.

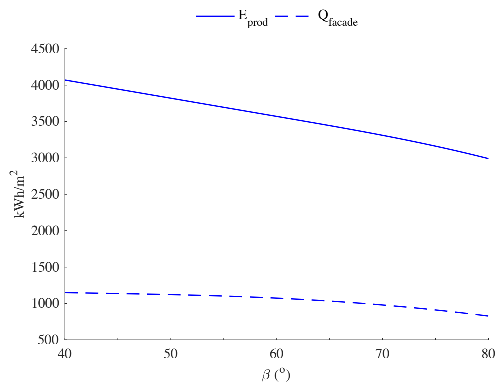


Figure 3: E_{prod} and Q_{facade} for various values of β.

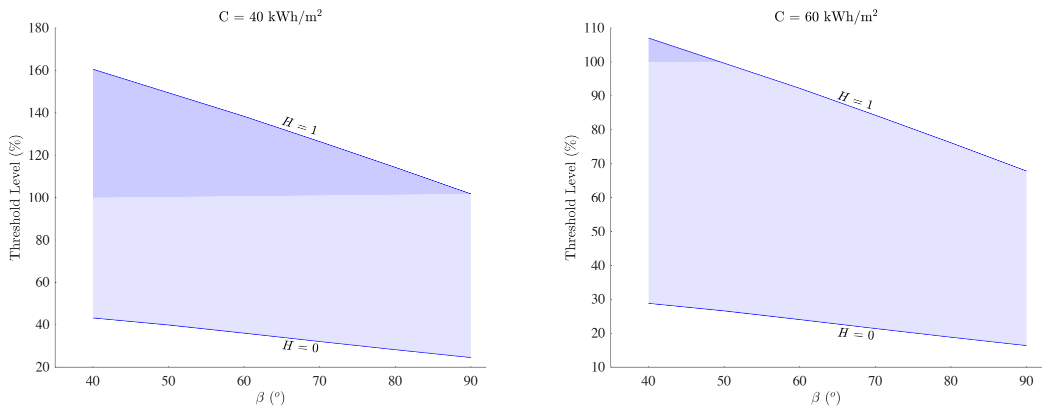


Figure 4: Energy production thresholds with shading factor H and tilt angle β. The darker region corresponds to fulfilling the net-zero criterion.

4. Conclusion

The design and implementation procedure of BIPV as a renewable energy system was carried out in order to find its best performance with various building conditions, taking into consideration comparison between different façade applications, orientations, and relevant tilt angles. In terms of parameters, the most effective methods of maximizing PV's energy production would involve factors such as specification of the building's surface-to-volume ratio (S/V), orientation, and the effect of PV tilt angle (β) on energy targets. The goal of this work was to establish a mathematical relationship for the heat transfer through a BIPV façade system. To this end, components of conduction and radiation were separately considered, and the dependence of β on the radiation component through the solar heat gain coefficient was described in detail.

This paper linked the BIPV performance to heat gain through the building envelope. It is suggested that heat gain is directly proportional. There is a considerable utility with such multidimensional problem of maximizing energy production and minimizing heat gain. Both E_{prod} and Q_{facade} were shown to be directly proportional to S/V. The positive correlation of Q_{facade} with S/V was nearly linear with a slope of around 41.8 kWh/m^2/m^{-1}. The average positive correlation of E_{prod} with S/V was approximately 3.4 times higher. The difference of E_{prod} and Q_{facade} was analyzed against S/V to investigate the most suitable geometry in terms of net energy gain. It was found that under continental conditions considered, S/V of 0.14 m^{-1} yielded the highest difference between energy production and heat gain. In terms of PV tilt β, the results demonstrated that both E_{prod} and Q_{facade} are maximized when β is close to the site's latitude. The negative slope of E_{prod} with respect to β was about 2.12 times higher than that displayed by Q_{facade}, concluding that the site's latitude is most optimal in terms of $E_{prod} - Q_{facade}$.

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Assessment System for Sustainable Buildings of the German Government (BNB): Calculation tool for the ventilation rate and the resulting carbon dioxide concentration in the ambient air

Schütz H, Böttcher O

Federal Institute for Research on Building, Urban Affairs and Spatial Development
Straße des 17. Juni 112
10623 Berlin, Germany

Heidemarie.Schuetz@BBR.Bund.de, Olaf.Boettcher@BBR.Bund.de

Abstract. An important criterion for Assessment of the sustainability of buildings owned and occupied by the Federal Government is the indoor air quality. The stated aim is to avoid pollutants from construction products and unacceptable carbon dioxide concentrations. Regarding the limitation of the carbon dioxide concentration especially in rooms with high occupancy the challenge is to find a suitable ventilation concept. That concerns natural ventilation as well as mechanical ventilation or the combination of both.
Although there are normative rules for the required air change it is hardly verifiable during building planning whether the proportion of natural ventilation is sufficient in practice. Various evaluation reports in the past have shown that natural ventilation comparability mostly did not work, especially in rooms with high occupancy. In addition, it was also shown that comparability of the test results was usually not given and therefore no conclusions could be drawn on functioning ventilation concepts.
To be able to determine and evaluate the air exchange (in case of natural ventilation) and the resulting development of the carbon dioxide concentration in a room, the development of a calculation tool is part of a recent research project. The tool is used to calculate the outdoor air volume flow with natural ventilation depending on multiple parameters (as examples: wind, temperature, window size, window opening). In the same step CO_2 concentration for a certain number of CO_2 sources in the room will be determined automatically. Thereby the tool will be very helpful in an early stage of planning to find a proper ventilation concept. In addition to its use as a planning aid, the tool offers two different applications for assessing carbon dioxide concentration in a room: The calculation under specified conditions provides the opportunity to classify the expected carbon dioxide emissions as part of the assessment of sustainable buildings. The tool is also suitable for checking the air exchange under extreme climatic or other individually selectable conditions. At the end the calculation results of each individual constellation are shown in graphical diagrams.

1. Introduction

For many years sustainable building has been a natural part of the planning and construction processes for Buildings which are owned and used by the Federal Government. In order to achieve future requirements for holistically optimized buildings the Federal Building Ministry has set up binding quality requirements and quality criteria which are described and constantly being developed in the Sustainable Building Guide and the Sustainable Building Assessment System (BNB). The Division

Sustainable Buildings in the Federal Institute of Research on Building, Urban Affairs and Spatial Development (BBSR) has the task to support the Federal Building Ministry in questions of sustainable construction. Therefor it elaborates the basics, is responsible for the continuation of the BNB and supervises corresponding research projects.

The BNB, which has been mandatory for federal building since October 2013, describes the building qualities in a transparent, comprehensible and verifiable manner. On the one hand it is an essential assessment system for defining the goals in the sustainability of a building and the integration of sustainability aspects into the planning process. On the other hand, the final assessment of sustainability after building completion leads to a certificate, which summarizes the evaluation of 46 individual criteria into an overall grade.

As human beings and their needs are an integral and important part of sustainable construction, equivalent to environmental and economic goals, the BNB also includes a number of criteria relating to the health and comfort of building users. The most important criterion in this regard is the indoor air quality [1] which assesses the pollutants from construction products and carbon dioxide emissions caused by room users. Failure to keep the boundary valuewill result in the exclusion of the BNB certification.

To ensure that the carbon dioxide concentration does not exceed the level of occupational health and safety regulations (max. 1000 ppm CO_2 in the interior – see also Table 1.) a sufficient air exchange is required.

Table 1. CO_2 concentration in the indoor air according to ASR [2] A3.6 and AIR [3].

CO_2 Concentration [ppm]	Hygienic Valuation	Measures
<1000	Hygienic inoffensive	• No further measures (as long as the room use causes no increase in concentration over 1000 ppm).
1000-2000	Hygienic conspicuous	• Check and improvement of airing habits • Preparing an airing plan (e.g.. to determine responsibilities) • Airing measures (e.g. outdoor air volume flow or raising air exchange)
>2000	Hygienic unacceptable	• Further measures necessary (z. B. enhanced airing, reduction of the number of people in the room)

2. Need for research / Purpose

Various evaluation reports in the past have shown that natural ventilation mostly did not work, especially in rooms with high occupancy. Nevertheless, for example school buildings in Germany are usually still built without a mechanical ventilation system. On the basis of this insight, existing measurement studies in German schools were analyzed on behalf of the BBSR according to the respective spatial conditions and the corresponding ventilation behavior. The aim was to draw conclusions about the practicability of various concepts of natural ventilation for rooms with difficult conditions [4]. The result of this investigation has shown that, although the measurements series presented the CO_2 concentrations, various determining boundary conditions of the respective room situation were not documented. Therefore, neither comparability nor evaluability were given and the desired conclusions impossible. But yet, it has been shown that a basic supply via a mechanical ventilation system in combination with natural ventilation seems quite practicable. Even with such so-called hybrid ventilation concepts, however, considering natural ventilation in planning is a particular challenge.

Although there are normative rules for the required outdoor air volume flow and for the calculation of required window opening area, in natural ventilation it is hardly verifiable during building planning whether the proportion of natural ventilation is sufficient in practice. By developing ventilation concepts the ventilation scenarios as well as the local spatial and climatic conditions (e.g. speed and direction of the wind, temperature difference inside / outside, internal thermal loads) are critical parameters for the calculation of volume flows achieved by natural ventilation and the resulting CO2 concentration in the room.

Therefore, such evidence is usually provided indirectly in compliance with the requirements of the standard. So far suitable tools for the development of effective ventilation concepts in the planning phase are missing. This results in a need for corresponding specialist information and a transparent tool for calculation carbon dioxide concentrations in the interior as an approximate planning assessment tool according to sustainable building.

The research project „Entwicklung von Handlungsempfehlungen für praxisgerechte Lüftungskonzepte und Entwicklung eines CO_2-Berechnungstools“[5] presented below is intended to develope instruments for planning the CO_2 concentrations during the phase of use and for verifying the functionality of different ventilation concepts. Furthermore, the possibility of an automated BNB assessment should be created. In detail, the following goals are to be achieved:

a) Identification of opportunities and limitations of natural, hybrid and mechanical ventilation under clearly defined parameters at different use scenarios and under considering all aspects of thermal comfort.

b) Development of a valuation tool through which both the required outside air volume flows and the resulting CO_2 concentrations can be determined especially for window ventilation and in combination with mechanical ventilation according to the respective framework conditions.

c) Drafting of descriptive recommendations for different ventilation concepts and room constellations which can be published within the framework of the BBSR.

3. Concept and method

The possibilities and limitations of natural ventilation in rooms with high occupancy are studied in an experimental test station under laboratory conditions. Through that the numerous factors influencing natural ventilation can be better controlled and logged. The test station simulates a typical classroom situation.The study series includes stationary and transient experiments.

3.1 Experimental test station

The basic structure of the test station (Figure 1) consists of two areas: The climate area 1 simulates the outdoor area and the climate area 2 forms the section of a typical classroom with a need for space of about 2 m²/ child. This area is equipped with rows of tables and people simulators which generate the heat load and CO_2 emissions per person. Both areas are separated by a wall in which the windows to be examined are installed. The selected depth of the test station allows the installation of up to 2 windows allowing experiments with openings of only one or both window axes can be performed.

Adjustable radiators are arranged below the windows. Through a decentralized ventilation system, the climatic area 2 can also be mechanically ventilated. The vertical ventilation system installed on the external wall has two ventilation openings in the parapet area and one exhaust opening in the ceiling area of the facade. Radiators and decentralized ventilation are not shown in Figure 1.

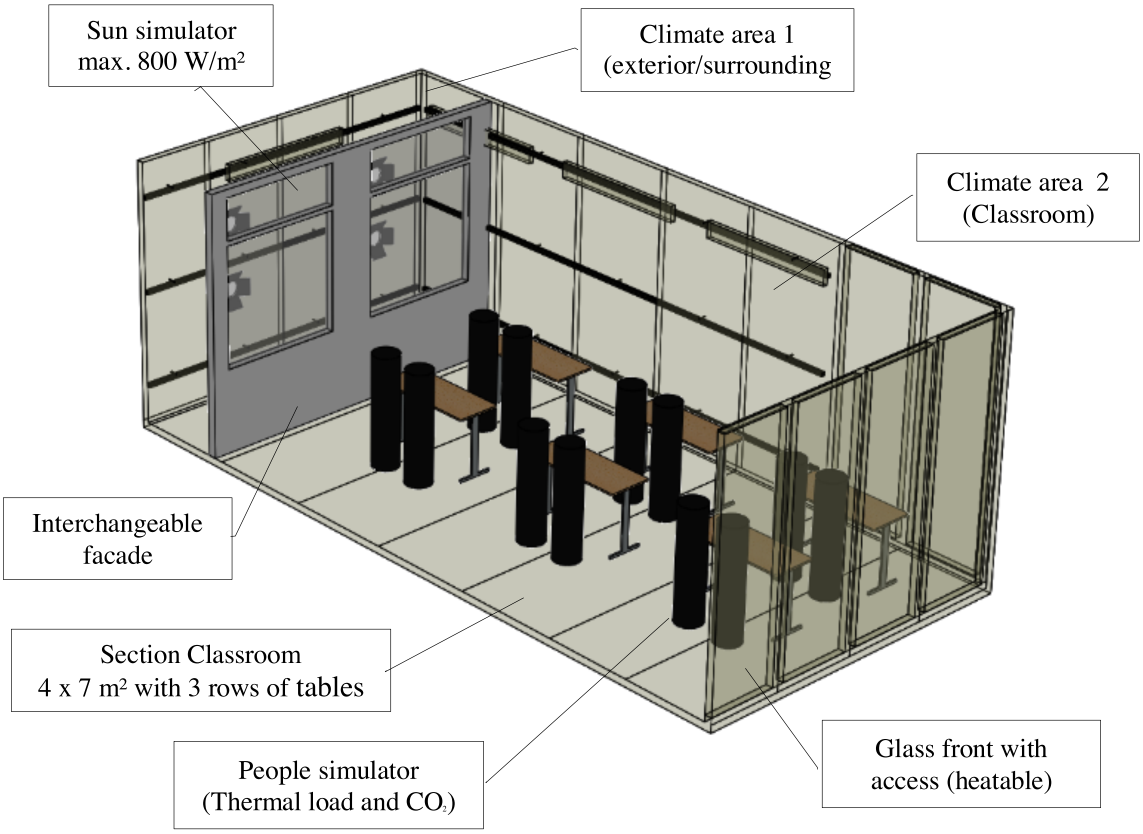

Figure 1. Basic setup of the test station.

The following data are recorded through these measurements:

- Temperature distribution in the classroom distributed up to 27 different points horizontally and vertically
- CO_2 distribution in space at up to 4 positions horizontally and in 2-3 levels at 4-6 positions each
- Thermal comfort at a defined measurement point (operating temperature, air velocity, CO_2)

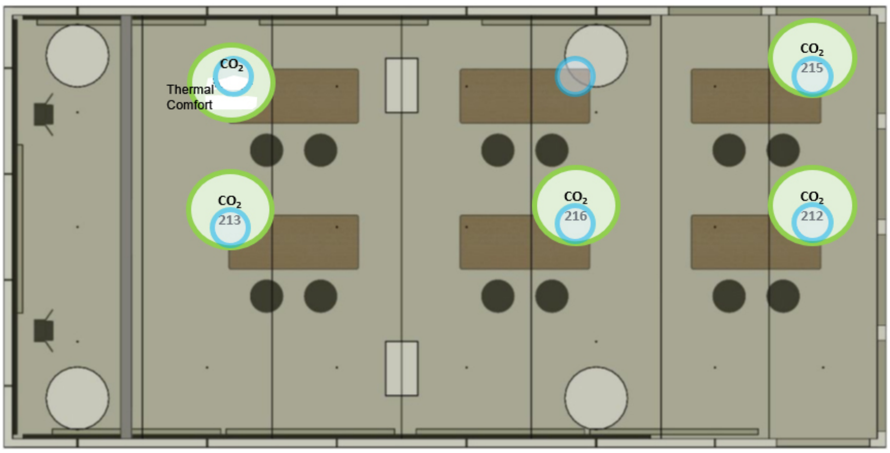

Figure 2. Measurement points ground plan.

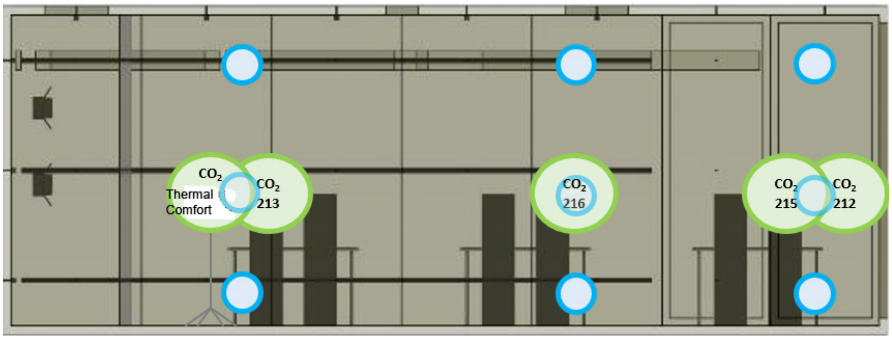

Figure 3. Measurement points sectional drawing.

In the studies on natural ventilation, the resulting volume flows were not measured directly, but indirectly determined by the tracer gas method via the decay of the CO_2 concentration in the indoor air.

3.2 Stationary test

The stationary tests are concerned with the effectiveness of different ventilation scenarios (natural ventilation, mechanical ventilation, hybrid ventilation) under constant conditions to determine the actual outside air volume flows and the resulting CO2-concentrations in the room.

The focus of these studies is initially on windows with turn and tilt wings, as this type of window is the most widespread. As a next step, other types of windows will be examined. In the test series, different boundary conditions vary, such as outside temperature (0 °C, 13 °C, 26 °C), solar heat input (with / without), wind speed (0 m/s, 3 m/s) and window opening positions.

The results for the outside air volume flows in the stationary tests with focus on natural ventilation are the base for the comparison which calculation approach is best suited for the calculation tool. The standards listed below are generally suitable for the calculation of volume flows from natural ventilation:

DIN EN 15242 [6]
DIN EN 16798-7 [7]
DIN SPEC 4108-4 (draft) [8]

Within the BNB assessment the calculation of the volume flow according to DIN EN 15242 [6] is mandatory. For the closer examination of the carbon dioxide concentration in the course of the day with freely selectable parameters no calculation rule has been defined yet in the BNB. For this purpose, prospectively the calculation formula which comes closest to the measurement results should be selected.

3.3 Transients tests

The series of measurements under transient conditions should provide insights about the spatial distribution and development of the CO_2 concentration over a longer period under certain ventilation scenarios and operating conditions. The results of the measurements are also used to evaluate the CO_2 tool which is used to calculate CO_2 developments over longer periods of time. Table 2 shows an example of a corresponding daily profile.

Table 2. Usage profile of a lesson day for a transient test.

Time-Start	Time-End		Presence of Children	Occupancy	Window Position
08:00 am	08:45 am	1. period	yes	100%	all closed
08:45 am	08:50 am	5-min-break	yes	100%	upper part tilted, lower part 140 mm
08:50 am	09:35 am	2. period	yes	100%	all closed
09:35 am	09:55 am	20-min-break	yes	50%	upper part tilted, lower part 140 mm
09:55 am	10:40 am	3. period	yes	100%	all closed
10:40 am	10:45 am	5-min-break	yes	100%	upper part tilted, lower part 140 mm
10:45 am	11:30 am	4. period	yes	100%	all closed
11:30 am	12:00 am	30-min-break	no	0%	upper part tilted, lower part opened 90°
12:00 am	12:45 am	5. period	yes	100%	all closed
12:45 am	12:50 am	5-min-break	yes	100%	upper part tilted, lower part 140 mm
12:50 am	01:35 pm	6. period	yes	100%	all closed
01:35 pm	01:45 pm	10-min-break	yes	50%	upper part tilted, lower part 140 mm
01:45 pm	02:30 pm	7. period	yes	100%	all closed
02:30 pm	03:15 pm	8. period	yes	100%	all closed

The results lead to planning and action recommendations for the creation and implementation of ventilation concepts.

3.4 Tool development

The new CO_2 tool is based on Excel and serves as an instrument through which both the outside air volume flows and the CO_2 concentration in the indoor air can be determined. Particularly the contribution of pure natural ventilation is of interest, but also their contribution in combination with mechanical ventilation according to the respective framework. The tool has two modes:

a) Calculation of the CO_2 concentration according to BNB-criteria 3.1.3 (V2015) under fixed conditions
b) Calculation of the CO_2 concentration during the day under free conditions

Case a) serves to demonstrate the indoor CO2 concentration within a ventilation interval in accordance to the requirements of the corresponding BNB assessment criterion under following conditions.

- Intensive airing for 5 min. once after 60 Min. or during lessons once after 45 Min.
- Temperature difference inside / outside: 7 K
- Outside CO_2 concentration: 400 ppm
- One-sided room ventilation
- Average wind speed 3 m/s

The case of application b) also allows the CO2 concentration profile to be determined via a self-selected daily profile and / or under changed climatic conditions in order to be able to check different usage scenarios under different conditions.

4. Summary of the results

In the studies on the effectiveness of natural ventilation through windows with turn / tilt wings, 28 different configurations of the relevant variables were considered. In addition, 8 hybrid and 2 mechanical ventilation scenarios were examined. The number of experiments with mechanical ventilation could be kept low since the expected decrease in concentration occurred. To ensure result transferability to other types of windows corresponding series of tests are currently in progress.

4.1 Algorithm for the calculation of volume flows in natural ventilation

An essential aim of the studies on natural ventilation was to find out which of the existing calculation rules in the standards best reflects the results of the experiments. Therefore the experimentally determined volume flow of a test series was compared with the calculated volume flows of the three considered standards.

The summarized results in Table 3 show that the use of the calculation regulation from DIN SPEC 4108-8 (draft)[8] gives the smallest deviations from the experimental volume flows. The calculation of this standard is therefore used calculating the air volume flows for window ventilation in the CO_2 tool.

Table 3. Summary of the results with regard to frequency of deviations as well as the absolute and percentage deviation of the measured values from the calculated values.

Standards	Number of lowest Deviation total	Up from that	Down from that	Absolute Average Deviation in m³/h	Relative Average Deviation in %
DIN EN 15242	7	4	3	84	16
DIN EN 16498-7	5	3	2	266	54
DIN SPEC 4108-8 (draft)	16	2	14	20	15

4.2 CO_2 Tool

For natural ventilation, the calculation tool considers the algorithm for determining the volumetric flow chosen in Section 4.1. The volume flows of the mechanical ventilation are entered directly into the tool. The CO_2 concentration of the indoor air can be determined by a pollutant balance of the considered area at any point in time. The tool is separated into three sections:

- **Input section:** In this part all relevant parameters for every room, which has to be considered, are entered (e.g. climate, room geometry, windows, users, usage profile).
- **Calculation section:** The calculation of the respective carbon dioxide concertation curves for all individual rooms occurs after the completed data entry.
- **Result section:** Graphical representations of the carbon dioxide concentration profiles are shown (see Figure 4). In addition the BNB assessment is shown for the use case a).

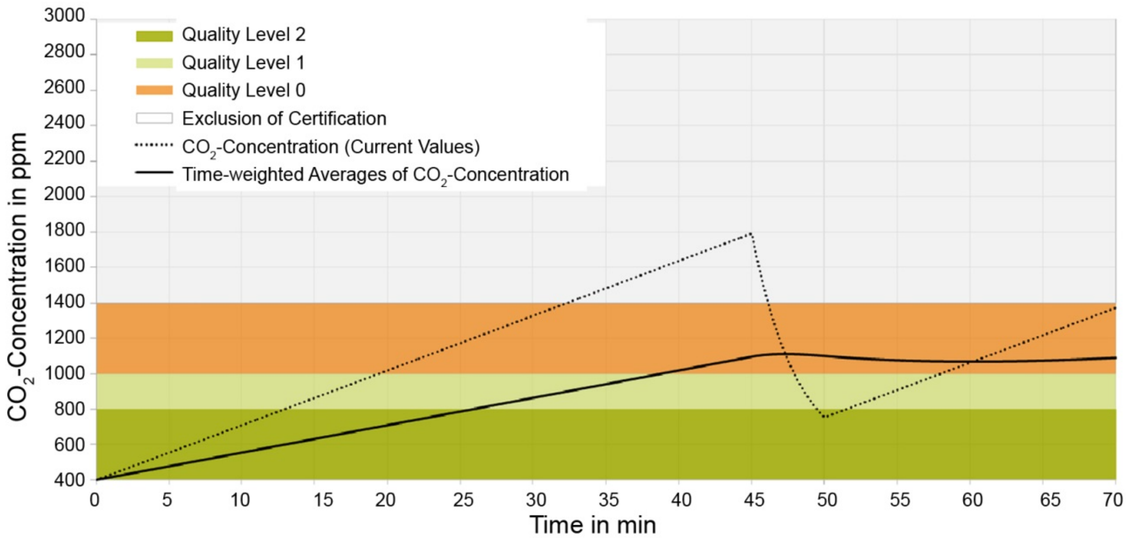

Figure 4. Graphical representation of the carbon dioxide trend and assignment of quality levels according to BNB 3.1.3 version 2015.

4.3 Results of the transient investigations during the course of the day

The CO_2 concentration developments during the day are represented very well based on the different studied usage and ventilation scenarios. Therefor any ventilation concepts can already be modelled in early planning phases and simultaneously its effectiveness is assessable. The exemplified ventilation concept, shown in Figure 5, illustrates that neither ventilation during breaks nor permanently tilted windows – over the entire teaching period – are sufficient to keep the hygienic CO_2 concentrations of max. 1000 ppm on average. Longer periods of intensive airing during lunch break causes a clear subsidence, but this is insufficient for lesson units over several hours.

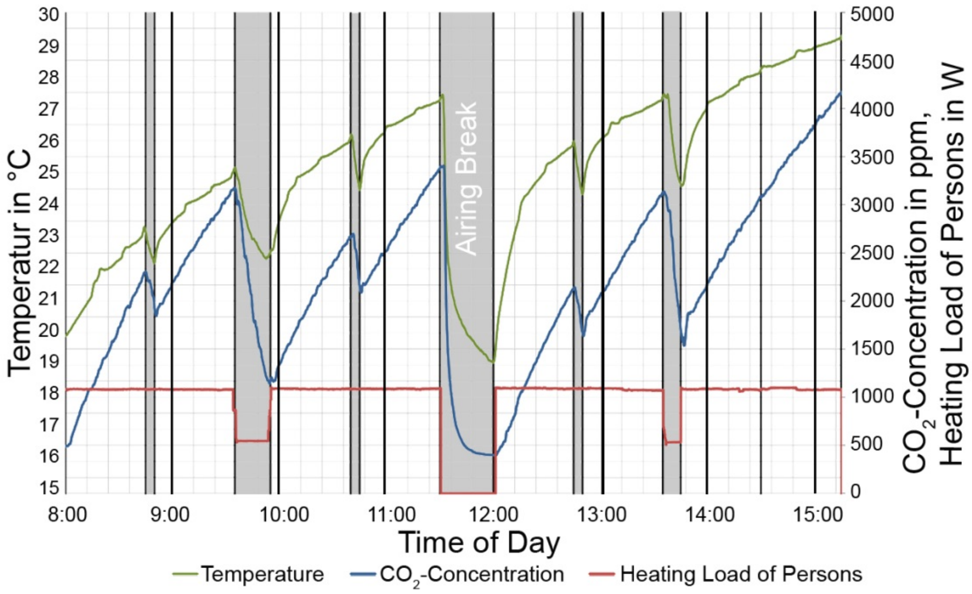

Figure 5. Average temperature and CO_2 concentration curve – transient test at 13 °C outside air temperature (see also Table 3.).

5. Conclusion and outlook

The result of the research project reveals for the first time a tool with user-friendly and intuitive applications, which can already be used during the planning phase and is also suitable for the proof of the expected carbon dioxide content in interiors within the framework of the BNB assessment. The advantage of this procedure of furnishing proof lies in the clarity, comparability and traceability due to its graphic and tabular evaluation. Furthermore, the assessment result is calculated automatically for each individual room and for the entire building at the same time.

All results of the project lead to a manual in the form of a BBSR brochure. Both basics and indicators for functioning ventilation concepts are presented and case studies are used to show which parameters influence the course of the CO2 concentration. Thereby the most problematic spatial constellations with a high occupancy rate are discussed in the example of typical school situations and possible solutions are shown with the help of the tool application.

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Impact of dynamic CO_2 emission factors for the public electricity supply on the life-cycle assessment of energy efficient residential buildings

Müller A[1,2], Wörner P[1]

[1] Institute of Concrete and Masonry Structures, Technische Universität Darmstadt, Franziska-Braun-Str. 3, 64287 Darmstadt, Germany

[2] Institute for Housing and Environment, Rheinstr. 65, 64295 Darmstadt, Germany

a.mueller@massivbau.tu-darmstadt.de

Abstract. Climate change and its effects are the reasons for the energy transition in Germany and lead to an increasing exploitation of renewable energy sources. At the same time, energy efficient buildings reduce the heat demand significantly and allow for the operation of electricity based heating systems. With the aid of dynamic CO_2 emission factors, the life-cycle assessment (LCA) for buildings can be adapted to reflect the fluctuating nature of renewable energy sources and the dynamics of heating power demand during the use phase more precisely. A case study using dynamic building simulation and static as well as dynamic emission factors for the year 2017 shows deviations of 3.4 % in the building's GHG emissions. Furthermore, two emission factors for 2030 and 2050, which reflect the national 80 % carbon dioxide reduction target, are developed and applied to the case study. For these emission factors, the overall building's GHG emissions decline drastically, whereas the deviation between the LCA using static or dynamic emission factors increases significantly. It can be seen that the application of a more dynamic approach for LCA adds substantial value to the investigation. However, further investigation on a broader set of dynamic input parameters for the LCA of energy efficient buildings seems to be reasonable.

1. Introduction

Climate change and its effects are threatening the lives of millions of humans globally. Since the beginning of industrialization in the end of the 19th century, an anthropogenic greenhouse effect caused by carbon dioxide and other greenhouse gases has led to an increase of the global mean temperature and a more frequent occurrence of extreme weather phenomena. In order to prevent major impacts on the livelihood of mankind, climate change needs to be limited to a maximum increase of around 1.5 °C compared to pre-industrial ages. [1] This is why the German federal government has set the ambitious target to reduce greenhouse gas emissions about 80 % to 95 % compared to the base year 1990. As the largest part of German greenhouse gas emissions is caused by the combustion of fossil energy carriers in the electricity sector, the German *Energiewende* initially concentrated most of its efforts on increasing the share of electricity generation from technologies based on renewable energy carriers. Today, Germany's energy transition affects the three sectors electricity, heat and mobility, equally. [2, 3] At first glance, Germany has succeeded in enhancing the electricity generation from renewable energy sources significantly. In 2017, more than one third of the national gross electricity consumption was covered by renewable energies. However, the corresponding GHG emission factor for the public electricity supply in Germany reflects this progress only in part. [4] A stronger penetration with renewable energy sources in all sectors and the implementation of innovative, highly efficient cross-sectoral technologies will help to accelerate the reduction of energy-related GHG emissions. Therefore, sector coupling is considered to be a prerequisite for the next phase of energy transition. [5, 6]

Against this background, it is still uncertain which technologies in which sectors may come up with particularly low GHG emissions if the share of volatile renewable energy sources in the German electricity mix increases steadily until 2030 and beyond. To some extent, this uncertainty can be ascribed to the current methods for the evaluation of environmental impacts of products and processes. The common approach to use static emission factor for the electricity mix, which are defined as an average ratio regarding the produced electric energy over the period of one year, does not lead to realistic results as it neglects the real operation of building technology when assessing the annual energy consumption. Moreover, the integration of more flexible innovative technologies for the power and heat supply asks for more dynamic approaches. As a consequence, any future environmental assessment has to consider the dynamics of both energy supply and consumption.

For this reason, the authors developed a methodology to create electricity generation profiles for Germany in a temporal resolution of 15 minutes, which are transformed into a time series of GHG emission factors in a subsequent step. These dynamic emission factors provide the opportunity for realistic evaluations under consideration of real operation. Furthermore, the high temporal resolution is suitable for complex dynamic simulations. [7]

The paper is organised as follows: Chapter 2 starts with a brief description of the life-cycle assessment (LCA) framework and the adaptations necessary to incorporate dynamic emission factors, followed by an overview of the approach mentioned to develop dynamic emission factors based on [7]. In the end of Chapter 2, future scenarios for the public electricity mix in 2030 and 2050 are presented. In Chapter 3, a case study depicts the application of dynamic emission factors in the course of an LCA. The applicability of the dynamic GHG emission factors for building LCA and the benefits are discussed in Chapter 4. Finally, Chapter 5 gives an outlook on how to further develop dynamic building LCA methods.

2. Methodology

The following chapter gives an overview of methods and databases that are the basis for the authors' approach to develop dynamic emission factors for the German electricity mix together with a brief description of the developed technique itself. For further details about the complex methodology to process given electricity generation data and to convert it into emission factors please refer to [7].

2.1. Environmental evaluation of buildings and the built environment

2.1.1. Life-cycle assessment (LCA) and building-related LCA. The methodological basis for the calculation of emission factors for the public electricity supply is the life-cycle assessment (LCA) technique, a well-established methodology to account environmental impacts of products and services along their life-cycle. Common principles of LCAs are the definition of a specific research subject for each assessment as well as the definition of a functional unit to enable a comparison of different products or processes on the basis of their benefit for the user. In the context of fuel combustion related to electricity generation, calculated emission factors either just consider the environmental impact of fossil fuels while burning the fuel or also the upstream chain from fuel extraction and transportation, which corresponds to the LCA approach. [8, 9]

In accordance with the general LCA, building-related LCAs facilitate the evaluation of the environmental impacts during the construction, use, renovation, reutilization and demolition phase of buildings. Amongst others, the German Sustainable Building Council (DGNB) established a methodology for a holistic assessment of the sustainability of buildings, which contains a building-related LCA as major part of the ecological assessment criteria. Therefore, relevant environmental impact categories (e.g. GHG emissions) from building construction, use and reuse, recycling as well as disposal are calculated over a period of 50 years. There exist multiple databases that contain various environmental product declarations (EPDs) for building materials. In addition, numerous data sets feature mean values for a certain category or technology of construction related components like the Sustainable Construction Information Portal ÖKOBAUDAT. [10, 11]

While data sets can easily be used for the calculation of construction, transport and disposal related impacts, the use phase of a building – and in particular the energy supply for heating, domestic hot water and electricity – require additional information, input parameters and demand calculations. Besides information about the technical equipment, e.g. heat generators and storages, the final energy demand for the chosen energy carriers has to be determined. This final energy demand can be calculated according to different energy balance schemes, which in turn serve as a requirement for the issuance of energy performance certificates. [12] Anyway, all of these calculation methods usually deliver the total final energy demand per year as an input to the building-related LCA, which is then converted into a certain environmental impact using the current impact or emission factor for the corresponding energy carrier. The overall impact for the use phase is projected by multiplying the annual impact based on the final energy demand with the duration of the use phase.

2.1.2. Adapted environmental impact analysis for the use phase. In order to incorporate dynamic emission factors with a higher temporal resolution than one year, some adaptations to the described application of the building-related LCA have to be made. First and most important, the established energy demand calculation methods cannot be used any longer. Instead, dynamic building simulations replace traditional energy balance schemes giving the opportunity to simulate profiles for the space heating and the electrical power demand in a higher temporal resolution of 15 minutes. As a basis for this simulation, a building model must be elaborated that reflects the energy related behaviour of the building assessed using the LCA. Afterwards, the multiplication of the energy demand q in each time step i with the corresponding emission factor f_{GHG} leads to a dynamic profile for the environmental impact, e.g. GHG emissions c per time step i (see Eq. 1). The input to the LCA is the sum of all greenhouse gas emissions c_{total} during the period under review which is calculated from the sum of GHG emissions (c_{annual}) for all time steps multiplied by the number of years (n_{years}) of the period reviewed (cf. Eq. 2).

$$c_{\mathrm{GHG},i} = q_i * f_{\mathrm{GHG},i} \tag{1}$$

$$c_{\mathrm{total}} = c_{\mathrm{annual}} * n_{years} = \sum_i (c_{\mathrm{GHG},i}) * n_{\mathrm{years}} \tag{2}$$

2.2. Dynamic emission factors for the German electricity mix

2.2.1. Power generation and energy-related emissions. The basis for the calculation of dynamic emission factors for the public electricity supply in [7] is a set of different data on German electric power generation and consumption. For this reason, aggregated data from the transparency platform of the European Network of Transmission System Operators for Electricity (ENTSO-E) serves as the main input. [13] The data is available in 15 minute time steps and represents a mean value of the power generation from 17 different types of electricity generation. However, the data has to be processed to comply as good as possible with German national energy and emission balances. As a result, a dataset is available which shows the power generation from different types of energy carriers and power plants in the same temporal resolution on the one hand and with the correct sum of produced electricity over one year on the other.

Finally, the electricity generation time series needs to be converted into dynamic GHG emission factors, which is done by using specific environmental impact factors for different types of electricity generation provided by [14]. The resulting dynamic emission factors refer to the total consumed electric power in each of the time steps and, hence, can be used to assess the electricity demand of a building as part of a building-related LCA.

2.2.2. Modelling of future emission factors. The methodology described above is applied to calculate the German public electricity supply on the basis of actual power generation data and assessments of the environmental impact of technologies reflecting the status quo (cf. [7]). To evaluate how an increasing share of electricity generation from renewable energy sources impacts the LCA results and the dynamic approach, in particular, requires the modelling of future emission factors. This modelling is subject to certain simplifications and estimations: *a)* A major simplification is that the LCA results for all power generation technologies are considered to be constant, i.e. the environmental impact of a unit of electricity generated from a certain technology in the future will be the same as it is today. *b)* A scenario for the increasing installed capacity and power generation from renewable energy technologies is used to obtain the annual power generation from these renewable sources as well as from conventional technologies. *c)* The profile of feed-in of electrical power from renewable energies for the future has the same pattern as in 2017. This means, the increased annual power generation in the future leads to a scaling of the respective profile for the year 2017. At the same time, conventional power production is restricted to gas-fired power plants only, which are modelled as combined-cycle power plants capable for base load and gas turbine power plants in order to cover peak loads.

With these simplifications and principles, dynamic emission factors for the years 2030 and 2050 were derived from scenarios developed in [15]. While [15] discusses multiple scenarios, only the scenarios aligned to the German policies on climate change reflecting a 80 % reduction of CO_2 emissions compared to the base year 1990 will be used in this paper. Table 1 summarises some of the key parameters of the model. The GHG emission profiles for 2017, 2030 and 2050 are illustrated for a period of one week in Figure 1.

Table 1. Parameters of the most important energy carriers of the model of dynamic emission factors.

	2017	**2030**	**2050**
Annual power generation (in TWh)			
Net annual production	619.4	578	627.1
Photovoltaics	39.3	70	100
Wind-Onshore	87.6	136	188
Wind-Offshore	17.6	63	208
Biomass	46.7	46.8	36.8
Other renewable	26.3	27.2	27.3
Conventional fossil	401.9	235	67
Consumption weighted annual GHG emission factor for the public electricity supply (in $g_{CO_2\ eq}$ /kWh)			
direct	524.5	340.6	77.6
incl. upstream chains	594.1	401.4	119.6

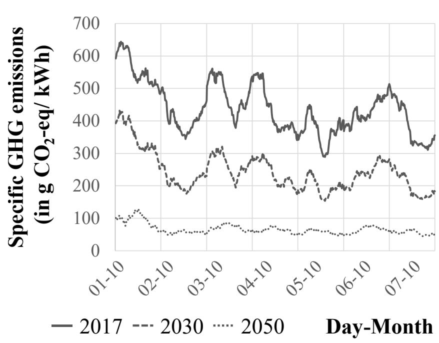

Figure 1. Dynamic GHG emission factors in a temporal resolution of 15 minutes for the years 2017, 2030 and 2050 in the period of 1st October to 7th October.

3. Case study

The following case study shall demonstrate the application of dynamic GHG emission factors on the building-related LCA. Remarks focus on those variations in results that occur from applying dynamic input parameters instead of static emission factors. Furthermore, the sensitivity of the simplified LCA approach becomes evident when comparing the results based on today's public electricity supply with those referring to a scenario with higher shares of renewable energies.

3.1. Building Model and simulation environment

In order to carry out the LCA, the experimental design of this study case is based on a generic building model. Its geometry is derived from [16] and used to set up a simulation model for the dynamic simulation software IDA Indoor Climate and Energy 4.81 [17]. The aim is to simulate the building's final energy demand in a high temporal resolution. Afterwards, the details on the building construction as well as the energy demand profile are used as inputs for the adapted LCA described before. [10] has already proved the general applicability of the chosen generic building models in the course of a profound scenario analysis. For the case study of this paper, a residential single family home will be investigated, which was modelled by [10] in accordance with the minimum requirements of the latest Energy Saving Ordinance (EnEV). In the building model, an air-to-water heat pump covers the building's space heating demand in combination with a floor heating system. Table 2 outlines the most relevant model parameters and boundary conditions of the simulation.

Table 2. Simulation and building model parameters.

Building design	2 floors	
	Net floor area	197 m²
	Gabled roof	
Heat transmission coefficient of the building envelope		*W/(m² K)*
	Wall	0.19
	Roof	0.20
	Floor	0.15
	Windows *(glazing / total)*	0.60 / 0.74
	Thermal bridges	0.05
Sun shading	External sun blinds	
Infiltration		*Air change rate per hour*
	Fixed natural infiltration	0.21
Ventilation	Window opening	
Internal loads	Residents	4 / MET 1.
	Equipment	370.2 W
Location, climate data, simulation year	Potsdam	
	Test reference year 2010	
	2014	
Heat generation	Air-to-water heat pump	
	Nominal power	9.28 kW
	COP / Annual performance ratio	3.5 / 2.95
Heat transfer	Floor heating	
Room temperature	Heating period	min. 20 °C
	Cooling period	max. 26 °C

Among others, the case study in this paper is subject to the following boundary conditions: *a)* First, the simulation model includes both, heating demand for zone conditioning and hot water demand. The latter is implemented as a hot water demand profile for a household of 4 persons calculated with DHWcalc. [18 in 10] *b)* A base load of approximately 370 W reflects the household's internal heat source due to electrical equipment, which leads to an annual electricity consumption of approximately 3,240 kWh. The power demand for lighting is not modelled in detail, but is part of the base load power consumption. *c)* The ecological assessment follows a simplified approach compliant with the DGNB certification system and [19] which comprises the thermal envelope of the building and the technical equipment for heating and ventilation. Building components that do not have any direct influence on the energy performance of the building are left aside for this case study. Furthermore, the impact of doors or other opaque openings is not reflected. *d)* The review period is 50 years. *e)* The environmental impact assessment is based on [11] and focuses on the GHG emissions of the building. Other impact categories are neglected, since the emission factors developed in [7] cover carbon dioxide and GHG emissions only. *f)* The dynamic GHG emission factors used for the assessment of the electrical power consumption include the impact of upstream chains for the electrical power generation.

3.2. Simulation and LCA results

The annual building's energy consumption is about 6,420 kWh. Because of the fact, that the heat generator is an electrically powered heat pump, the only energy carrier consumed is electricity. The overall consumption comprises 3,180 kWh for heating and auxiliary equipment as well as 3,240 kWh for the household's power consumption. Figure 2 depicts the distribution of power consumption for the heat generation and the household's power consumption on a monthly basis. It is obvious, that most of the power consumption for heating occurs from October to April during the heating period.

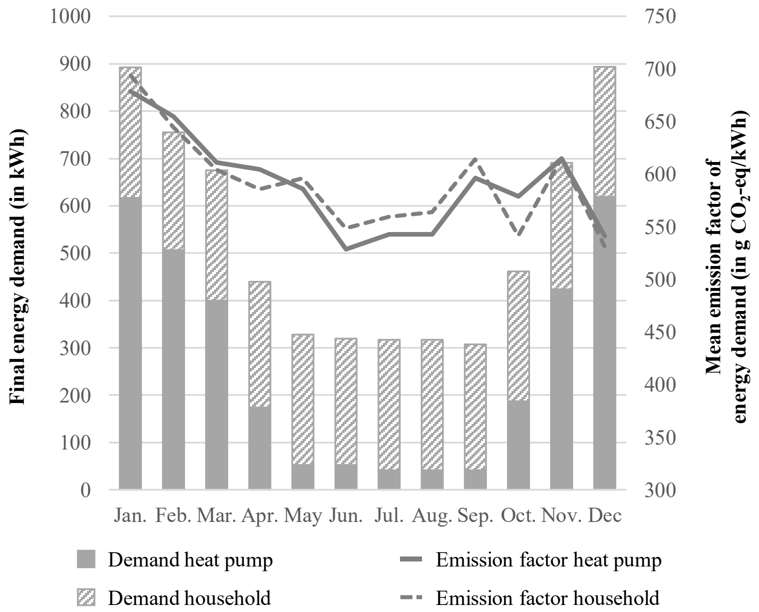

Figure 2. Final energy demand of the building for heating (incl. domestic hot water) and household's power consumption as well as monthly mean emission factors of the demand.

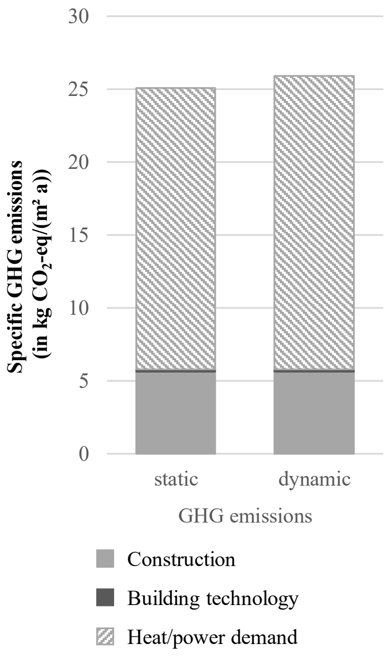

Figure 3. Results of simplified building LCA with static and dynamic GHG emission factors for the energy demand in the use phase.

As shown in Figure 3, the results of the simplified LCA reveal that the construction and disposal of the building causes 5.6 kg CO_2-eq per square meter floor area[1] and annum. At the same time, the consumption of heat and electrical power during the use phase of the building accounts for 20.2 kg CO_2-eq per square meter floor area and annum over a period of 50 years. The heat generator accounts

[1] The reference area is the gross floor area less the area for construction of external walls.

for less than 1 % of the GHG emissions of the building and is not of major importance for the LCA. A comparison of LCA results using the static method against the approach based on dynamic GHG emission factors shows a deviation of the specific emissions of about 3.4 %. This means, the GHG emissions of the energy consumed in the use phase of the building are higher than estimated by the standard calculation method. The reason for this situation is quite clear: While the static emission factor averages the annual emissions from all power generation technologies and renewable energy sources despite their varying seasonal distribution, the electrical power consumed for heating during the heating period lacks a high share of (almost carbon-neutral) photovoltaic power generation. Nevertheless, the deviation is quite small, when taking into account that many of the LCA input data sets reflect average values for components and materials.

3.3. LCA using dynamic emission factors for 2030 and 2050

As already demonstrated for the LCA results with 2017 GHG emission factors, a deviation from the static to the dynamic approach exists. To evaluate how the increasing share of electricity generation from technologies based on renewable energy carriers will impact the adapted LCA of buildings, 2030 and 2050 emission profiles are used for the investigation.

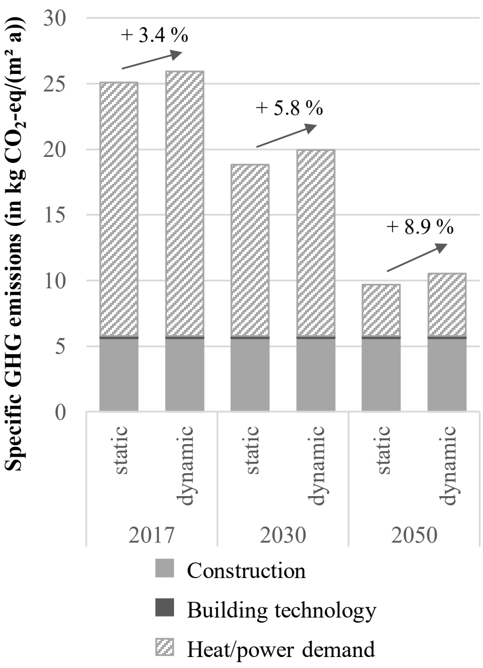

Figure 4. LCA results for GHG emissions profiles of the years 2017, 2030 and 2050

Table 3. Comparison of static vs. dynamic LCA results for scenarios (GHG emissions in $kg_{CO2\text{-}eq}/(m^2\ a)$)

	Construction	Building Technology	Heat/power demand
2017			
static	5.61	0.17	19.31
		Total	**25.09**
dynamic	5.61	0.17	20.15
		Total	**25.93**
		Deviation	*3.4 %*
2030			
static	5.61	0.17	13.05
		Total	**18.83**
dynamic	5.61	0.17	14.14
		Total	**19.92**
		Deviation	*5.8 %*
2050			
static	5.61	0.17	3.89
		Total	**9.67**
dynamic	5.61	0.17	4.74
		Total	**10.52**
		Deviation	*9.8 %*

Very clearly, Figure 4 shows the reduced GHG emissions of the electrical power consumed during the use phase of the building, provided that the share of renewable energies in the public electricity supply increases until 2030 and 2050, respectively. In this case study, the LCA input parameters for the construction and disposal phases are not adapted for the scenarios. Thus, only the electricity demand during the use phase changes according to the calculated dynamic GHG emission factor profiles. For the static LCA approach, the GHG emissions of the use phase decreases from 25.1 kg CO_2-eq to 18.8 kg CO_2-eq in 2030 and 9.7 kg CO_2-eq per square meter floor area and annum in 2050 (Table 3). This corresponds to a 25 % and 61 % reduction of GHG emissions, respectively. The comparison of static and dynamic LCA results shows that the deviation between both calculation methods is increasing with the rising share of power produced from renewable energy sources. While the deviation is 3.4 % with emission factors for the year 2017, it increases to 5.8 % in 2030 and 9.8 % in 2050, respectively (cf. Table 3).

4. Conclusion

In this conference paper, dynamic emission factors for the public electricity supply have been applied in a high temporal resolution to the life-cycle assessment of buildings. The paper shows that a dynamic simulation instead of an energy balance can be used as a methodological adaptation to the LCA. The impact of the adapted LCA approach is demonstrated in a case study, which reveals an increase of LCA results about 3.4 % for the building's life-cycle GHG emissions with a dynamic emission profile for the year 2017. In addition, the calculation of future GHG emission factors for 2030 and 2050 and their application to the LCA shows that although the overall GHG emissions for the use phase of the building decrease, a tripling of the deviation between the static and the dynamic LCA approach occurs. The building model investigated in the case study follows an electricity-only concept. Thus, deviations are higher than for a conventional setting with a non-electric heat generator. However, the combination of an increasing share of houses equipped with heat pumps in Germany along with higher efficiency requirements for buildings to achieve emission targets and the overall need for integrated energy systems underline the necessity that corresponding LCA results should match reality as good as possible. In contrast, the results of the conducted case study show the imperative to improve established assessment methods if LCAs shall help to achieve the emission targets on building level as well as on the level of national and global GHG inventories, respectively.

5. Outlook

Three main aspects regarding a building-related LCA that considers the fluctuating character of electricity from renewable energy sources have not yet been considered in this study. First, other dynamics in the power consumption of households (e.g. power demand for lighting) are not taken into account. German standard load profiles show winter-summer dynamics, which could also lead to higher emissions when incorporating them into a LCA with dynamic emission factors. In addition, the study case does not consider mechanical ventilation and, in particular, cooling in summer time. Most probably, the electrical cooling demand will have a reverse effect on the total GHG emissions compared to the heating loads when using dynamic load and emission profiles. Second, the building-related LCA uses dynamic load and emission profiles to assess the environmental impact of the use phase. However, the LCA is still restricted to multiplying the annual GHG emission in a certain year of investigation with the number of years reviewed (cf. Eq. 2). An approach for a more realistic evaluation of a certain building could be the use of a scenario model, which determines dynamic emission profiles for each year of the review period. Third, the overall impact of energy transition and lower emission factors for the public electricity supply is not reflected in this case study with regard to building components and materials that have a high electricity demand in the production phase. Scenario-specific data sets of LCA input parameters for components and materials, which reflect a decreasing emission factor of the German electricity supply would enable a profound evaluation of environmental impacts of future buildings. In this context, the potential of using dynamic CO_2 and GHG emission factors for reducing the overall environmental impact could be investigated more comprehensive.

Acknowledgments

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Comparison of the environmental assessment of an identical office building with national methods

Frischknecht R[1], Birgisdottir H[2], Chae C-U[3], Lützkendorf T[4], Passer A[5], Alsema E[6], Balouktsi M[4], Berg B[7], Dowdell D[7], García Martínez A[8], Habert G[9], Hollberg A[9], König H[10], Lasvaux S[11], Llatas C[8], Nygaard Rasmussen F[2], Peuportier B[12], Ramseier L[1], Röck M[5], Soust Verdaguer B[8], Szalay Z[13], Bohne R A[14], Bragança L[15], Cellura M[16], Chau C K[17], Dixit M[18], Francart N[19], Gomes V[20], Huang L[14], Longo S[16], Lupíšek A[21], Martel J[22], Mateus R[15], Ouellet-Plamondon C[23], Pomponi F [24], Ryklová P[21], Trigaux D[25], Yang W[26]

[1] treeze Ltd., Switzerland
[2] Aalborg University, Denmark
[3] Korea Institute of Civil Engineering & Building Technology, Korea
[4] Karlsruhe Institute of Technology, Germany
[5] Graz University of Technology, Austria
[6] W/E Consultants, Netherlands
[7] BRANZ, New Zealand
[8] Universidad de Sevilla, Spain
[9] ETH Zurich, Switzerland
[10] Ascona, Germany
[11] HES-SO, IGT-LESBAT, Switzerland
[12] MINES ParisTech, France
[13] Budapest University of Technology and Economics, Hungary
[14] NTNU – Norwegian University of Science and Technology, Norway
[15] University of Minho, Portugal
[16] University of Palermo, Italy
[17] The Hong Kong Polytechnic University, Hong-Kong
[18] Texas A&M University, USA
[19] KTH Royal Institute of Technology, Sweden
[20] University of Campinas, Brazil
[21] Czech Technical University in Prague, University Centre for Energy Efficient Buildings, Czech Republic
[22] Groupe Ageco, Canada
[23] École de technologie supérieure, Canada
[24] Resource Efficient Built Environment Lab (REBEL), Edinburgh Napier University, United Kingdom
[25] EnergyVille / KU Leuven / VITO, Belgium
[26] Tianjin University, China

frischknecht@treeze.ch

Abstract. The IEA EBC Annex 72 focuses on the assessment of the primary energy demand, greenhouse gas emissions and environmental impacts of buildings during production, construction, use (including repair and replacement) and end of life (dismantling), i.e. during the entire life cycle of buildings. In one of its activities, reference buildings (size, materialisation, operational energy demand, etc.) were defined on which the existing national assessment methods are applied using national (if available) databases and (national/regional) approaches. The "be2226" office building in Lustenau, Austria was selected as one of the reference buildings. TU Graz established a BIM model and quantified the amount of building elements as well as construction materials required and the operational energy demand. The building assessment was carried out using the same material and energy demand but applying the LCA approach used in the different countries represented by the participating Annex experts. The results of these assessments are compared in view of identifying major discrepancies. Preliminary findings show that the greenhouse gas emissions per kg of building material differ up to a factor of two and more. Major differences in the building assessments are observed in the transports to the construction site (imports) and the construction activities as well as in the greenhouse gas emissions of the operational energy demand (electricity). The experts document their practical difficulties and how they overcame them. The results of this activity are used to better target harmonisation efforts.

1. Introduction

One major cause of greenhouse gas emissions (GHG), primary energy demand and environmental impacts is the construction of buildings and their operational energy demand for heating and cooling [1-4]. To support decision making in reducing environmental impacts, it is important to quantify the impacts and show opportunities for optimization. Environmental life cycle assessment (LCA) is commonly used to assess the environmental impacts of buildings during production, construction, use (including repair and replacement) and end of life. The LCA approach is standardized in ISO 14040 and 14044 [5, 6]. In addition, there are European standards (EN15978 [7] and EN15804 [8]) for the assessment of environmental performance of buildings and the development of environmental product declarations (EPD) of building products, respectively.

Today, there is disparity in the level of application of LCA on buildings and the existence of LCA databases targeted to the building sector across the world. The international research project IEA EBC Annex 72 focuses on the assessment of the primary energy demand, GHG emissions and environmental impacts of buildings occurring during production, construction, use and end of life. The main objectives of IEA EBC Annex 72 are among others to foster [9]:

- the discussion and harmonisation of methodology guidelines;
- the use of environmental information in an early design stage;
- the development and use of benchmarks;
- the development of national databases targeted to the construction sector.

To be able to establish harmonized methodology guidelines and identify areas of disagreement existing national methods are compared. Reference buildings are defined for that purpose on which the national LCA methods are applied. If available, national databases are used to quantify the primary energy demand, GHG emissions and environmental impacts.

2. Reference building

The "be2226" office building, located in Lustenau, Austria, is used as a reference building to evaluate existing national LCA methods. The building was designed by the architects Baumschlager Eberle architekten and built in 2013. It is a massive construction and can be seen as a low-tech building. The primary structure consists of pre-stressed and prefabricated concrete ceilings with overlay concrete and 76 cm thick exterior walls in composite masonry. The exterior walls consist of two layers of hollow perforated bricks, whereby the outer bricks are optimised for the insulating effect and the inner bricks bear the loads. The façades are covered on the outside as well as on the inside with lime plaster.

Due to its compact building shape, small and cleverly situated windows and thick exterior walls with a high thermal capacity, neither additional thermal insulation nor active heating and air-conditioning is required. The building is "heated" exclusively by the internal loads from devices and the lighting in combination with the heat dissipation of the people[27,28]. A Building Information Model (BIM) of the building was established by TU Graz. Based on this model the amount of building elements and materials required is quantified. The energy reference area of the building is 2421 m^2. All results shown in this paper are quantified against the energy reference area. The electricity demand for lighting and operating equipment is 196 MJ/m^2a.

3. Methods and databases

3.1. Used national methods including study period and databases

The assessment of the building was carried out by 22 different institutions using the same material and energy demand but applying different LCA approaches. Within the different approaches the primary energy demand, GHG emissions and environmental impacts were assessed. The focus in this paper is on the GHG emissions. In total 21 different national or regional LCA approaches were applied. The assessments of the be2226 building were carried out by the national experts, and results were reported in a uniform template that allowed for comparison between the countries. The applied methods are mainly used as part of a sustainability assessment and for certification schemes of buildings, design aid and in research activities in the respective countries.

The methods apply different reference study periods. 15 methods use a reference study period of 50 years for this case study[29]and six methods use 60 years. Denmark uses 80 years as reference study period (see Table 1). The reference study period has an influence on the relative importance of the GHG emissions of manufacture, construction, replacements and end of life stages on one hand, and the operational GHG emissions on the other. Furthermore, the methods differ in the used service life of building elements/components and the modelling of the end of life treatment of the materials. In cases the service life of a building element exceeds the reference study period, the reference study period is applied.

Table 1: Overview of the reference study periods and databases used within the LCA methods applied to assess the environmental impacts of the **"**be2226**"** building.

	Reference study period [years]	**Database**	**Field of application**
AT	50	ecoinvent 3.2[10]	Research
BE	60	ecoinvent 3.3 [11] adapted to Belgian context	Research and webtool (TOTEM)
BR	50	ecoinvent 3.4 [12] adapted to Brazilian context	Research
CA	60	ecoinvent 3.4 [12] adapted to Canadian context and EPDs	Building certification schemes, EPDs
CH, ETHZ	60	KBOB LCA data DQRv2 [13]	Building certification schemes
CH, HES-SO	60	KBOB LCA data DQRv2 [13]	Building certification schemes
CN	50	ecoinvent 3.5[14]; CLCD-China-ECER 0.8.1, Oekobau.dat [15, 16]	Building certification scheme
CZ	50	ecoinvent 3.3 [11], boundary condition from SBToolCZ methodology [17]	Decision-making tool, voluntary certification

[27] https://www.baumschlager-eberle.com/en/work/projects/translate-to-english-projekte-details/2226/ last visited on: 8.3.2019

[28] It could be argued that the internal loads from devices are a free heating source (waste heat) and that their electricity consumption shall not be attributed to the building's operational energy demand. However, for the purpose of this paper (comparing national assessment methods) electricity demand of devices is considered part of the operational energy demand.

[29] France is one of them, but usually uses 80 years.

	Reference study period [years]	Database	Field of application
DE	50	Ökobau.dat 2018 [16]	BNB
DK	80	Ökobau.dat 2016 [15]	DGNB Denmark
ES	50	ecoinvent 2.0 [18]	research
FR	No official requirement, 50 years in this case study, default value 80 years	ecoinvent 2.2 [19] adapted to French context	EQUER
HK	50	Studies and statistics [20-22]	Research
HU	50	ecoinvent 2.0 [18] adapted to Hungarian conditions wherever relevant (for products primarily produced in Hungary, adaptation of the electricity mix and natural gas)	Education and research
IT	50	Ecoinvent 3.4 [12], EPDs	Research
NL	50	National Environmental Database for building products (NMD 2.2) [23] - producer-specific data and generic LCA data from ecoinvent 3.3 [11].	Building permits
NO	60	Ecoinvent 3.3 [11], EPDs	Research, decision-making tool
NZ	60	NZ whole building whole of life framework - materials data developed from EPDs for materials and modelling in ecoinvent 3.1 [24] (specific process data with NZ Grid electricity)	Certification, research
PT	50	LCIA Database for Portuguese Building Technologies [25], based on generic data from Ecoinvent 2.1 [26], Ecoinvent version 3.3 [11]	Research
SE	50	Swedish Building Sector Environmental Calculation Tool (BM) [27]	Building certification schemes
UK	50	Database embedded in OneClickLCA[a]	Building certification schemes
US	50	Database embedded in ATHENA Impact Estimator[b]	Building certification schemes and research

[a] https://www.oneclicklca.com/support/faq-and-guidance/documentation/database/, last visited on: 23.5.19
[b] https://calculatelca.com/software/impact-estimator/lca-database-reports/, last visited on: 24.5.2019

Mostly different versions of the ecoinvent database (i.e. [10-12, 14, 18, 19, 24, 26]) were used to assess the environmental impacts of the building. Some institutions applied country specific databases (see Table 1). The life cycle stages included in the respective approaches are shown in Table 2.

Table 2: Overview of the life cycle stages included in the applied approaches.

Life cycle stages	A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
AT	X	X					X		X	X		X	X	X	
BE	X	X	X		X		X	X	X	X	X	X	X	X	
BR	X	X	X				X		X	X	X	X			
CA	X	X	X				X		X	X	X	X	X	X	
CH, ETHZ	X						X		X		X	X	X	X	
CH, HES-SO	X						X		X		X	X	X	X	
CN	X						X		X					X	X
CZ	X						X		X						
DE	X						X		X				X	X	X
DK	X						X		X				X	X	
ES	X	X	X		X	X	X	X	X	X	X	X	X	X	
FR	X	X	X				X		X	X		X	X		X
HK	X	X	X	X	X	X	X	X	X		X	X	X	X	
HU	X	X	X			X	X		X			X	X	X	
IT	X					X	X	X	X	X					
NL	X	X	X		X	X	X	X	X		X	X	X	X	X

Life cycle stages	A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
NO	X						X		X				X	X	
NZ	X	X	X		X		X		X	X	X	X	X	X	X
PT	X								X	X					
SE	X	X	X												
UK	X	X	X				X	X	X		X	X	X	X	X
US	X	X	X		X		X		X		X	X	X	X	X

3.2. GHG emissions of construction materials

A preliminary contribution analysis of the different building elements to the total GHG emissions showed that bricks, concrete, windows and reinforcing steel are important. In Figure 1 the GHG emissions of brick along the life cycle stages (Modules A-D) as defined in EN 15804:2012 [8] are presented. Hong-Kong and the Netherlands did not report the emissions according to the life cycle stages. In all countries, which reported the emissions according to the life cycle stages, most of the GHG emissions of bricks are emitted in the product stage. While the GHG emissions in the product stage (A1-A3) of bricks are similar in all countries, differences are observed in the construction process stage (A4-A5). New Zealand reported a substantially higher impact in this life cycle stage than the other countries, mainly due to the large import distances of bricks from Australia to New Zealand (no domestic production). In the end of life stage (modules C1-C4) differences in the results are based on different assumptions on recycling shares, waste processing and final disposal scenarios. Germany reported negative GHG emissions in the end of life stage of bricks. According to the LCA data they use, the treatment in the decomposition phase leads to a complete carbonation of the free alkali- and alkaline earth oxides, which is accounted for as a credit. China assumed a high recycling potential for bricks and therefore reported high negative GHG emissions in the end of life stage. The highest GHG emissions of bricks are reported by Hong-Kong. Over all life cycle stages (i.e. without Module D) and excluding New Zealand and Hong-Kong the GHG emissions of bricks reported by the countries differ by a factor of 1.6.

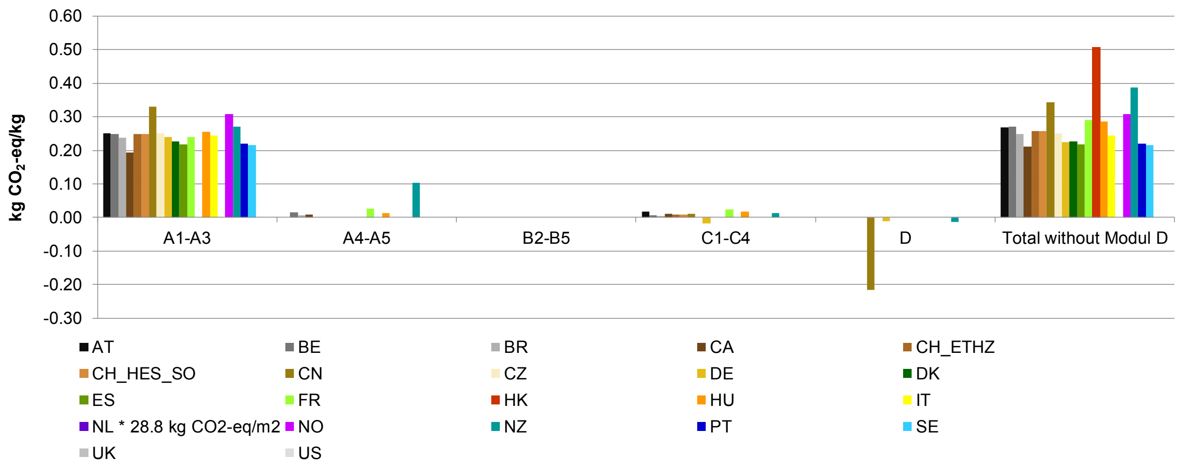

Figure 1. GHG emissions of bricks caused in the different life cycle stages in kg CO_2-eq/kg assessed according the national LCA approaches from the countries listed.

In Figure 2, the GHG emissions in kg CO_2-eq/kg of concrete are presented. Most of the GHG emissions of concrete are emitted in the product stage. The emissions differ up to a factor of 2.2 between the countries. The main reasons are different energy mixes in clinker production (share of traditional and secondary fossil fuels such as hard coal, lignite, fuel oil and natural gas or used tires), different average shares of clinker in 1 kg cement and different cement contents in 1 m^3 concrete.

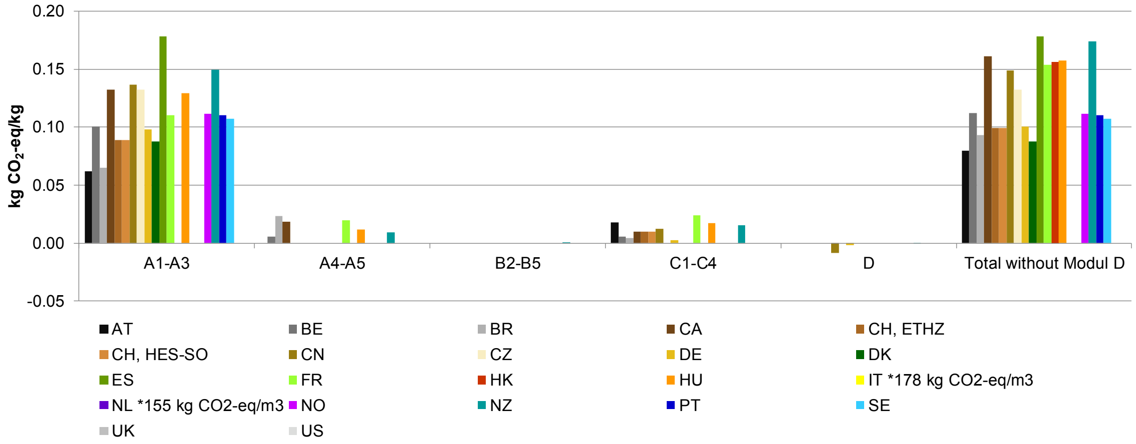

Figure 2. GHG emissions of concrete during different life cycle stages in kg CO_2-eq/kg assessed according the national LCA approaches from the countries listed.

The GHG emissions in kg CO_2-eq/kg reinforcing steel are shown in Figure 3. In all country assessments the product stage of reinforcing steel contributes most to the GHG emissions. The highest reported emissions are around 6 times higher than the lowest ones. The main reason is the share of recycled content in the reinforcing steel. The approaches applied in China, France and New Zealand report the net benefits and loads beyond the system boundaries. In China the net benefit is 53 % of the total GHG emissions of reinforcing steel reported for A1-C4. In France, the net benefit amounts to 57 % of the A1-C4 emissions and in New Zealand 8 %.

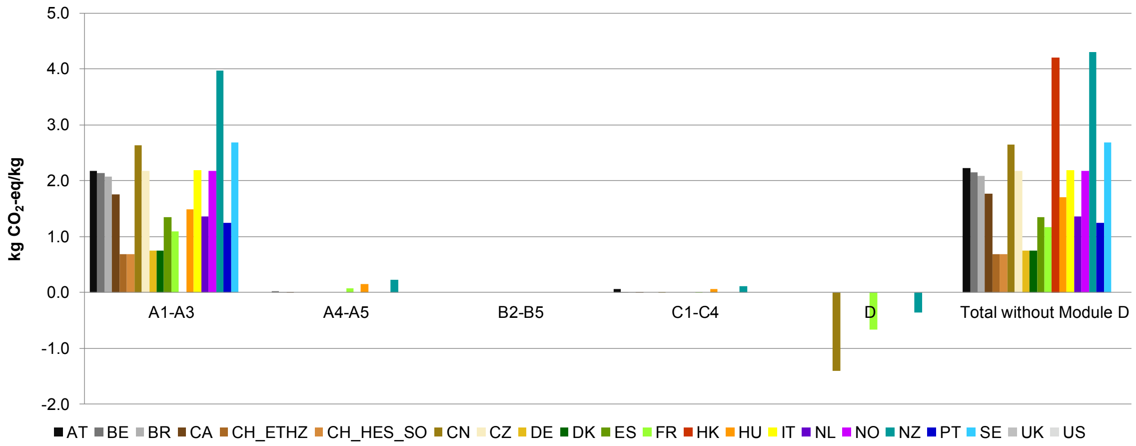

Figure 3. GHG emissions of reinforcing steel during different life cycle stages in kg CO_2-eq/kg assessed according the national LCA approaches from the countries listed.

3.3. GHG emissions of electricity mixes

The GHG emissions of the electricity used in operation reported by the different countries differ substantially (see Figure 4). While Denmark, Norway and France report low GHG emissions of their electricity mix, China, Czech Republic, Hong-Kong, Hungary and the Netherlands report comparatively high GHG emissions. The highest reported emissions are 30 times higher than the lowest reported emissions. These differences in GHG emission from electricity reflect the real existing differences in the national electricity supply. Denmark is the only country reporting a future average mix based on renewable energies only.

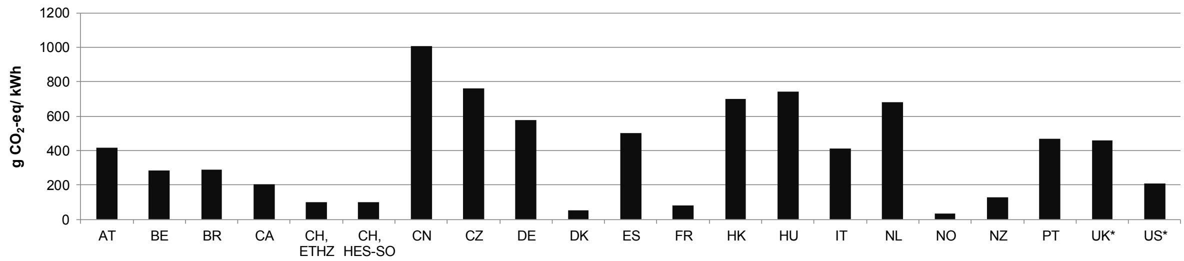

Figure 4. GHG emissions of the electricity mixes applied in the assessment of the operational electricity demand (module B6) of the reference building in g CO2-eq/kWh.
*: value back-calculated from the GHG emissions of B6

3.4. Issues encountered during the assessment

During the assessment of the reference building the authors of this paper encountered several issues with the provided data. Most of the issues were related to missing life cycle inventory data for specific materials, such as “vacuum insulation panels” and different aggregation stages in the information provided and the data available. The issue encountered with the aggregation level concerned the product level (e.g. reinforced concrete, instead of having separate LCI data on concrete and reinforcing steel) and the life cycle stages (e.g. data only available for the whole life cycle and not for Modules A, B and C separately). Furthermore, differences in the units of the building data and the available LCA data occurred (e.g. pieces vs. m^3 of stairs). To overcome the limitations of lacking LCI data for materials the authors used proxies, EPDs or did not consider the material and building elements at all (e.g. elevator).

4. Preliminary results: greenhouse gas emissions caused by the be2226 building

The preliminary results of the assessment of the GHG emissions caused by the manufacturing, construction, use and end of life of the reference building “be2226” are presented in Figure 5. The total GHG emissions reported are between 10 and 71 kg CO_2-eq/m^2a depending on the national approach used.

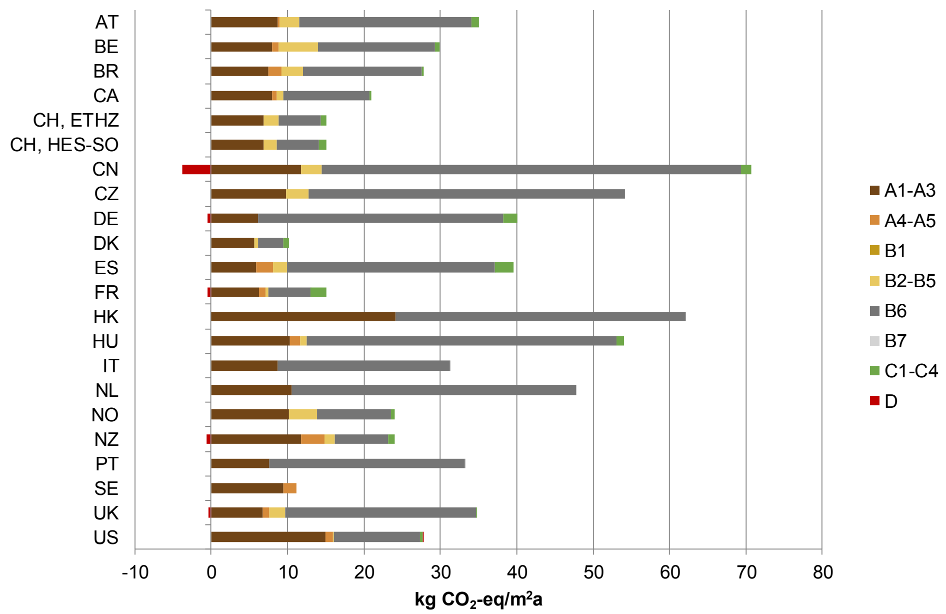

Figure 5. Greenhouse gas emissions in kg CO_2-eq per m^2 and year of the reference building **“be2226”** assessed according to the national/regional approaches of the countries listed (preliminary results).

Different life cycle stages were taken into account depending on the national approaches (see Table 2). Most of the countries were able to report the GHG emissions according to the life cycle stages defined in EN 15804:2012 [8] and EN 15978:2011 [7]. Hong-Kong and the Netherlands reported the emissions of modules A4, A5, B, C and D all together in the product stage (modules A1-A3) except the operational energy use (B6)[30]. The product stage was assessed by all countries and varies between 5.7 and 15 kg CO_2-eq/m^{2}a. Within the product stage the GHG emissions vary by a factor of 2.6 (excluding Hong-Kong). The transport to site and the construction and installation process (construction process stage A4 and A5) was addressed by 13 approaches. Over all countries those life cycle stages vary between 0.3 and 3.1 kg CO_2-eq/m^{2}a.

All national approaches, except Portugal and Sweden took the replacement (B4) of materials and building elements into account. However, only few approaches consider the maintenance (B2), repair (B3) and refurbishment (B5). Overall, the use stage (B2-B5) varies between 0.1 and 5.2 kg CO_2-eq/m^{2}a. A very high variability can be seen in the contribution of the operational energy use stage. It directly reflects the differences in GHG emissions of the electricity mixes (see Section 3.3) because electricity is the only energy carrier used in operation. The end of life stages (C1-C4) vary between 0.2 and 2.4 kg CO_2-eq/m^{2}a. This variation is not linked to the scope of end of life stage modules considered. Net benefits and loads beyond the system boundary were reported by six approaches out of 21. The approach applied in the Netherlands includes energy recovery from waste incineration and product reuse or recycling. However, the net benefits are not reported separately in the Dutch assessment. Where reported separately, the benefits are between 0.1 and 3.7 kg CO_2-eq/m^{2}a.

5. Discussion

In all assessments, most GHG emissions occurred either in the product stage or during the operational energy use. The differences in the operational energy use are due to the substantial difference in the GHG-intensity of the national electricity mixes. The variance of the GHG emissions occurring in the product stage is due to the different GHG emissions of the construction materials (see Section 3.2) and to the differences in the reference study period applied.

The Danish assessment shows the lowest GHG emissions per m^2 and year. Firstly, a reference study period of 80 years leads to lower annual emissions from the product stage (A1-A5) compared to the reference study period of 50 or 60 years. Secondly, the electricity mix applied during operation is a future national mix based on renewable energies with comparatively low GHG emissions per MJ.

The annual specific GHG emissions of this building are mainly influenced by the GHG intensity of the electricity mix used during operation. The GHG intensity of the construction materials used (Modules A1-A5) as well as the difference in reference study period cause additional differences in the annual specific GHG emissions of the "be2226" reference building. The contributions from the end of life stage are minor. The building hardly uses plastics and plastics-based insulation materials which would give rise for substantial GHG emissions when incinerated. On the building level, the potential loads and benefits beyond the system boundary are hardly visible.

The different applied approaches result in a wide range of the total GHG emissions of the "be2226" building. The differences in the results of the assessments of the "be2226" building are due to the substantially different CO_2-footprints of the energy carriers and the construction materials rather than methodological differences between the approaches applied. Hence, the relatively large differences are no cause for concern. Depending on the national context low carbon footprint buildings are achieved using different concepts. It is crucial however, that environmental benchmarks for buildings in a country are based on the LCA approaches and LCA databases used in that particular country.

[30] For reasons of confidentiality the Dutch National LCA database comprises only aggregated emissions data for the stages A, B, C and D together, in case of producer-specific LCA data.

6. Outlook

The comparison of all the national LCA approaches applied will be used to better target harmonization efforts and identify areas of disagreement. Furthermore, a second reference building, a Chinese high-rise building will be assessed by the IEA EBC Annex 72 participants to get a deeper understanding of the different approaches applied on a more complex building. The insights gained from both comparative exercises will be used along with other results of the international research project IEA EBC Annex 72 to develop and extend the methodology guideline on LCA of buildings and life cycle related environmental benchmarks.

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New Portfolio-Rating-System based on LEVEL(S)

Bernegger H J
ZHAW Zurich University of Applied Sciences, IFM Institute for Facility Management
8820 Wädenswil - Switzerland

heinz.bernegger@zhaw.ch

Abstract. In Switzerland, there are currently no instruments for the holistic and easily applicable assessment of the sustainability of existing buildings, which can also be applied to larger real estate portfolios and which are structurally based on Swiss or European sustainability standards. The instrument, developed as part of a ZHAW R&D project for the City of Zurich, Public Real Estate Management, is based on the already existing LEVEL(S) criteria structure. As distinguished from LEVEL(S), it can be applied to all types of buildings, including mixed buildings, and also scalable to larger portfolios of cities, banks, insurances or real estate investment funds. LEVEL(S) is a voluntary reporting framework to improve the sustainability of buildings. Using existing standards, LEVEL(S) provides a common EU approach to the assessment of environmental performance in the built environment. In the current Version LEVEL(S) is suitable for new office and residential buildings and existing buildings at the time of a major refurbishment. The paper shows, how the rating structures of Agenda2030/SDG's/GAPFRAME, ESCI City Rating System, DGNB and LEVEL(S) can be combined into a holistic evaluation system. If required, the developed portfolio analysis instrument can be coupled - with a more detailed building analysis as an intermediate step - directly with a DGNB renovation certification. It will show how sustaining property owners can be supported in this holistic way. Finally, the first findings from the practical application are explained. It will be shown how it is possible to support sustainably acting portfolio holders in this holistic way.

1. Introduction

Currently, the Swiss building park consists of approx. 2.5 million buildings with a total value of over EUR 2 trillion and approx. 1 billion m2 of floor space. Of these, approx. 1.7 million buildings are residential properties (approx. 1/5 of professional or institutional investors) and approx. 600,000 office und commercial properties (approx. 1/3 of professional or institutional investors). The annual building construction expenditure in Switzerland amounts to more than 50 billion EUR [1]. At present, professional or in particular institutional investors are becoming increasingly interested in being able to invest in new buildings and in refurbishing existing ones, while also taking sustainability into account.

From the perspective of Swiss portfolio holders, the first thing to do is to gain an overview of the sustainability of one's own real estate portfolio. This allows the portfolio to be broken down into sub-segments for which specific restructuring or investment strategies can then be developed and implemented.

The instruments currently used to assess the sustainability of real estate portfolios in Switzerland are usually only "one-dimensional" or relate to very few criteria. In the case of the economic dimension, for example, the parameters taken into account refer only to the structural condition of the buildings or, in the case of the ecological dimension, only to the specific and consumption-dependent environmental parameters (energy consumption). In many cases, social parameters, especially those relating to user satisfaction, are not collected, and if only unsystematically or incompletely.

In Switzerland, there are currently no instruments for the holistic and easily applicable assessment of the sustainability of existing buildings, which can also be applied to larger real estate portfolios and which are structurally based on Swiss or European sustainability standards. In the specific area of listed real estate properties, GRESB is used as an international ESG benchmarking tool. But, GRESB focuses primarily on the organization and the management processes and considers the single building limited to a few KPI's (LEED based). A holistic performance assessment as well as the derivation of concrete optimization measures at the level of individual buildings is therefore not possible.

Many of the major Swiss portfolio holders are also feeling the pressure at management level for greater sustainability transparency, driven on the one hand by an ever-increasing public debate on sustainability and on the other by increasingly stringent and detailed CSR guidelines and the associated requirements for company-specific sustainability reporting. At present, it is primarily a question of the transparency resulting from an evaluation and the possibility of better supporting decisions on necessary investments. Large-scale certification of the company's own real estate is generally not considered necessary immediately. However, it is expected that this will become necessary in the medium or longer term. In this respect, the interest in an appropriate evaluation instrument also corresponds to the need to find a way of gradually preparing for future CSR-requirements.

Based on these findings, the overriding problem or question that arises is how a future portfolio rating instrument should be designed which, on the one hand, is able to meet the general requirements of Swiss portfolio holders and, on the other hand, has the highest possible connectivity to all relevant national and international sustainability instruments.

The needs of the interviewed portfolio holder can be clustered into the following sub-requirements groups:

General requirements for the instrument:

1. Simple, effective and cost-effective applicability (time expenditure)
2. Flexible applicability due to the heterogeneity of the objects
3. Holistic assessment on all three dimensions of sustainability
4. General applicability (for public and private portfolio holders)
5. Focus on relevant aspects, central consideration of the climate topic
6. Performance-oriented definition of the criteria
7. Scientifically referenced criteria and indicators
8. Compatibility with international rating standards

General requirements for the structure of the instrument

1. Coordination with Agenda 2030 [2] and SNE (Sustainable Development Strategy for Switzerland) [3]
   in order to be able to support corresponding reporting requirements in the future.
2. Consideration of the structural condition under
   a) Alignment with national frameworks on sustainability
   b) Coordination with international frameworks with relevance for Switzerland
3. Adequate consideration of operational aspects

In summary, the main reasons to applicate a portfolio-rating-system can be derived from the following three core benefits:

- The benefits of continuous transparency through reporting in the CSR or Agenda 2030 context as well as with reference to risk management the identification of "risk objects" in the portfolio
- The benefits of hedging investments in new construction and renovation resp. the direct derivation of measures or at least as a basis for this and
- The benefit of optimizing building operations

2. Methodology

The structure of the research project is divided into three phases

1. Basic analysis, system development and definition of criteria
2. Development of the evaluation tool, pilot application
3. Monitoring and scientific evaluation

Only the results of the first phase are presented in more detail in this paper.

2.1 Basic analysis

The basic analysis comprised the evaluation of all national and international instruments existing in Switzerland with regard to their suitability relating to the evaluated requirements of the Swiss portfolio holders. This formed the basis for the selection of instruments which were used as a basis for the development of the new system architecture and criteria structure.

2.2 System development

During system development, the comparison was first made between the respective superstructures and the criteria of the selected instruments. In a further step, those criteria were evaluated which essentially form the intersection of the various sets of criteria analyzed. When selecting the criteria, however, not only the number of mentions was decisive, but also the relevance of the respective instruments (norm compatibility).

2.3 Definition of criteria and indicators

In a final sub-work package, adequate indicator definitions were sought in order to make the selected criteria assessable at portfolio level as well. On the one hand, these should be geared to the central theme of the criterion and at the same time permit simple evaluation at portfolio level.

The structure of the criteria descriptions is divided into four sub-areas:

1_Criterion_Name
2_Dimension:
3_Subject area:
4_Percentage of total evaluation:

5_Contribution to sustainable development:
6_Objective:
7_Explanation/benefit:
8_Added value (ecological/economic/sociocultural)

9_Method:
10_System limit (delimitation/inclusion)
11_Valuation (a) qualitative:
12_Evaluation (b) quantitative:

13_Type of evaluation:
14_Measured variables & characteristic values:
15_Referencing (National & International Instruments)
16_Further sources (literature, standards, guidelines, etc.)

3. Theoretical background

Switzerland has a large number of instruments for optimizing the sustainability of real estate.

The following aspects were selected as criteria for consideration in the context of instrument development:

- Comprehensive set of criteria in all three dimensions of sustainability
  - ➢ This excludes e.g. Minergie, GEAK, Energiestadt, GI, Stratus
- Public accessibility and usability
  - ➢ This excludes e.g. NRI, GeNaB, iCD, CS Green Property
- Relevance resp. distribution
  - ➢ This excludes e.g. ESI / NUWEL, INrate, SAM, BREEAM IN USE
- Relation to the local market and local norms (Switzerland, European Union)
  - ➢ This excludes e.g. LEED, WELL
- Relation to the use for individual buildings and aggregation on a portfolio scale
  - ➢ This excludes e.g. GRESB

Based on these “negative” selection criteria, 15 existing instruments were selected for detailed analysis. The aim of the analysis was, on the one hand, to find a set of criteria that is limited to the essential aspects of the sustainability of existing buildings in order to remain applicable to larger portfolios. On the other hand, all sustainability resp. performance dimensions should be considered equal and the structure should be compatible with as many instruments as possible. The instruments selected for the detailed analysis can also be assigned to the general requirements of the surveyed Swiss portfolio holders, as shown below:

3.1. Coordination with Agenda 2030 and SNE (Sustainable Development Strategy Switzerland)

- ➢ Inclusion of the Agenda 2030 at the level of sub-goals and inclusion of the gap frame instrument, as this is the only instrument known in Switzerland to provide an adequate translation resp. specification of SDG targets at company level, which also applies to building portfolios.
- ➢ Inclusion of the "Circle Indicateurs" instrument [5], as this is an instrument for the sustainability rating of Swiss cities that is aligned with the objectives of the SNE
- ➢ Inclusion of the Swiss «2000 Watt Area» Certification System [5]

3.2. Consideration of the structural condition

a) Matching national sustainability frameworks

- ➢ Inclusion of the SNBS - Standard Sustainable Building Switzerland [6]
- ➢ Inclusion of the SIA112/1 standard [7]: Sustainable construction - Building construction - Communication standard for SIA 112
- ➢ Inclusion of the KBOB/IPB guideline for sustainable real estate management of public and private clients [8]

b) Voting on international frameworks relevant to Switzerland

- ➢ Inclusion of the SIA 490 [9] as Swiss adaptation of the European Sustainability Standard CEN/TC350, which also operationalized at the detailed level via the DGNB/SGNI system
- ➢ Inclusion of the LEVEL(S) system [10], as the first EU-wide reporting tool for the sustainability performance of buildings.

3.3. Adequate consideration of operational aspects

- ➢ Inclusion of the GEFMA 160 classification [11], since requirements from the point of view Facility Management in the European area are most detailed in this instrument.
- ➢ Inclusion of the GiB instrument (Building in use) [12] in the context of the DGNB classification

In addition to these directly derivable instruments, the following two instruments were also considered:

- Inclusion of the SMEO system [13], as it is already used at the portfolio level, but is primarily used in French-speaking Switzerland
- Inclusion of the European ESCI City Rating System (Emerging and Sustainable Cities Initiative) [14], as it contains a detailed criteria and indicator structure that is also applicable to Swiss cities

4. Results

The overall structure is divided into the classic three performance dimensions of sustainability, each of which is equally weighted at 33.3%, and each of which is divided into three subject areas. This upper structure is the result of a comprehensive structural comparison of the 15 instruments examined and shows optimal compatibility based on the relevance of the instruments (norm compatibility).

Environment	**Society**	**Economy**
U1_Climate protection & energy	G1_Health & Wellbeing	W1_Building performance
U2_Material cycles	G2_Safety & Accessibility	W2_Building attractiveness
U3_Nature & Landscape	G3_Quality of spaces & communication	W3_Building resilience

Parallel to the analysis of the superordinate structures, the criteria of the selected 15 instruments were also compared in more detail, with the DGNB system [15] forming the reference structure. As a result of this time-consuming comparison, 23 criteria resulted, which essentially form the intersection of the different sets of criteria analyzed, limited to the performance-related criteria from the three dimensions of environment, society and economy of sustainable development.

As a result, the developed set of criteria is in good agreement with LEVEL(S) but is designed for existing buildings rather than new buildings or existing buildings at the point of major renovation and complements the European LEVEL(S) system with the following criteria:

- Inclusion of mobility in the life cycle assessment
- Inclusion of biodiversity issues
- Security & Accessibility
- Quality of stay & communication
- Building condition analysis
- Identity & (Building) Cultural Value

In comparison with GRESB (LEED based), the main KPIs of energy, greenhouse gas emissions, water consumption and waste are also calculated quantitatively.

In comparison to the existing DGNB usage profiles for new buildings and buildings in operation, the portfolio analysis tool developed concentrates on the actual performance dimensions. Only a few references are made to criteria from the process and technical quality dimensions. Nevertheless, the instrument developed has a consistent system for DGNB building analysis and DGNB refurbishment certification.

In the portfolio evaluation, the weighting shares of the other criteria to be "served" from the process and technical quality dimension are equally distributed among all evaluated portfolio criteria, resulting in 33.3% for each dimension. When switching from the portfolio to the more detailed building analysis view, these criteria then regain their original weighting. In project phase 2, the significance of the weighting mechanism will be checked in practical tests and, if necessary, adjusted on the basis of the results.

5. Discussion

The criteria structure developed shows for the considered topics an almost complete coverage ratio for "LEVEL(S)" and the "SGNI/DGNB system" (environment/society/economy dimensions). It is also very high for the two instruments "SNBS" and "KBOB Factsheets" (70-80%) and structurally very well compatible. In principle, a high coverage ratio with these instruments is a major advantage of the system developed. The strong link to the established European and international sustainability standards (LEVEL(S) & DGNB) promotes a high international and national reputation, makes the system compatible with international and European developments and future-proof, and makes it easier to communicate. A high degree of coverage of the national planning instruments "SNBS" and "KBOB Factsheets" is important insofar as it enables continuity and uniform consideration of issues during the planning phase and subsequently during operation or over the entire life cycle. Indirectly, the effectiveness of sustainable planning and its effects in operation can also be better assessed and plausibility checked.

In project phase 2, the significance of the weighting mechanism will be checked in practical tests and, if necessary, adjusted on the basis of the results.

The coordination to instruments such as the "cercle indicateurs" or the "2000-Watt Area Certification" is somewhat less high, as these have a broader focus that goes beyond the building itself. The "Cercle indicateurs" was developed to cover the whole range of sustainable development issues. Many of these themes cannot be influenced by buildings, or only indirectly. However, those that can be influenced by buildings are also supported to a large extent. The same applies to the "2000-Watt Areas" system, which considers an entire area or neighbourhood. However, many criteria (e.g. participation, urban development, diversity of use, etc.) are geared to planning here and can only be influenced to a very limited extent in existing buildings.

The relationship to strongly planning-oriented instruments such as "SIA112-1" and "SMEO" is also somewhat less good. On the one hand, this is due to the fact that in the case of "SIA112-1" it is difficult to make a concrete allocation due to the fact that the existing thematic structure (e.g. solidarity, balance, consolidation, innovation) is only superordinate. With "SMEO", on the other hand, direct assignment is made more difficult by the phase-based structuring as well as by many purely planning-oriented criteria (e.g. location & architecture, development, construction site management, etc.).

With the operation process-oriented instruments such as "GEFMA160" or "SGNI-GiB Building in Use" many topics are considered process-oriented but not performance-oriented. For example, the "GEFMA160" has many process-related special requirements from pure management, which have no relevance at portfolio level or only indirectly influence the actual performance criteria (e.g. document & knowledge management, CAFM, etc.).

A comparison with the goals of "Agenda 2030" shows that a considerable number of subgoals can be directly or indirectly supported to varying degrees. This is likely to become increasingly important, especially in the future, when it comes to showing and reporting the sustainability impact of these instruments in more detail.

6. Conclusion

The developed portfolio rating instrument can offer a solution on how individual existing buildings can be holistically evaluated with regard to sustainability. Analogous to the same system as DGNB for buildings in operation, entire portfolios can be assessed with little effort. For each criterion, all buildings that have comparable basic conditions or characteristics are grouped into clusters for the evaluation.

A unique selling point is the combination of high standards compatibility with SIA 490 (CEN/TC 350), SIA 112/1 and SNBS in combination with high connectivity to international assessment instruments such as LEVEL(S) and the DGNB system.

Whether the system is also easy to apply, highly effective in its evaluation methodology and highly informative in terms of the evaluation and meaningfulness of derived measures will be seen in the next phase with pilot application.

The first application tests are currently only allowing provisional conclusions to be drawn in this respect. The first clear challenges are thus emerging at portfolio level. On the one hand, it is very difficult to distinguish many properties by specific criteria. On the other hand, due to the range of criteria, the required information must be gathered from a relatively large number of different data sources. In this respect, it is only possible to estimate how much initial effort can generally be expected on the basis of the pilot application.

Experience has shown, however, that this effort decreases considerably with a cyclically repeated evaluation.

The portfolio analysis instrument developed is designed in such a way that it can be coupled optionally or, if required, directly via a more detailed DGNB-based building analysis as an intermediate step to a final DGNB remediation certification. Here, too, it will only become apparent through effective application whether the chosen approach of deriving the weighting factors from the respective new building usage profile will in reality help to derive suitable conversion and refurbishment measures.

However, the first application results for simpler objects already show that the criteria are generally well applicable and also yield meaningful results. It can therefore be expected that in the future it will be possible in this way to use the developed portfolio rating instrument to provide holistic support to portfolio holders who act sustainably.

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Portfolio Rating Tool			LEVEL(S)		
themes	Nr	criteria	themes		criteria
U1_ Climate Protection & Energy	1	LCA CO2	1. Greenhouse gas emissions along the building life cycle	1.2	Life cycle Global Warming Potential
	2	LCA Energy		1.1.1	Primary energy demand
	3	LCA Mobility		1.1.2	Delivered energy demand (supporting indicator)
U2_ Ressourcen cycles	4	Sustainable procurement	2. Resource efficient and circular material life cycles	2.1	Materials of the building
				2.2	Scenarios for lifespan, adaptability and deconstruction
	5	Recyclables Management		2.3	Construction and demolition waste and materials
				2.4	Cradle to grave Life Cycle Assessment
	6	Water Management	3. Efficient use of water resources	3.1	Total water consumption
U3_ Nature & Landscape	7	Green Spaces & Biodiversity			
G1_ Health & Wellbeing	8	Indoor air quality - fresh air supply	4. Healthy and comfortable spaces	4.1	Indoor air quality
	9	Indoor air quality - pollutants			
	10	Thermal comfort - winter		4.2	Time out of thermal comfort range
	11	Thermal comfort - summer			
	12	Visual comfort		4.3	Lighting and visual comfort (Future Aspect)
	13	Acoustic comfort		4.4	Acoustics and protection against noise (Future Aspect)
G2_ Security & Accessibility	14	Security			
	15	Accessibility			
G3_ Room Quality & Communication	16	Room quality indoor			
	17	Room quality outside			
			6. Optimised life cycle cost and value	6.1	Life cycle costs
W1_ Building performance	18	Operating cost			
	19	Building substance (repair backlog)			
W2_ Building attractiveness	20	Usability & space efficiency		6.2	Value creation and risk factors
	21	Identity-creating & (cultural) cultural value			
W3_ Building resilience	22	Temperature resilience	5. Adaptation and resilience to climate change	5.1	Scenarios for projected future climatic conditions
	23	Extreme weather resilience		5.2	Increased risk of extreme weather events
				5.3	Increased risk of flood events
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Table 1: Comparison of the structure of the new portfolio rating tool with the LEVEL(S) structure

The BNK Assessment Tool for the sustainability performance of small residential buildings in Germany – Lessons learnt

Essig N

Munich University of Applied Science, Faculty of Architecture, Karlstrasse 6, 80333 Munich, Germany

natalie.essig@hm.edu

Abstract. Several instruments for the assessment of the sustainable building performance such as BREEAM (Great Britain), LEED (USA) and DGNB or BNB (Germany) have been developed in the last years. These methodologies have the same intent - advancement of the sustainable building performance. These systems focus mostly on commercial buildings. However the sustainability assessment of the residential sector is getting more important. Giving that around 115,000 owner-occupied detached houses are built up per year in Germany, a new assessment method (BNK system) for small residential houses was developed on behalf of the Federal Ministry for the Interior, Building and Community (BMI) in 2015. To ensure the suitability of the assessment system, the BNK method was tested in a pilot phase and from 2016 on it is available for general use and the assessment is financially supported by public funds (KfW Banking Group). To date more than 100 of small residential buildings have been certified with BNK. This paper will show the development and experience with the sustainability assessment of buildings in Germany in general, as well as the intents, indicators and real case projects of the BNK-Tool for small residential buildings (up to five dwelling units) and its further development.

1. Introduction

If future generations are to have a quality of life comparable to the one we enjoy at present, then we need to act sustainably towards our environment. This applies to everyone, including the construction industry. Up until now, the term "sustainable construction" has been associated mainly with efforts to reduce the impact a construction project has on the environment, and to improve its energy efficiency. In fact, however, this is only part of what sustainability means [2].

At least in relation to the construction industry, sustainability is actually much more complex than that. Sociocultural, functional and economic aspects, and the building's technical and process and location specific characteristics, are also important. To build sustainably, it is therefore not enough just to follow a rigid set of guidelines.

Special concepts, solutions, alternatives and measures need to be developed, all tailored to the construction project in question. Sustainability quality labels are important as a tool for achieving and assessing sustainability in a building: they ensure that all of the above aspects are given equal attention during the planning process, and they take into account all stages of the building's life cycle. In recent years, numerous labels and certificates of this kind have been developed around the world, all designed to allow a building to be assessed as a complete system. They draw on existing planning tools and aspects of sustainable construction, and complement existing national standards and legislation. They give planners and clients an assessment of their project during its very early stages, which can be used in drawing up sustainable planning objectives and improving the building's sustainability credentials right from the planning stage. Building certificates are additionally an easy-to-understand way for users and operators of finished projects to obtain information on the building's level of sustainability. Certification systems do not only assess the sustainability of the building as it stands, but it also provides added quality assurance by requiring the compilation of suitable building documentation [2] [3].

2. Sustainability Assessment Methods for Buildings

2.1. Methods for Assessing Sustainability – International

The established international methods for assessing the sustainability of buildings are the British system BREEAM (BRE Environmental Assessment Method), the American method LEED (Leadership in Energy and Environmental Design) and the German DGNB certificate. BREEAM and LEED were both developed in the 1990s. In 2009 two systems were launched in Germany – the Sustainable Construction Evaluation System (BNB) of the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB), and the DGNB certificate of the German Sustainable Building Council (DGNB), that, unlike previous methods, did not focus solely on the building's environment-friendliness and energy efficiency, but instead considered its entire life cycle [2].

Thanks to their successful marketing strategy aimed at promoting the "green building" concept, the American LEED and the British BREEAM system are currently the best-known certification systems worldwide. This is shown also in the number of certifications, like 100,100 LEED and 18,800 BREEAM certified buildings [4] [5]. BREEAM owes this success also to the fact that the British government has enshrined sustainability standards for the UK construction industry in law [6]. Notable documents are the 2006 "Sustainable Procurement Action Plan", according to which all new and refurbished government buildings must achieve the "BREEAM Excellent" standard, and the "Code for Sustainable Homes", which since May 2008 has required that all new residential buildings be built according to specific sustainability standards, and subsequently rated [6].

2.2. Methods for Assessing Sustainability – in Germany

In 2007, the German Sustainable Building Council (DGNB) was set up with the aim of developing a German quality label for assessing the sustainability of buildings. At the same time, the Federal Ministry of the Interior, Building and Community (BMI, former BMVBS Federal Ministry of the Interior, Building and Community) started work on a method for the evaluation of sustainable buildings. The DGNB and the former BMVBS soon decided to join forces and worked together in this area. In 2009, on the basis of past experience, international and European standards for sustainable construction such as the international standard ISO TC 59 SC 17 (Sustainability in building construction) and the European standard CEN/TC 350 (Sustainability of construction works), and the results of the "Round Table on Sustainable Construction" and "Guideline for Sustainable Building" of the BMI, the first list of criteria for the "German Certification Method for Sustainable Building" was published [2] [7].

There are now two systems in Germany based on that original joint list of criteria: firstly the DGNB certificate, which is mainly for commercial buildings in the private sector. The DGNB itself is responsible for promoting the system internationally. Over 1,500 buildings have been certified to date under this system [7]. The BNB system from the former BMVBS (now BMI), on the other hand, is for all buildings that are of significant relevance to the general public, for example federal buildings. So far 25 buildings have been certified under this system [8].

3. Sustainability Assessment Method for Small Residential Buildings in Germany – the BNK System

3.1. Why detached and semi-detached houses?

Up until now, it has been almost exclusively buildings such as office buildings, schools, industrial buildings and large residential buildings (i.e. those containing six or more dwelling units) that have been assessed for sustainability in Germany. Insufficient attention has been given to smaller residential buildings ranging from detached houses to apartment blocks with up to five flats, even though these buildings represent a large share of total residential new build – up to 60 percent [9]. The former BMUB has tackled this problem, together with Munich University of Applied Sciences (MUAS) and other building experts and researchers, by developing a list of criteria specifically for these smaller residential buildings. A wide range of industry players were subsequently called upon to fine-tune this list, which was then subjected to pilot test to test its suitability for the market. These included housing construction industry associations, architects, engineers, and the prefabricated house industry [1].

Outside Germany, residential buildings have long since been assessed against sustainability criteria. Some 1,700 residential buildings (more than 426,000 dwellings) have so far been assessed under the BREEAM "Code for Sustainable Homes" system, for example. This is thanks to the UK government's decision in 2008 to enshrine in law the sustainability assessment of buildings [5] [10]. More buildings are being assessed with other systems as well, under the LEED quality label 28,900 single and multifamily homes and under the Swiss Minergie label (21,800 detached and semi-detached houses as well as 20,900 multifamily houses) [4] [11].

In Germany, the Sustainable Housing Construction Quality Label (NaWoh) and individual system variants of the DGNB certificate are available for assessing residential buildings, although the formers are only available for structures containing six or more dwellings [7] [12]. However, the list of criteria of both systems is very complicated and costly to implement. With an average of 120,000 new detached and semi-detached houses being built each year in Germany, a cost-effective, lean, simple assessment system for residential buildings that all clients can apply, and that is designed to encourage sustainability in small residential buildings, is essential [13]. Therefor the BNK system was developed and is available on the market since 2015 [1].

Figure 1. Sustainability qualities of BNK [1]

3.2. BNK-System: Criteria for sustainable small residential buildings

The list of criteria for sustainable small residential buildings is divided up into the four categories

- Sociocultural and functional quality
- Economic quality
- Environmental quality
- Process quality

broken down into a total of 19 criteria [1]. Figure 1 shows a summary of the qualities for small residential buildings, Figure 2 the 19 BNK sustainability criteria.

The system is based on the Sustainable Construction Evaluation System (BNB). However, due to the importance of the social aspects in determining the sustainability of small residential buildings, the category of “Sociocultural and functional quality” comes first in the list of criteria for detached and semi-detached houses, rather than environmental quality, which is the top category for the other building types. Each of the four categories accounts for 25 % of the overall result [14].

3.2.1. Sociocultural and functional quality. Social aspects are particularly important in determining the sustainability of small residential buildings. In the category of “Sociocultural and functional quality” the aspects of quality of life, comfort, safety, security and adaptability are assessed. The level of comfort is determined by measuring the characteristics of the building from the building physics point of view. This is based on a number of calculations regarding thermal, acoustic and visual comfort and by assessing the inherent level of air hygiene inside the building. Because the system takes into account the aspects of safety and security, accessibility, and the user-friendliness of the building services, it helps to enhance residents’ quality of life.

3.2.2. Economic quality. The goal of the “Economic quality” category is to determine selected costs incurred during the building’s life cycle, and to assess its long-term viability. The calculation of life cycle costs is based on the standard DIN 276 (Building costs – Building construction). Long-term viability is based on the assessment results for various criteria such as accessibility and thermal insulation in summer, and the extent to which the building’s energy efficiency figures exceed those demanded by the German Energy Saving Regulation, the degree to which the rooms are designed in a neutral way to allow for alternative uses, and the extent to which the client has been briefed to enable them to maintain the building’s value over time.

3.2.3. Environmental quality. The environmental quality of a detached or semi-detached house is assessed by carrying out a life cycle assessment (LCA). The LCA is prepared using the online tool “eLCA” provided by the BMI and the BBSR (German Federal Institute for Research on Building, Urban Affairs and Spatial Development) [15]. The LCA looks at the building’s entire life cycle, this include the building fabric and the building services. The most important indicators used are Primary Energy Consumption and Global Warming Potential. Other aspects such as recyclability, the use of local or certified wood, measures taken to reduce drinking water consumption, and the efficient use of space in order to minimize soil sealing are considered.

3.2.4. Process quality. The main aim of the “Process quality” category in relation to residential buildings with up to five dwellings is to ensure the quality of planning, construction and documentation, and to provide a building dossier including a user manual. The building dossier includes the latest plans, energy performance certificates, measurement records, safety certificates, data sheets, care instructions, and all documents relevant to the operation and maintenance of the building. Process quality also includes having the quality of construction verified by an external assessor.

3.3. BNK-System: Assessment Methodology and Certification Authority

For each criterion there is a description of the assessment method and indicators, general information, an assessment scale, and the documents required as evidence of adherence to that criterion. The result of the assessment is represented by a score between 1 to 5, and its percentage. The scores and percentages relate to one another as follows [1] [14]:

- 80 % or more: score of 1.5 or better
- 65 % or more: score of 2.0 or better
- 50 % or more: score of 3.0 or better

The building owner will receive the BNK certificate, in case one point in each criterion is achieved. The certificate will be proved and over given by BiRN (Bauinstitut für Ressourceneffizientes und Nachhaltiges Bauen GmbH). BiRN is the official certification authority for the BNK system and is accredited by the BMI. Furthermore BiRN is responsible for the training of BNK auditors and for the development of the BNK system [16].

Figure 2 List of BNK criteria [1]

3.4. BNK System: Further development

To ensure the practicability and user-friendliness of the sustainability assessment of small residential buildings in the long term the intents, the standards, methodologies and benchmarks referring to the BNK system are updated and developed at regular intervals.

In 2018 the results of the research project "Further development of the criteria indoor air hygiene, pollutant emissions, dismantling and dismantling friendliness and resilience of the BNK system“ was published by BiRN. This research project was developed by BiRN in close collaboration with building experts from all over Germany [17]. It was funded by the research initiative "Zukunft Bau" of the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR). In addition to the revision of already existing criteria, new aspects of sustainability were taken up.

These criteria have been proofed in real case studies involving building owners, developers, project managers, architects and engineers. A pilot study was carried out in order to check the suitability of the new and overworked criteria on real detached and semi-detached houses. Around ten single family housing have taken part. In the following the four new developed criteria will be shown:

- Criteria “Indoor hygiene and risk-based emissions of construction products”:
  New assessment processes and methodologies were added to the existing criterion. Further on benchmarks of the existing indicator were revised. Originally the listing of used construction products was sufficient for assessing small residential buildings. In the new version

benchmarks and parameters for "Volatile Organic Compounds" (VOCs) and other risk-based substances were defined and added. For this purpose, different digital tools have been developed to implement the new assessment methodology in a simple and practicable way.
- Criteria “Consultation, agreeing objectives and risk assessment against natural hazards”: The methodology for assessing the risks for natural hazards has been newly integrated into this criterion. Natural hazards, like wind, heavy rain, hail, lightning, snow load, flood, radon and earthquake will be considered now. The assessment was divided into three risks classes "low", "medium" and "high" risk.
- Criteria “Building dossier including user manual, demolition and dismantling-friendliness”: The topic of deconstruction, separation and the re-use of buildings product was taken into account. Aspects for resource-efficiency and waste-minimizing of buildings were extensively overworked. A new process for the preparation and evaluation of dismantling concepts was integrated into the criteria. Therefor a component catalogue with dismantling and separation option was developed that includes the mass balance of building products coming out from Life Cycle Analyses (LCA).
- Criteria “Quality assurance in planning, construction and use”: In addition to an editorial revision, the benchmarks were adjusted in this criterion during the research project.

4. Outlook and Benefits of Assessing Building Sustainability

Since April 2015 the BNK system is available for general use as a simple and cost-effective assessment system for small residential buildings. Assessments are carried out by “Sustainability Coordinators” who hold a specialist qualification in sustainable building by BiRN and who monitor the project during planning and construction. To ensure that all certificates are of a suitably high quality, the assessments are checked furthermore by BiRN [16]. From 2016 the KfW Banking Group is providing financial support to help projects achieve the sustainability certificate for houses with one to five dwellings, similar to the support it offers for those seeking to achieve the Efficiency House standard.

Based on the results of the research project the new criteria will be integrated in the BNK system in a new version at the end of 2019. Furthermore the system will be extended to cover residential buildings with up to five dwellings; in future it is conceivable that it will also allow the assessment of refurbishment work on existing residential buildings.

Summarizing the abstract - the advantages of applying sustainability tools and criteria for small residential housing are the follows [2] [3]:
- benchmarks help to reduce and monitor the building’s impact on the environment,
- allows quality of different buildings to be compared,
- helps in setting sustainable planning objectives (e.g. checklists),
- improves the transparency of planning and construction work,
- provides a project management tool for ensuring that sustainability is achieved,
- better building documentation (e.g. building passport),
- more competitive at all stages of life cycle.

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A stakeholder- and function-based planning method for space-efficient buildings

Von Both P[1]

[1] Department Building Lifecycle Management, Karlsruhe Institute for Technology, Karlsruhe, DE

petra.both@kit.edu

Abstract. Space efficiency has proved to be one of the basic parameters for achieving a high level of sustainability of buildings. By optimizing the required space to fulfil functional requirements, high potential savings can be achieved in terms of space, material and energy consumption. This presupposes, however, that – following the principles of an integrated design process - the use-related functional requirements of buildings have been determined in the early planning phases and that architects take these functional requirements into account accordingly - also with regard to possible organizational, logistic and process-related options. So, interdependencies and (temporal) overlays can be reflected and the topological structure can be transferred into space-efficient spatial structures. But adequate tools and methods are currently missing that support this process of user-based functional demand planning in the sense of an integrated participatory process. This contribution introduces a methodology for early planning phases, which is based on a stakeholder analysis and helps to specify process-related user functions as well as qualified functional correlations. The functional relationships can be described, for example, spatiotemporally or in relation to the flow of materials and can be mapped in an adjacency matrix. The planner is thus actively encouraged to think about area- and space-related optimization potentials and can transfer the topological structure of functions into an space-efficient floor plan concept. Also a prototypical implementation of this method will be presented as a web-based tool that supports a participatory user and stakeholder-related planning process.

1. Introduction

To implement sustainability strategies in the construction sector holistically, a rethinking of pure technical (eco)-efficiency strategies is necessary that includes also social and user-related considerations and sufficiency strategies [2, 3, 4]. Only after the analysis and reflection of the real functional demands of building users, we can answer the question of 'how much and what kind of resources are used for achieving the desired purpose', needs and functions' and offer a quality response to these needs [1]. Boulanger [3] speaks about the 'Satisfaction/Service ratio' with the superordinate goals of well-being, happiness or needs satisfaction.

In the construction sector, an important starting point is the fundamental question about the construction volume or space that is necessary to fulfill the relevant user functions and to enable an adequate execution of processes. Thus, space efficiency is one of the key factors for achieving a high level of sustainability of buildings. By optimizing the required space to fulfill functional requirements, high potential savings can be achieved in terms of space, material and energy consumption.

This is particularly evident in the field of residential buildings. Housing is currently one of the most important and much-debated topics of architectural design in Europe. Due to current political and sociological changes such as migration growth, demographic change and urban-rural movements, the demand for affordable and sustainable living space is growing. The latest changes in legal framework conditions for the densification of existing urban structures in Germany exemplify the urgency of the problem [4].

The topic of space- and thus resource and cost-efficient construction gets a special meaning here. However, space efficiency can only be achieved, if the implementation of the functional requirements is taken into account in a systemic manner to create adequate and sustainable building structures and typologies.

A look at the available planning literature and construction practice, however, shows that standard solutions and traditional typologies are used without any reflection. They represent current energy-saving regulations but are hardly capable of dealing with the current sociological changes in the resident respectively family structures and also in the living behaviour.

Standard literature such as floor plan compendia for dwelling houses (for example the German ‘Grundrissatlas Wohnungsbau’ [6]) focus mainly on the subject of single-family dwellings and floor plan typologies, which originate from the 1950s and thus serve primarily family structures such as the classical nuclear family and a very traditional understanding of roles. These are in today's time, however, from a sociological point of view, hardly available and desirable. Unfortunately, there are hardly any planning aids and generalized examples of new approaches such as residential communities, intergenerational living or cooperative housing. The ever more popular approach of minimal and often modularized Tiny Houses [7] provides first good approaches to space efficiency, but focuses – often combined with concepts of ressources self-sufficiency - on very specific target groups and can therefore hardly be generalized.

Niklas Maak - Chief editor of the culture department of the Frankfurter Allgemeine Zeitung and a well-known architecture critic - for example, in his book "Baukomplex" [8] calls for a fundamental rethinking of current planning practice and explains the need for the development of new user-related typologies that can adequately serve today's functional and structural needs of different user groups.

This presupposes, however, that – following the principles of an integrated design process - the use-related functional requirements of buildings are determined in the early planning phases and that architects take these functional requirements into account accordingly - also with regard to possible organizational, logistic and process-related options. So, interdependencies and (temporal) overlays can be reflected and the topological structure can be transferred into space-efficient spatial structures.
But adequate tools and methods are currently missing that support this process of user-based functional demand planning in the sense of an integrated participatory process.

This article introduces a methodology and planning means for the early planning phases, which begins with a stakeholder analysis and helps to specify process-related user processes and functions and which supports their transfer into topological concepts and floor plans. The function-based methodology for architectural design has been applied, evaluated and enhanced in teaching design projects for over 3 years now and will be presented with students’ design examples in the following.

Application context of these teaching projects has been housing projects as well as hybride buildings that should cover the design principles of mixed-use, flexibility and space efficiency. But the principles of the methodology are generalizable and not limited to a specific typology of buildings.

2. Methodical Conception

One important prerequisite for successful design projects is the existence of a holistic target system that makes the impact of planning activities assessable with regard to the entire life cycle of the planning object or system. Taking into account its interactions with the superordinate systems and stakeholders [9]. From the objectives of this superordinate system, the purpose and utility of buildings and thus the specific object-related objectives and functional requirements (including functional performance) of the planning subject can be deduced. Here, it is important to analyse the value systems, consumer behaviour and development strategies of the clients and also later building users [10], if possible by a participatory process.

If the customer is also the future user, the application of target planning methods and tools [11] can support the direct interaction. In the case of, for example, investor projects or the design of rental properties, in which the future user is not yet (concretely) known, the (functional) needs can be generalized at the level of target groups by means of marketing methods, such as the persona method

[12]. An important mean for the identification of value systems and consumer behavior are socio-scientific approaches of life-world studies [13] like the sinus milieu data [14].

The methodical approach, that bases on this system of objectives, supports the design process on two levels (see figure 1): At the structural level, the development of spatial-functional topologies and spatial structures takes place, basing on the relevant user processes and their interactions.

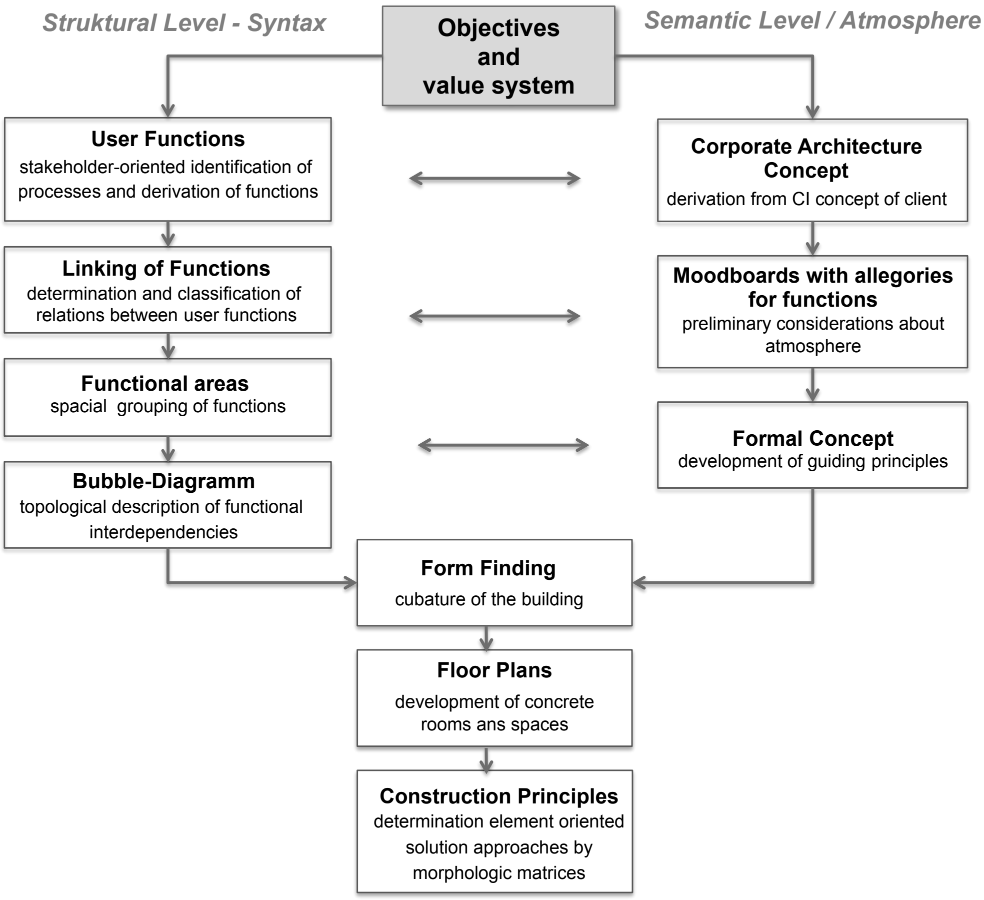

Figure 1: Process-logic of the Function-based Methodology

This process starts with a stakeholder and user analysis and is supported by a so called „structure matrix' - an adjacency matrix, which helps to analyse, qualitatively specify and formalize process-related user functions for the different stakeholders (see figure 2), that should be developed in interaction with the functional requirements in the target system. The analysis and overlay of daily and annual routines of the different users can reveal first relevant correlations. Here, it is very important to specify the functions qualitatively, because it has different spatial consequences.

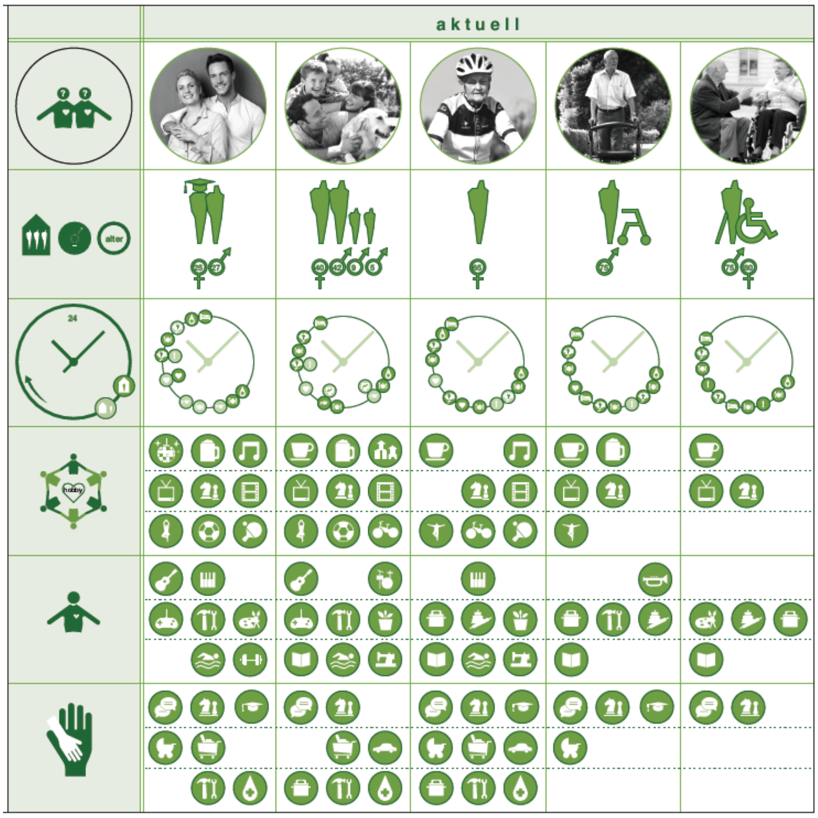

Figure 2: Comparison of Daily Routines of Different Stakeholders, student example of a mixed-used housing project: 'Marketplace of Generations', Noel Rabuffetti 2017 [15]

Currently a student's master project deals with the analysis of the possibilities to apply the methods in the area of healthcare and hospital buildings, which have a very high complexity concerning the logistics. Here the DIN 13080:2016-06 - Division of hospitals into functional areas and functional sections - can serve as a kind of check-list to choose the relevant user functions for the structure-matrix [16].

The next step is the analysis and survey of qualified functional correlations. The use-related functional relationships can be described, for example, spatiotemporally or in relation to the flow of materials or persons (logistics) and can be mapped in the adjacency matrix (see Figure 3). Here, the challenge is to identify possibilities for (temporal) spatial overlaps and mixed-use spaces.

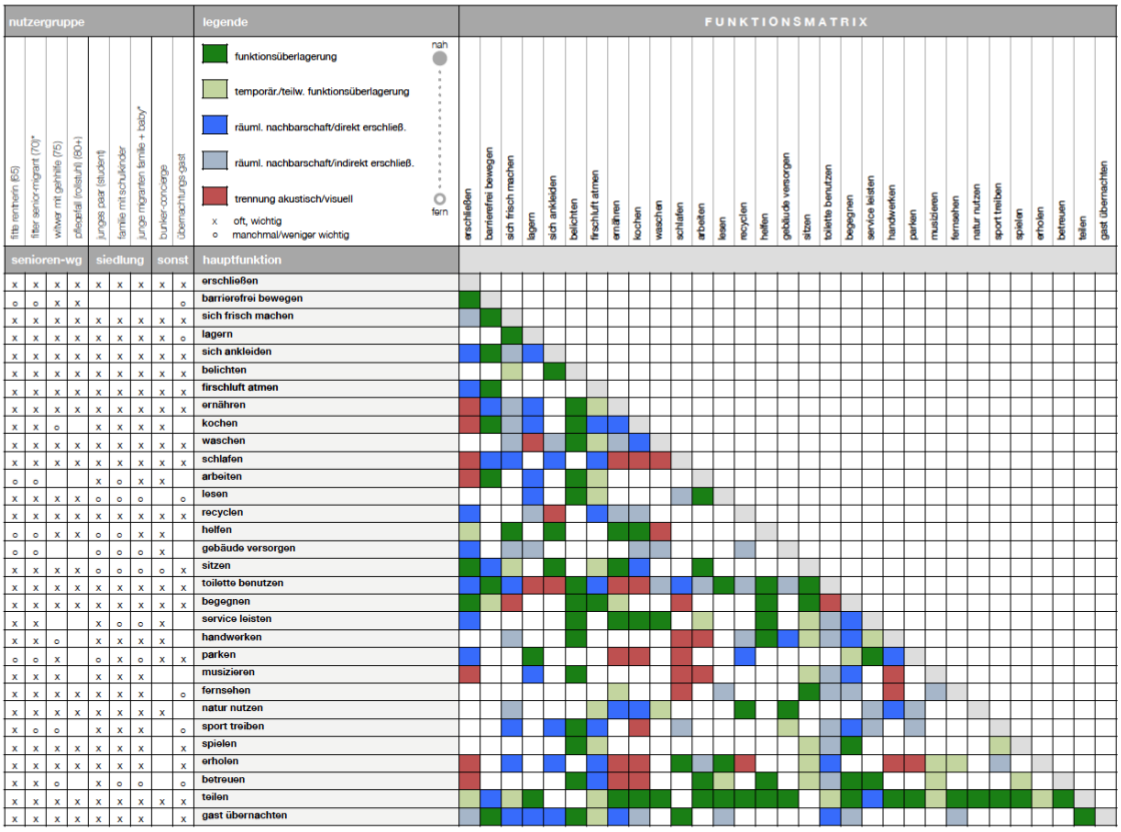

Figure 3: Structure-Matrix for the Analysis of Functional Correlations; student example of a mixed-used housing project, Noel Rabuffetti, 2017 [15]

Considerations about the required technical and physical conditions as well as emissions of the functions with regard to lighting, air conditioning, acoustics and other aspects, describe additional preconditions for the structural formation process in the sense of a systemic approach. An assessment (e.g. by using ranges from one to five) of functional output and required or permitted Input of the system dimensions serves as complementary base for the mapping and structuring (see figure 4).

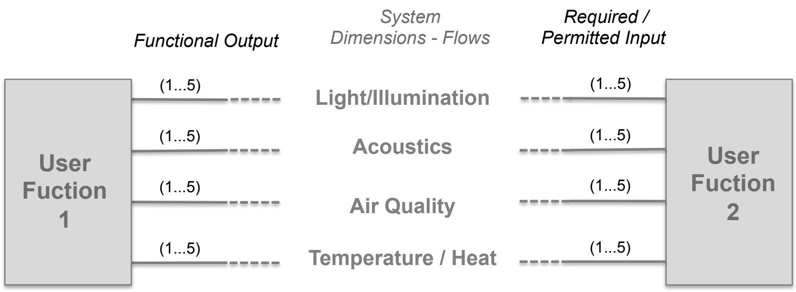

Figure 4: Mapping of Functions with Regard to System Flows

Based on these identified relations and functional conditions, first arrangements of functional groups and areas and for the spatial positioning of functions in the system ‚building' can be made in a reflected way as a first step toward the following space-formation. Here, the functional mapping supports the identification of overlay and flexibility options, which can later be realized, for example, via so-called cluster-flats, a combination of minimized apartments and shared living area and kitchen or so-called joker rooms, which could be assigned to different housing units temporarily.

The planner is, thus, actively encouraged to think about area- and space-related optimization potentials and can transfer the topological structure of functions into a space-efficient floor plan concept. Sustainability assessment systems here also speak about functional equivalence.

A feedback loop with the stakeholder-oriented processes and time-schedules can help to evaluate the logistic quality of the floor-plans.

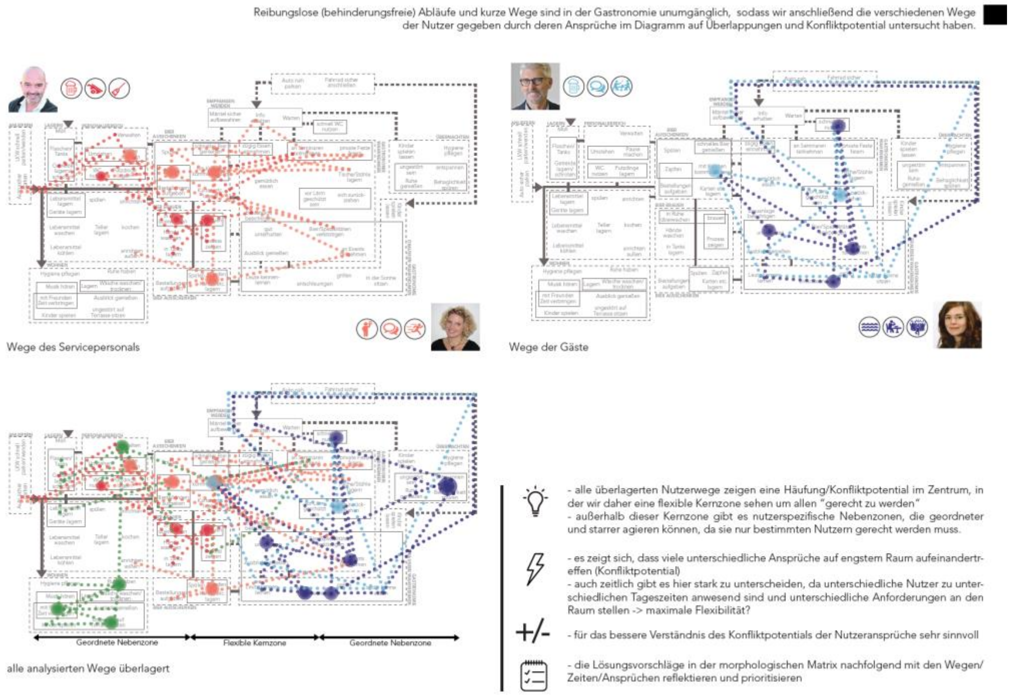

Figure 5: Example of a Students Project: Evaluation of the Floorplan by Overlaying the User Processes, K.Grötsch und Th. Müller 2017, design project ' Brewery at the lake' [17]

To avoid a pure technocratic approach, the building conception in the early planning stages also takes place on a semantic level, in which the designer deals with corporate architecture and questions about the required atmosphere of the functional areas as a basis of later form-finding and spatial design. Here the analysed value systems of the customer helps to develop a specific customer and user oriented architectural statement and semantic.

So, an important step is the elaboration of suitable guiding principles and atmospheric concepts for the identified functions. Working with mood boards, ideographs and symbols for the functions and functional areas supports an abstract and thus more experimental approach, which has been seen to be able to expand the range of solutions consciously. The Maggie's Centre in Glasgow, a hospital for people with cancer, designed by Rem Koolhaas is a very good example for the creation of a surprising atypical and cosy atmosphere that is conducive to the healing process [18].

The merging of structural and semantic level leads to the reflexive conception of the cubature of the building. Input workshops about form finding methods [19] can enhance the quality of results noticeable. Under consideration of the cubature and the functional topology, now the floor plans can be elaborated. Supported by morphological matrices also first ideas about constructive and design principles can be elaborated. Also on level of the building elements the elaborated strategies for the flexibilisation of spaced shall be implemented by appropriate constructive solutions.

3. Technical Implementation as IT-based Tool

To facilitate the application of the method, a web-based tool, the 'functionsTool', has been prototypically implementation of this method will be presented as a web-based tool that facilitates a participatory stakeholder-related design process. The so-called 'functionsTool' supports the user oriented development, structuring and grouping of user functions. Based on this, a qualified allocation of the functions and their spatial-temporal interdependencies can be done. Based on these interdependencies, the tool generates automatically a structural bubble-diagram– an abstract topological graph schema – from the entries and qualified relations in the adjacency matrix. Figure 6 shows a screenshot of the functionsTool with a students' design project - functional conception of a Digital Detox Camp (DDC) using the functionsTool.

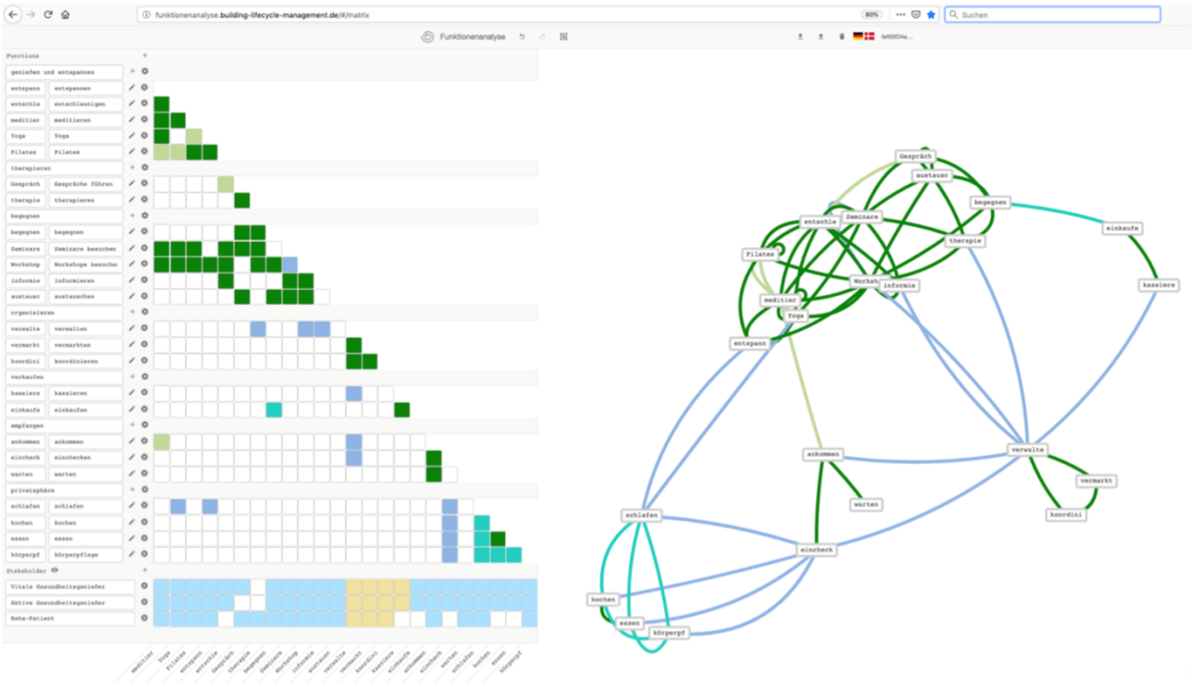

Figure 6: Screenshot of the 'functionsTool' that shows the Structure Matrix and the Automatically Generated Bubble Diagram, (C.Conway and S. Djokic, 2018) [20]

Also, graphics and ideographs can be stored and provided. So, the functional and topological structure of the building can be presented and edited in a transparent and ergonomic way. Here, differentiations in colour allow an easier comprehension and, depending on the quality of the relations, different spatial distances between the functions facilitate the pre-structuring and grouping of functions as base for the next step, the spatial location of functional areas and the geometric room generation.

In a next step, also the specification and representation of system dimensions and their flows as output and input (see figure 4) shall be implemented in the tool. Thus, also the qualified system flows can influence the attraction forces of the functional bubbles and the finally the topology of functional areas.

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Sustainability assessment of a Flemish office building with Level(s): a Level 1 assessment

Ramon D, Pironnet C, Allacker K

Department of Architecture, Faculty of Engineering Science, KU Leuven, Leuven, Belgium

delphine.ramon@kuleuven.be

Abstract. Recently, Level(s) has been developed by the European Commission as a common EU framework to assess sustainability of buildings with the intention to provide a consistent and comparable framework across national boundaries. It aims at providing a general language for sustainability for buildings and to promote life cycle thinking. This paper describes the application and results of a Level 1 assessment for the design stage of a Flemish office building. Level 1 is a common performance assessment which aims to be used amongst others by building professionals. Common standards and simplified methods are used for the indicators. The paper focusses on the experiences of testing the method by evaluating the user-friendliness of the assessment method for architects considering the information and calculations needed. The added value of applying the methodology in the design stage is furthermore discussed. Based on the test phase, further improvement is recommended by aligning current national tools for data gathering and by providing default values. A Level 1 assessment allows to gain insights in various performances of a building but does not aim to evaluate the "sustainability" level. A level 2 assessment is probably more useful for practitioners to make well-founded choices between different design options.

1. Introduction

The building industry, being one of the biggest waste creators and energy consumers, started to pay significantly more attention to sustainable buildings during the past decades. Since the first mentioning of sustainable development in 1987 in 'Our Common Future', the assessment of sustainable development in the building sector has gone through an evolution [1]. Different stakeholders have to make informed decisions in order to meet sustainability goals [2]. Hence, sustainable building had to become 'measurable'. John Elkington defined the three fundaments of the Brundtland report as 'triple P' (People, Planet and Profit) in 1994 [3], but without defining the importance of each the three pillars. Based on personal interests and views on society, different attitudes towards sustainable development have appeared, reflected in a proliferation of sustainability assessment methods for buildings [4].

Worldwide, more than 600 sustainability tools are available for products and buildings [2]. The United Kingdom developed the first one for buildings, called BREEAM, in 1990. After that, western Europe (e.g. HQE) and North America (e.g. LEED) followed in the 1990's, Asia (e.g. CASBEE) in the 2000's and finally South America (e.g. Processo AQUA) in 2008 [2]. At first, single indicator metrics were developed in order to assess for example CO_2 emissions or construction waste [4]. Gradually, the evaluation methods and related tools became more complex and evolved to more holistic and comprehensive approaches. Eventually, the idea of life cycle analysis was introduced to prevent burden shifting between different domains and life cycle phases [4]. The nature of the different tools can be categorized into two groups: quantitative and qualitative tools. However, due to a lack of international regulations, different national assessment frameworks have been developed with each their own focus, amongst others Active House (Denmark 2017), DGNB (Germany 2007), Milojöbyggnad (Sweden 2005) and GRO (Belgium 2017) [2,5].

To respond to the concern of the proliferation of assessment methods in Europe, the Level(s) framework for environmental impact assessments was developed by the Joint Research Centre (JRC) in close co-operation with industry stakeholders [6]. The EC aimed for a consistent and comparable framework across national boundaries as well as for promoting life cycle thinking. Level(s) features three different assessment levels: the common performance assessment (Level 1), the comparative performance assessment (Level 2), and the optimized performance assessment (Level 3). Level(s) can be used during different phases in the design process as well as for the post-occupancy phase. The framework is launched in 2018 and is currently going through a two-year test phase to get insights in cost, application and time implications.

This paper discusses the application of a Level 1 assessment for the design stage of a Flemish office building and describes the experiences of testing the method by evaluating its user-friendliness for building practitioners. The added value of applying the methodology in the design stage is furthermore discussed by showing how the results might influence decision taking. The scope of the paper is limited to the indicators which are closely related to life cycle assessment and life cycle costing. Further, only the most relevant results are shown due to the limited pages available.

2. Methodology

2.1. Level(s) framework

The Level(s) framework comprises assessment criteria related to six macro-objectives (see Table 1) of the EC in the field of sustainable building: (1) reduction of greenhouse gas emissions along the building life cycle, (2) increased resource efficiency and circular material life cycles, (3) increased efficient use of water resources, (4) provide healthy and comfortable spaces, (5) adaptation and resilience to climate change, and (6) optimized life cycle cost and value. The six macro-objectives can be linked to the three previously mentioned pillars of sustainability as indicated in Table 1. Indicator 2.4 'Cradle to cradle life cycle assessment (LCA) is an overarching assessment method which covers the first three macro-objectives [7].

Table 1. Overview of the Level(s) macro-objectives and indicators to be assessed.

Pillar	Macro-objective	Indicator	
PLANET	1 Greenhouse gas emission along a building life cycle	1.1 Use stage energy performance	2.4 Cradle to cradle life cycle assessment (LCA) (overarching assessment method)
		1.2 Life cycle global warming potential	
	2 Resource efficient and circular material life cycles	2.1 Building bill of materials	
		2.2 Scenarios (3) for lifespan, adaptability and deconstruction	
		2.3 Construction & demolition waste and materials	
	3 Efficient use of water resources	3.1 Use stage water consumption	
PEOPLE	4 Health and comfortable spaces	4.1 Indoor air quality	
		4.2 Time out of thermal comfort range	
		Potential future aspects: 4.3 Lighting and visual comfort 4.4 Acoustics and protection against noise	
PROFIT	5 Adaptation and resilience to climate change	5.1 Scenarios for projected future climatic conditions	
		Potential future aspects: 5.2 Increased risk of extreme weather events 5.3 Increased risk of flood events	
	6 Optimized life cycle cost and value	6.1 Life cycle cost	
		6.2 Value creation and risk factors	

Most of the indicators are further divided in sub-indicators, which are described more detailed in section 3. As this paper focusses on the indicators which are closely related to life cycle assessment and life cycle costing, the indicators belonging to macro-objective 4 and 5 are not further discussed. A reporting excel file is available and used (version Beta v1.1) for this Level 1 assessment.

In addition to the sustainability indicators, also a data quality indicator is included in Level(s), entitled "reliability rating of the performance assessment" [8]. This indicator must be evaluated for each of the sustainability indicators assessed, but is not further elaborated in this paper.

2.2. Case study building - BelOrta

The BelOrta office building is located in Sint-Katelijne-Waver in Flanders (Belgium) and has a net floor surface of approximately 3000m². The office is designed by the architectural office ar-te and is finished in 2014. The building is an extension to the existing auction hall of the BelOrta company. The two-floor building has a compact layout with an inner courtyard and consists of landscape and cellular offices, and meeting rooms. It is seen as a representative Flemish office building regarding building typology, energy performance and technologies. For the Level(s) assessment, the scope was limited to the building itself excluding external works. This case study was selected because of previous analysis. Hence, al lot of the building data was already inventoried based on a BIM-model, bill of materials, performance documents and technical information sheets. It moreover allows to compare the results of the Level(s) testing with results obtained using other assessment methods such as the Belgian method GRO and the EC PEF (Product Environmental Footprint) method. A detailed description of the case is not included in the paper but can be found in [9] and [10]. Although the building is already in use, the design stage documents are used for the assessment as an assessment during the design stage is focussed on.

2.3. MMG+_KULeuven tool

As shown in table 1, the Level(s) framework requires to perform a cradle to cradle environmental life cycle assessment (criterion 2.4) and financial life cycle costing (criterion 6.1) of the building. National tools in line with EN 15978 [11] and EN 15804 [12] can be used for this assessment. For the cradle to cradle life cycle assessment and life cycle costing the excel-based MMG_+KU Leuven tool has been used. The latter uses the Belgian LCA method for buildings, called the MMG method ("Environmental profile of building elements") [13] and allows to calculate financial life cycle costs too. The MMG method is in line with the European standards EN 15804 and EN 15978, but considers ten additional impact categories (in line with the recommendations of the International reference Life Cycle Data (ILCD) Handbook). For the life cycle inventory, the Ecoinvent database (version 2.2) is used. The life cycle stage of module D (as referred to in the EN15978 standard) is currently not considered in the MMG method [13]. The life cycle cost calculation in the MMG_+KU Leuven tool includes material and labour costs based on data from the ASPEN database [14] and the British Spon's Price Books External Works and Landscape Price Book [15], with 2015 as reference year. The financial cost is calculated as the sum of the present values of all costs occurring during the life cycle of the building.

3. Application

This section describes the application of the different indicators for the Level 1 assessment. An overview is given of the requirements to perform this assessment and the repercussions for architectural firms.

3.1. Indicator 1.1: Use stage energy performance

The use stage energy performance requires information about the primary and delivered energy demands for spatial heating, cooling, ventilation, production of hot water and lighting. In case the energy calculation method used is able to calculate unregulated energy uses (e.g. electricity use for appliances, elevators …), a section with 'small power' and 'other uses' is provided.

For the Belgian case, the energy performance is calculated based on the NBN EN 15603 with the EPB software Flanders version 1.8.5. Such calculation is required in Belgium during the design stage and was hence provided by the architectural firm. For the primary energy demands, the EPB calculations suffice to fill in the required data for Level(s) (see Table 2) but some small additional calculations are needed (e.g. breakdown of auxiliary energy use). Further, the delivered energy demand differentiated between the different energy sources used is asked for (e.g. renewable and non-renewable electricity use, fuels used).

Table 2. Primary energy data of the BelOrta building (design stage) as required by Level(s)

		Total ($kWh/m^2/yr$)	**Energy uses ($kWh/m_2/yr$)**				
			Heating	**Cooling**	**Ventilation**	**Hot water**	**Lighting**
1.1.1 Use stage primary energy demand							
Total primary energy demand		116.8	57.9	21.1	11.4	0.0	26.4
Non-renewable primary energy demand		116.8	57.9	21.1	11.4	0.0	26.4
Renewable primary energy demand		0.0	0.0	0.0	0.0	0.0	0.0
Exported energy generated		0.0	0.0	0.0	0.0	0.0	0.0
1.1.2 Use stage delivered energy demand							
Fuels	Natural Gas	57.2	57.2	0.0	0.0	0.0	0.0
Electricity	Non renewable	15.9	0.0	8.4	4.5	0.0	2.9

3.2. Indicator 1.2: Life Cycle global warming potential (GWP)

For the evaluation of the GWP of the building, Level(s) differentiates fossil carbon, biogenic carbon and biogenic carbon related to land occupation and land transformation. A simplified assessment is possible for Level 1 including the product stage (A1-3) and use stage (B4-5, B6) called an "incomplete life cycle". A building service life of 60 years is assumed, which is in line with the Belgian MMG method.

The MMG+_KULeuven tool was used to calculate the GWP of the building. As this tool does not include module D, the simplified reporting option was chosen. The Belgian MMG method furthermore does not include biogenic carbon, hence only GWP due to fossil carbon has been assessed (see Table 4 in section 3.6). Further, only the building elements of the shell are assessed defined as minimum building scope for a Level 1 assessment.

A material inventory of the building is needed to calculate the GWP. In general, architects do not have such a detailed list readily available and hence this is a time-consuming activity. If an inventory exists, it often has a different focus (e.g. cost sheet) and is mostly not as detailed as required for an LCA. It is hence recommended to provide a list of predefined elements per country with pre-calculated GWP values. As mentioned in Röck et al. [16] harmonization between the existing LCA and BIM standardization could help to facilitate LCA studies and improve the accuracy of the life cycle inventory.

3.3. Indicator 2.1: Building bill of materials

With this indicator an overview of the total mass of the building materials is provided, categorised into four material types defined by Eurostat (i.e. metal, non-metallic mineral, biomass and fossil energy) [7]. 99% of the total building mass should be covered and at least encompass the shell, core and external work elements [7]. For this assessment, the external works were not included in the scope and left out.

The data inventory for this indicator was taken from a BIM model provided by the architects, complemented with extra information found in technical information sheets, building construction plans, tender document. Such inventory is time consuming, but was already available (in a different format than the one required by Level(s)) from a previous LCA study of the same building. Although the format was different, the bill of materials was already structured per building element. Such detailed bill of materials is however not standard practice in architectural offices and hence will require additional efforts from architects assessing their building design with Level(s) [16]. It is furthermore important to note that the table format as required by Level(s) does not provide sufficient information for a hotspot analysis and hence will be of limited value for architects to improve their design in a time-efficient way.

3.4. *Indicator 2.2 Scenarios for lifespan, adaptability and deconstruction*

3.4.1. S1: Scenarios for life span. For every building element defined in indicator 2.1 the expected life span and corresponding data source should be provided. Four possible data sources can be used: 1) typical life spans based on reported averages, 2) life span estimate calculated by building professional, 3) life span estimate provided by building element manufacturer; or 4) life span estimate obtained from field experience. In this assessment, the default life spans of the materials and building components according to the Belgian MMG method were used.

3.4.2. S2: Scenarios for adaptability. Firstly, an overview of the addressed design aspects related to adaptability and refurbishment is required (e.g. column grid span, flexible cabling patterns, …). For office buildings three focus areas are brought forward: 1) changes in user space requirements; 2) changes to building servicing; and 3) changes to building structure. A description of the design solutions should be added for each of these (see Table 3). Secondly, it is asked whether a property market check is carried out or not, which was not the case in this project. To retrieve the needed information, additional interviews with the architects were required in addition to the available building documentation.

Table 3. Design aspects considering adaptability of the building design

Aspects addressed			Description of design solution(s)
Building Type	**Focus area**	**Design aspect**	
Office	Change in user space requirements	Internal wall system	System walls that can be (re)moved.
Office	Change in user space requirements	Column grid spans	Possibility to convert the landscape office to office rooms on both sides of a corridor.
Office	Changes to building servicing	Flexible cabling patterns	There horizontal and vertical cable trays everywhere. Lowered ceiling
Office	Change to building structure	Future-proofing of load bearing capacity	Structure allows adding an extra storey later.

3.4.3. S3: Scenarios for deconstruction. Firstly, the availability of building inventories and a deconstruction plan is quested. The specific deconstruction, reuse and recycling characteristics of the building have to be described. For each topic a series of design aspects are presented, such as “mechanical and reversible connections” or “constituent materials can be easily separated” Similar to the previous, an additional interview with the architects was required.

3.5. *Indicator 2.3: Construction and demolition waste*

The waste indicator aims at gathering information about the total amount of waste and the types of waste (hazardous or non-hazardous) during construction and at the end of life. Pre-estimates or actual data can be used as source. Further, possibilities for reuse and recycling and for recovery during specific life cycle stages (i.e. A3, A5, C1/3 and module D) are asked for.

As for the BelOrta building, no special attention was given by the architects to end of life recycling or reuse, the default end-of-life scenarios of the Belgian MMG method for each of the materials were assumed. The MMG method does not include information about waste being hazardous or not. This hence had to be inventoried which is time intensive if a detailed material list is not available.

3.6. *Indicator 2.4: Cradle to cradle life cycle assessment*

The Level(s) framework has selected a set of nine environmental indicators to be evaluated with a corresponding measurement unit in line with EN 15978 and EN15804. With exception of use of renewable primary energy sources used as raw material and use of non-metallic mineral resources all indicators are listed in Table 4. The indicators have to be assessed separately for the five different modules (life cycle stages) defined in EN 15978.

Similar as for indicator 1.2 (life cycle GWP), the MMG+_KULeuven tool was used to assess the various environmental impact categories required (this would not have been the case if a carbon foot printing calculation tool was used). The same simplified reporting option and building scope are used for this indicator as discussed above. Similar challenges were faced as for indicator 1.2. Results can be found in Table 4.

Table 4. Environmental impacts per life cycle stage and environmental indicator

Global Warming Potential for each life cycle stage					
Indicator	**Unit**	**Product (A1-3)**	**Construction process (A4-5)**	**Use stage (B1-7)**	**End of life (C1-4)**
Global Warming Potential (GWP)	kg CO_2 eq	982958	117775	5429271	115390
Depletion potential of the stratospheric ozone layer (ODP)	kg CFC11 eq	0.3	0.0	0.7	0.0
Acidification Potential of land and water (AP)	kg SO_2 eq	2926	516	11024	391
Eutrophication Potential (EP)	kg $(PO_4)_3$ eq	419	102	2632	88
Formation potential of tropospheric ozone photochemical oxidants (POCP)	kg C_2H_4 eq	230	23	682	11
ADP elements	kg Sb eq	1.8	0.3	7.7	0.1
ADP fossil fuels	MJ (LHV)	11709810	1612427	92140796	878090

3.7. Indicator 3.1: Use stage water consumption

Indicator 3.1 deals with the operational water use of the building, expressed in litres per occupant per year. An extra calculation file is provided to calculate the water use based on various inputs. First, the country and river basin of the case study are asked for to generate the water exploitation index[1] and ranking. Second, based on the entered occupancy conditions (i.e. gender distribution, building use factor and occupants behaviour) the volume of water per occupant per day is calculated (see Table 5). If the building is located in an area with water stress, which is not the case for the case study, extra reporting on the division of water consumption into potable and non-potable water is required. As no detailed information was available (except the absence of showers), the provided default values file were used.

In general, this default values simplified the needed calculations for this indicator and the availability of these default values could also be of interest for other indicators.

Table 5. Water consumption (litre) per occupant per day

Male occupants	0.5	Female occupants	0.5	Sum of occupants	1.0		
Building use factor	250	days/annum					
Sanitary fittings	Consumption rates		Usage factor		Daily consumption per occupant		
Toilet (full flush)	7.5	L/full flush	1	flushes/o/day	7.5	L/o/d	
Toilet (small flush)	4	L/small-flush	2	flushes/o/day	4	L/o/d	
Urinal	3	L/flush	2	flushes/o/day	3	L/o/d	
Bathroom tap	4	L/minute	45	seconds/o/day	3	L/o/d	
Shower	0	L/minute	30	seconds/o/day	0	L/o/d	
Kitchenette tap	12	L/minute	30	seconds/o/day	6	L/o/d	
Total					**23.50**	**L/o/d**	

3.8. Indicator 6.1: Life cycle cost

This indicator evaluates the different costs occurring during the building service life. Various types of costs are distinguished according to their recurrence: the one-off costs, annual costs and periodical non-annual costs. Both the annual as periodic non-annual costs are based on the sum of the present values of

[1] "*The mean annual total abstraction of fresh water divided by the long-term average freshwater resources. It describes how the total water abstraction puts pressure on water resources.*" [7, p. 106]

those future costs [7,17]. The costs are subdivided according to the same life cycle stages as for the life cycle assessment (see Table 6).

A combination of data sources was used for the assessment of this indicator. The building tender gave information about the construction and production costs while the MMG+_KULeuven tool gave an estimate for the costs of the use stage and EoL stage. As there was not a concrete maintenance plan nor a plan for element replacements, default scenarios from the MMG method were used.

Table 6. Life Cycle costs of BelOrta building

Type of costs	Cost by life cycle stage (€/m²/yr)		
	Product and Construction stages	**Use stage**	**End of life stage**
One off costs	74.54	0.00	4.41
Annual recurrent costs	-	17.44 (Energy)	-
	-	1.68 (Water use)	-
	-	37.78 (Cleaning)	-
Projected non-annual costs	-	32.41 (Maintenance, repair and replacement)	-
Total costs	74.54	89.30	4.41

4. Discussion

Firstly, some of the main results of the assessment are discussed followed by the main lessons learned in terms of time effort, actors needed, required information, relevance of the different indicators and added value for the practitioners.

4.1. Results

Based on the assessment results, it is clear that the use phase has an important contribution to the buildings environmental impact (see Table 4) and financial costs (see Table 6). Likely the importance for the environmental impact is mainly caused by the energy use for heating (see Table 1), while for the financial cost, cleaning and maintenance are important. Further, the construction phase as well has a big influence on the costs and impacts. Lastly, it has to be recognised that multiple aspects considering future adaptability of the building to changing user needs are implemented in the building design as discussed section 3.4.2. However, based on these results, it is not possible to highlight the importance of the different building elements and to get insights about opportunities to improve the sustainability of the building. This would be an added value for practitioners as now a Level 1 assessment is limited to reporting only.

4.2. Time effort

The testing of the Level(s) to BelOrta revealed that for many of the indicators detailed life cycle inventory data is needed which cannot be directly retrieved from the architectural plans or documents. A complete assessment of all the indicators on a Level 1 requires a lot of time. The reporting itself is not time consuming due to the excel files provided. To reduce the time efforts, it is recommended to establish or improve the links with national tools (e.g. current link with EPB-software for indicator 1.1). Default values are seen as a second way to reduce time efforts (especially in the design stage) as was experienced for the water consumption indicator. Default values could for example be provided for cleaning costs for typical elements, for EoL scenarios of construction products and for life spans of building products. In addition to the above, it is important to mention that the documentation provided by the JRC revealed to be sufficiently complete and comprehensive, but sometimes confusing.

4.3. Actors needed

As a team of actors are typically involved in the design of buildings, it became clear that the data and knowledge required for Level(s) is spread over these different actors. For example, the EPB-document for indicator 1.1 was drafted by the collaborating engineer firm, the design strategies for indicators 2.2.S2-3 require interaction with a designer of the building, while the LCA and cost analysis were now performed by an academic institution. In order to work efficiently, it might be recommended that various actors are responsible for parts of the Level(s) reporting. Although this is probably more time efficient, a good overall coordination will then be required to ensure that the same assumptions are taken for the multiple calculations required. Linking as much as possible with available tools and interfaces (e.g. BIM-model) could enhance uniformity across different assessments and actors.

4.4. Required information

The testing revealed that most of the indicators are linked to assessment methods that require data structuring that is different than in architectural practice to date. This is for example the case for the LCA study: even if a BIM model is available, this model may provide information about the general composition of building elements and their amounts but information on sub-element composition is lacking, such as for example the kg of brick per m² wall or the kg of cement mortar per m² wall. Default element compositions and related amount of materials could help practitioners. Further alignment between different tools could moreover improve this information flow.

4.5. Relevance indicators

The scope of the Level(s) framework is office buildings and residential buildings [8]. However it was found that some parts of indicators are more relevant for office buildings than for residential and conversely. Water consumption is for example more relevant for residential buildings though not unimportant for office buildings neither. While the relevance of the cleaning cost could be questioned in case of residential buildings.

4.6. Added value for practitioners

The objective of the Level 1 assessment is "*to provide a common reference point for the performance assessment of buildings across Europe*" [8]. The testing phase is interesting for architects to become familiar with the assessment methodology, requirements and challenges. The assessment moreover provides general insights in the various environmental impacts, waste streams and costs their design is causing. However, it does not allow to evaluate the 'sustainability' level of their project as reference values are not available to compare with and detailed hotspot analysis is not possible. In order to increase the added value of the assessment for practitioners it is recommended to integrate such reference values (benchmarks) or more detailed reporting in future. To use Level(s) to date during a design phase, the authors would rather recommend to use a level 2 assessment to be able to compare various design options.

5. Conclusion

This paper discusses a Level(s) Level 1 application on an office building in Belgium. The assessment of the indicators related to the macro-objectives (1) Greenhouse gas emissions along a building life cycle; (2) Resource efficient and circular material life cycles; (3) Efficient use of water resources; and (6) Optimised life cycle cost and value have been presented. The study showed the implications of performing a Level 1 assessment for building practitioners in terms of information, time and experience needed. It was found that the assessment requires information and experience from practitioners which is not commonly available in current practice. Further improvement is recommended by aligning current national tools for data gathering and by providing default values. The testing furthermore revealed that Level 1 assessment allows to gain general insights in various performances of a building (e.g. waste streams, impacts across different indicators …) but does not allow to evaluate the "sustainability" level of the design as reference values are lacking as basis of comparison. As long as such reference values are not available, a level 2 assessment is probably more useful to make well-founded choices between different design options.

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IEA EBC Annex 72 - Assessing life cycle related environmental impacts caused by buildings – targets and tasks

Frischknecht R[1], Birgisdottir H[2], Chae C-U[3], Lützkendorf T[4], Passer A[5]

[1] treeze Ltd., Switzerland
[2] Aalborg University, Denmark
[3] Korea Institute of Civil Engineering & Building Technology, Korea
[4] Karlsruhe Institute of Technology, Germany
[5] Graz University of Technology, Austria

frischknecht@treeze.ch

Abstract. Investment decisions for buildings made today largely determine their environmental impacts over many future decades due to their long lifetimes. Such decisions involve a trade-off between additional investments today and potential savings during use and at end of life - in terms of economic costs, primary energy consumption, greenhouse gas emissions and other environmental impacts. Life cycle assessment (LCA) is suited to identify measures and action to increase the resource efficiency and the environmental performance of buildings and construction. This paper gives an overview of an ongoing international research project within the IEA EBC with the overall aim to harmonise LCA approaches on buildings and foster life cycle thinking in the real estate and construction sectors. The objectives of the project are i) to establish a common methodology guideline to assess the life cycle based environmental impacts caused by buildings, ii) to establish methods for the development of specific environmental benchmarks for different types of buildings, iii) to derive regionally differentiated guidelines and tools for the use of LCA in building design and tools such as BIM, and iv) to improve data availability by developing national or regional databases with regionally differentiated LCA data tailored to the construction sector. To ensure practical solutions a number of case studies will be used to test and illustrate the consensus approaches and research issues.

1. Introduction

In response to concerns about climate change, energy security and social equity, countries around the world are either planning to substantially reduce energy demand and greenhouse gas emissions or in the case of emerging economies to develop in less energy intensive ways. The construction as well as heating and cooling of buildings is one major cause of primary energy demand, greenhouse gas emissions and environmental impacts of developed and emerging economies [1-4]. Buildings have a long lifetime of between some decades to more than 100 years. The replacement rates in Europe for instance suggest that the average lifetime of residential buildings is well above 60 years. Thus, investment decisions on buildings today determine by and large the environmental impacts during several future decades. Furthermore, such decisions can involve a trade-off between additional investments today and potential savings during use and end of life (both in terms of economic costs on one hand and primary energy demand, greenhouse gas emissions and environmental impacts on the other). Today, natural resources such as clean air, clean water, biodiversity or natural resources are free and their use as a sink is hardly charged to those polluting them. The current price system does not (systematically) account for such external environmental effects (market failure) which leads to an inefficient (over)use of natural resources. That is why, environmental assessments of human activities are necessary to highlight the inefficient use of natural resources and to take measures and action to increase the resource efficiency of buildings and construction by substantially reduce consumption and pollution of natural resources.

The life cycle assessment (LCA) approach as standardised by ISO 14040 and 14044 [5, 6] is suited to quantify the environmental impacts of buildings based on the principles of ISO 15392 [7]. The assessments performed using the LCA approach are very much in line with an economic assessment which follows a life cycle costing approach. Hence, LCA is suited to complement economic information on buildings with information on their environmental impacts (see also Figure 1). Important developments on the topic in recent years have been the many international (such as ISO 21930 [8] and ISO 21931 [9]) and European (such as EN15978 [10] and EN15804 [11]) standards for the development of environmental product declarations of building products and the environmental performance assessment of construction works as well as the recently published report by the European Commission on resource efficiency and resource consumption mitigation opportunities in the building sector [12].

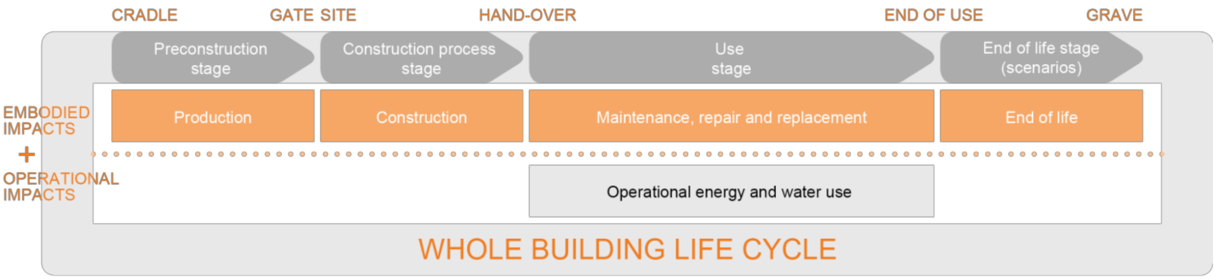

Figure 1. The different stages in the Life Cycle of buildings and the distinction between embodied and operational environmental impacts.

The environmental assessment of buildings using life cycle assessment approaches entails several research issues and issues which call for harmonisation and consensus, while respecting national and regional traditions. The following list of issues illustrates the kind of topics discussed in the international research project IEA EBC Annex 72, building on results of the former IEA EBC Annexes 31 [13] and 57 [14]:

- Environmental "optimisation": When considering the entire life cycle of buildings, efforts can be either focused on reducing embodied or operational impacts. With current discounting practices, the use and end of life phases are economically less important. This situation gives rise to the following questions: Where is the environmental optimum between gross zero operational energy buildings on one hand and minimised embodied impacts buildings on the other? Is it sensible to try to reduce energy consumption for heating and cooling close to zero or do the environmental impacts of the additional material and equipment overcompensate the reduced environmental impacts during operation?
- Net zero energy buildings: More and more buildings integrate on-site renewable energy systems to compensate their operational energy demand e.g., for the heating, ventilation, lighting and appliances uses or even to additionally compensate their embodied energy. The energy produced onsite can either be self-consumed or fed into the grid depending on the level of production and the simultaneity between production and the building energy demand. Previous LCA studies (e.g. in IEA EBC Annex 56 project, see e.g. [15]) have used an annual balance for estimating the building energy demand and production. Other approaches have

assessed the life cycle related impacts based on an hourly balance. Is there one particular preferable approach and if so, which one should be recommended? How should life cycle net zero impact buildings be defined, including rules for balancing and communication?

- Integration of environmental assessment in design process using tools such as building information modelling (BIM): For the aforementioned goal of an environmental optimisation of buildings during their lifecycle it seems necessary to include the environmental assessment in the early design stages to have a higher influence on the final outcome (see "McLeamy effort curve" [16] and potential shift through BIM). Current digital design tools and especially BIM provide the potential to include various kinds of assessment information and simulations (embodied and operational energy, daylighting, et cetera) in early design stages. Issues related to this integration in digital design tools are the different levels of modelling within the tools as well as the accuracy and reliability of information during the different stages of the design process. As this information is only gradually defined, assessment tools need to use constantly refined values and presumptions throughout the planning process. Can approved level of detail (LOD) definitions in design tools such as BIM and defined stages within the building design process be used to mark steps in which to incrementally assess and optimise the environmental performance of the building design? Which values and presumptions should be taken for the assessment at the different design stages? Which variability and safety factors have to be considered to achieve significant and complete assessment results?
- Service life: Some standards prescribe or suggest service lifetimes of building components and technical systems. However, observed lifetimes can be significantly different from the lifetimes prescribed or suggested in national standards. Buildings are long-living investments but office and industrial buildings in particular may have relatively short service lives. Some experts claim that environmental impacts caused by construction (and material supply) today should be balanced within one to maximum two generations, i.e. 30 to 60 years. What service life or reference study period should be chosen with such long-living investments like buildings? Should the reference study period be defined based on observed or default lifetimes or based on an argumentation based on intergenerational equity?
- Technology development: Buildings are expected to be used during 50 to 100 years or even longer. During this period, economy and in particular building elements, building technologies and energy supply systems (fuel oil, natural gas, coal, electricity, wood, biogas) will develop (see e.g. [17]). The following questions related to future scenario will be discussed in the IEA EBC Annex 72: Should technology developments and changes in the mixes related to electricity, heating, cooling and waste management be considered when assessing the environmental impacts of the use and end of life phases? How to deal with new building products and with technology developments of existing ones? How to deal with potential change in type and pattern of use of buildings?
- Aggregation and assessment of current and future emissions: A substantial part of the energy use, greenhouse gas emissions and environmental impacts occur several decades in the future. This raises the question of how to aggregate emissions occurring today (during production and construction stages) and emissions occurring during the use stage and in particular during the end of life stage and whether or not to apply any discounting approach (see e.g. [18]).

2. Objectives of IEA EBC Annex 72

The work of the IEA EBC Annex 72 is organized in five Subtasks which are closely interlinked.

The research work of the IEA EBC Annex 72 aims to achieve the following objectives:

- Establish a harmonised methodology guideline to assess the life cycle based primary energy demand, greenhouse gas emissions and environmental impacts caused by buildings.
- Establish methods for the development of specific environmental benchmarks for different types of buildings to help designing buildings with a minimum life cycle based primary energy demand, greenhouse gas emissions and environmental impacts.

- Derive guidelines on tools (building design tools, BIM and others) and workflows for design decision makers.
- Establish a number of case studies, focused to allow for answering some of the research issues described above and for deriving empirical benchmarks.
- Develop national/regional databases with regionally differentiated life cycle assessment data tailored to the construction sector, covering material production, building technology manufacture, energy supply, transport services and waste management services; share experiences with the setup and update of such databases.

3. Methods

3.1. Surveys

Surveys for LCA experts and for designers were established to learn more about the current situation of LCA in the building sector: One part of the survey is on the methodologies applied to assess the environmental impacts of buildings with regard to modelling aspects, system boundaries and environmental indicators. In addition, the degree of dissemination of the applied methodologies, the frequency of use among designers and their demand for assessment results is investigated. A second part is on national practices of workflows and planning tools, methods, data formats etc. used by LCA experts and design decision makers in the participating countries. Lastly, the surveys include a section on national/regional LCA databases and are exploring the national needs (data gaps) and the driving forces for the demand on LCA data and databases.

3.2. Round robin test and harmonised methodology

A round robin test to assess the greenhouse gas emissions, primary energy demand and other environmental impacts of two reference buildings are performed to identify the differences in national building assessment approaches [19].

The insights gained from the surveys and the round robin test will be used to develop and extend the methodology guideline on LCA of buildings and benchmarks. The guidelines and approaches agreed within IEA EBC Annex 57 [14, 20] serve as starting point. The guidelines will be extended to the full life cycle of buildings and will include:

- operational impacts,
- modelling aspects such as allocation and recycling,
- modelling onsite electricity production,
- reference service life / reference study period,
- technology development (e.g. in the electricity mix supplied to the building during its use phase)
- recommendations on environmental indicators.

A clear distinction is made between modelling practices on one hand and data and databases on the other. In addition the areas of disagreement will also be highlighted by offering at least two alternative approaches in such cases. Regional and national traditions will be captured to the extent feasible and necessary.

3.3. Work flows and data interfaces

The results of the survey on national practices of workflows (see Section 3.1) and semi-structured interviews with selected experts help to identify the current state and potentials of implementing the assessment of life cycle related environmental impacts of buildings during the design process. Besides the survey a systematic literature review is performed to identify the requirements for the implementation of life cycle related aspects in different stages of the design process. As a result, implementation strategies in view of internationally compatible solutions of design tools and formats (e.g. BIM) of life cycle information (e.g. following existing structures of a cost calculation approach) are proposed.

Based on building case studies (see Section 3.4.) an analysis on how differences in building models (completeness and detailing) can be considered throughout the planning process (e.g. application of correction factors) is performed. The aim is to establish guidelines for measuring the completeness of a building model and to indicate how it can be used for life cycle assessment of buildings. Furthermore, guidelines for design decision makers on how to use available information to assess the life cycle-related environmental performance of buildings during the design process for their improvement will be developed.

3.4. Case Studies

A substantial set of building case studies are analysed for which the life cycle based environmental impacts are quantified using either national/regional assessment practice or the methodology agreed in IEA EBC Annex 72 (see Section 3.2.). The buildings selected should be representative to the country/region. The set of case studies include different building types and different decision-making situations. A harmonized documentation of these case studies is developed, including the information on the use (covering e.g. use profiles) of the buildings analysed as well as the climatic zone.

These case studies are helpful in establishing empirical benchmarks based on the methodology developed in the IEA EBC Annex 72 (see Section 3.2.). To develop these benchmarks different reference units (functional equivalence, i.e. impacts per m^2 and year basis, impacts per person etc.) are analysed. The benchmarks shall apply on the entire life cycle of buildings and be subdivided into embodied environmental impacts (production of materials and technical systems, construction, use and end of life) and operational impacts during the use phase. The established benchmarks related to the primary energy demand, greenhouse gas emissions and environmental impacts of buildings are regionally differentiated and tied to different building types such as residential, office, or school buildings. It is explored whether or not a typology of climatic regions can be established to allow empirically derived benchmarks being applied across the participating nations.

Furthermore the case studies will serve as basis to classify and characterize different approaches to optimizing life cycle primary energy demand and greenhouse gas emissions performance of new buildings and renovation projects. The potential to reduce environmental impacts of different types of optimization strategies are assessed in order to develop guidelines for building design and decision-making.

The planning and design workflow have an impact on the whole life primary energy demand/greenhouse gas emissions of the building. Many decisions are taken with no thought of primary energy demand nor greenhouse gas emissions – for instance the choice of structural frame may be based on architectural layout and on construction industry standards for that country, while facade material may depend on local planning requirements, etc. The aim is therefore to further analyse the case studies focusing on the decisions in the planning and design workflow. As a result of this analysis examples and in-depth knowledge on process aspects promoting or hindering a relevant application of environmental life cycle thinking in building design are given.

3.5. LCA databases for the construction sector

The results of the section on national LCA databases in the surveys are used to document national databases used in the construction sector and provide recommendations in view of further improving the situation regarding data availability and suitability. The documentation includes a standardised description of existing database contents. The information gained in the survey on existing national databases helps to develop guidelines and practical hints on how to establish a publicly available LCA database suited for the building sector. It mainly addresses countries with a current lack of a reliable, country specific LCA database. The guidelines include considerations and information related to:

- the need of national databases,
- the contents of such databases,

- organisational aspects (e.g., on how to organise data collection and funding, how to organise updates, etc.).

In a next step the developed guidelines are implemented in country case studies. The aim is to compile a default set of publicly available national environmental indicator results of construction materials, building technology, energy supply, transport services and waste management. The default set of results shall be suited to be used in the preliminary design stage or in case of lack of more specific information.

4. Planned working steps and intermediate Results

4.1. Methodology guidelines (Subtask 1)

Subtask 1 (ST1) takes up the methodological foundations developed in IEA EBC Annex 57 [21] for the determination, assessment and influencing of embodied impacts and further develops them into a complete life cycle approach. Currently, ST1 discusses the following topics (among others): (a) how to avoid physical discounting in the GWP [22] on the one hand, and, at the same time, make possible the consideration of the time factor through the inclusion of external costs (here the damage costs of greenhouse gas emissions - see, inter alia, [23]). In this case, according to the social discounting rate approach [24] the lowest possible interest rate should be selected; (b) the possibilities of considering technical progress for different use cases in a specific way. For the analysis of scenarios this topic may be considered, but for the deterministic models [25] in the context of a sustainability assessment this should be excluded; (c) that although when reusing an existing building structure in the next life cycle the already consumed energy and resulting GHG emissions for the old structure are accounted for as zero (since they can no longer be influenced), the further maintenance, later replacement and the EoL must be taken into account.

Additionally, ST1 deals with the development and use of environmental benchmarks on the basis of the current standardization activities [26]. This standard aims to develop a typology of reference levels, to improve the transparency and traceability of published benchmarks and to describe typical application cases. Some of the authors are directly involved in the latter standardization process. One example of alignment with the ongoing standardization activity is that also Annex 72 adopts the system of limit, reference and target values. Own contributions under the ST1 focus on the basic principles of developing benchmarks for specific types of buildings and uses in different climate zones. However, it is also discussed how, on the basis of scientifically recognized needs and politically formulated goals, target values for the maximum greenhouse gas emissions caused by a building can be defined in a top-down approach, which correspond to a budget and contribute to a uniform net-zero emission approach.

4.2. Work flows and data interfaces (Subtask 2)

Thus far, the activities of Subtask 2 (ST2) have been closely coordinated with ST1 with respect to the establishment and execution of the global survey amongst design professionals. The public survey has been translated by Annex experts in 9 languages and is currently conducted in more than 20 countries.

On ST2 specific topics of LCA workflows and design integration, the work has been structured according to the following tasks:

a) Definition of design phases and milestones,
b) Building decomposition and element method,
c) Strategies for handling design variability and LCA uncertainty,
d) Sample cases for digital building models,
e) Definition of LCA exchange requirements,
f) Options for communication of LCA results.

The ST2 experts have been in regular exchange and have already shown their contributions in various publications on these topics: Yang et al. [27] analysed the environmental impacts in the Chinese context, highlighting the potential to reduce impacts during the design process.

Röck et al. [28] discussed the general challenges of coupling LCA and BIM based on case study implementation. Lupíšek et al. [29] shared their specific findings on the potential for interconnection of tools for cost estimation and life cycle assessment in the Czech context. Peuportier et al. [30] presented building life cycle assessment tools developed for the French context. In the aim of mainstreaming LCA in the building design process, the research of Szalay et al. [31] contributes by showcasing a modular methodology for life cycle assessment of buildings and building stocks. Contributing to both ST1 and ST2 topics, García-Martínez et al. [32] presented their BIM-based LCA approach for obtaining environmental benchmarks for the life cycle of buildings.

The Annex specific research thus has shown the challenges as well as great potential for integrating LCA in the building design process. At this point, ST2 is aiming to coordinate efforts and identify the common requirements for integrating the environmental assessment in different design stages. For this matter, the ST2 experts are elaborating their activities focusing on several key topics in order to: i) identify a common understanding of building decomposition based on existing systems (e.g. for cost estimation); ii) map LCA databases used along the design process in order to identify requirements for both LCA datasets as well as digital building models, as well as; iii) develop common strategies for the handling of variability and uncertainty in design-integrated LCA workflows.

In order to advance the discussion on the ST2 topics, a special session on 'Building assessment workflows' will be held in the framework of the SBE19 DACH conference in Graz, Austria.

4.3. Case studies (Subtask 3)

Experience with analysing a bulk of building cases from different countries in the Annex 57 project demonstrated how building LCA show large variations in assumptions and methodological choices resulting in large variation of numerical results, and which makes them impossible to be compared [33]. Therefore, understanding of methodology and work on harmonisation has had first priority. The first part of the work with case studies, which is in its beginning phase, will focus on collection of case studies displaying and evaluating the consequences of different methodological choices, such as use of dynamic energy modeling, the length of the reference study period, the functional unit and circular economy strategies. Moreover, the work with case studies will focus on displaying different national benchmarks which are already in use based on different methodology and assumptions. The results of this evaluation work can contribute to the development of suggestions for harmonised methods. Later in the project, case studies applying a harmonised method will be collected.

For the subtask on workflows and data interfaces, focus has been on gathering information across countries before collecting case studies. Case studies can be used to analyse how differences in building models (completeness and detailing) can be taken into account throughout the planning process (e.g. application of correction factors).

4.4. LCA databases for the construction sector (Subtask 4)

A preliminary screening about the types of databases used among the IEA EBC Annex 72 participating countries was performed. The participating countries were asked whether an own national database was developed and is being used and if so, by whom the database is developed and maintained. Further, they were asked, what type of data (generic or product specific) is used within their database. Generic data is usually data gathered from different sources of information; whereas product specific data is gathered from one or several producers for a specific construction product. Specific producer data can as well be published in the form of an environmental product declaration.

In total 23 countries filled in the questionnaire. Among the IEA EBC Annex 72 participants, 9 countries have developed their own databases, 10 countries use adapted datasets from foreign databases for their purpose and three countries did not develop or adapt own datasets. In two countries, the national database is developed and maintained by a public organisation. Several entities develop the databases but the database is maintained by the public sector in three countries. In 4 countries any organization can develop and maintain a database. To perform a building LCA, in 7 countries mainly generic datasets are used. 15 countries use both generic and specific datasets. In one country generic datasets are used in an early design stage and specific data in detailed design.

5. Outlook / Deliverables

The results of IEA EBC Annex 72 will help fostering the use of environmental information in the design and decision making process of buildings and thus lead to more resource efficient, environmentally sustainable buildings in the future. The deliverables will promote the importance and best practices of environmental life cycle assessment of buildings and will include a series of reports and national datasets:

- Report on harmonised guidelines on the environmental performance assessment of buildings, based on results of LCA;
- Report on establishing environmental benchmarks for buildings, including case study examples;
- Report on national LCA databases used in the construction sector, including a standardised characterisation of LCA databases relevant to the construction sector;
- Report on design decision maker's guidelines on optimization using building assessment workflows and tools, including case study examples;
- Report on building case studies (using a standardised template), including guidelines with good examples on the application of LCA in different stages of the design process;
- Report on how to establish national/regional LCA databases targeted to the construction sector, including recommendations for data exchange;
- Default publicly available, national data set(s) of LCA based environmental indicators.

The work of the IEA EBC Annex 72 will be finished by 2021 (http://annex72.iea-ebc.org/about).

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BIM based iterative simulation - efficient building design: a case study

Tallberg M, Bohne R

Norwegian University of Science and Technology

martita@stud.ntnu.no

Abstract. The aim of this case study was to evaluate the energy performance of utilizing different external materials reaching sustainable targets. Buildings are responsible for 40 percent of energy consumption and energy performance of buildings is a key element to achieving the European Unions goals. The EU has pledged to cut its consumption by 20 percent by 2020.
The main objective of this research was to explore the suitability of BIM for sustainabil-ity analysis at the conceptual design process. The procedure included analysis and discussion of the results for the lowest energy performance of materials. It was shown that changing the building envelope had a signi cant e ect on the annual energy performance of the case building. The limitations of the study was the limitations in the software. For further research, the paper nds it expedient to perform a even more detailed simuation analysis on the building design with other energy supply systems.
The value of the paper is to highlight the utilization of BIM to evaluate the material solutions to reach sustainable construction in the future, focusing on the need for lowering the energy consumption of tomorrows buildings.

1. Introduction

In 2015, the residential- and building sector counted for almost 40 percent of the energy con-sumption and 40 percent of the material use in Norway [4]. The energy- and environmental challenges make it necessarily to build with quality and aim for regular renewal of the existing building stock [3]. Sustainable quality in private homes, buildings, and built environments re-duces environmental impacts and improves quality of life for future generations [4]

In the context of the European Union e orts to reduce the growing energy expenditure, it is widely recognized that the building sector has an important role [1]. Directive on the En-ergy Performance of Building (EPBD) imposes the adoption of measures to improve energy e ciency in buildings, in order to reach the objective of all new buildings to be nearly Zero Energy Building (nZEB) by 2020 [1]. It is obvious that the design of a zero-energy building is not yet pro table in terms of costs [2]. The cost of materials and energy consumption will di er from each country and regional areas, the age of the building and it occupancy use.

The present article will present the results of the BIM based iterative energy performing simulations performed in IDA-ICE, with aim to establish a procedure for techno-economic opti mization. Hence, the aim of this paper was to evaluate the energy performance of a traditional apartment building designed for the norwegian TEK-17 standard, compared to the recommended thermal properties compiled by the reseach center on zero emission buildings. The building was designed using Autodesk Revit 2018 edition and exported as a IFC- le to IDA-ICE 4.8.

2. Theoretical framework

The design of low energy buildings involves two strategies minimizing the need for energy use in buildings through energy-e cient measures (EEM) and adopting renewable energy and other technologies (RET) [5]. RET represents photo voltaic (PV) or building-integrated photo voltaic (BIPV), wind turbines, solar thermal (solar water heaters) and heat pumps. EEMs include building services systems, internal conditions and building envelopes. These include life-cycle cost and environmental impacts, climate change and social policy issues [5, 6].

The consecration- rst approach to high performance building starts with advanced building envelope [3]. Guided by physics and building science, advanced building envelopes combine a simple suite of components to manage heat, air, and moisture and deliver superior e ciency, durability, comfort, and occupant health [2]. By controlling the movement of air across building assemblies, stabilizes the temperature and comfort in the building. The vapor barrier should be wrapped continuously, unbroken to prevent heat and moisture owing into the insulation materials. High-performance buildings employ a ventilated rain screen, a gap between the cladding and wall assembly that not only provides a channel for bulk water to drain away, but also generates air movement across the face of the assembly to dramatically increase drying [2]. A highly thermally resistant wall will have less drying capacity than a conventional wall, so the air movement provided by the ventilated rain screen helps ensure the resilience and durability of high performance wall assemblies [2].

3. Methodology

The envelope design was made as simplistic as possible, by improving the building envelope, simulating a air-to-air heat pump in combination with electric oor heating. For reducing the U-values in each occupant room and space, all the external walls were designed as both TEK-17 standard, and the nZEB standard classi cation. As glass surfaces are highly important for ex-ternal energy gains, it was important to evaluate the performance of the di erent window and door types. The baseline model was designed with a commercially available window frame and glazing unit with a U-value of 0.8 W/m2K. For internal heat, the heat gains from occupants, equipment and lightning were had the same default settings for both of the design scenarios. Figure 1 shows the building facades of the designed building using Autodesk Revit 2018 edition. Figure 2 shows the apartment design facades of the designed building using IDA-ICE 4.8 edition.

4. Case building

This chapter describes the designed case building in question and how it has been calibrated. This includes a description of the building envelope, model set up and calibration in Revit 2018 and IDA-ICE 4.8.

The investigated building was a conceptual low energy building which passive parameters are optimized and validated according to TEK-17 and ZEB standardization. The model was a residential building composed of four similar oor levels. Each oor level was divided into two apartments. The buildings net area (excluding balconies and non-conditioned spaces) was 464 m^2. All building rooms was modelled in the IDA-ICE-zone model. The thermo-physical

Figure 1. Building facades (Revit 2018)

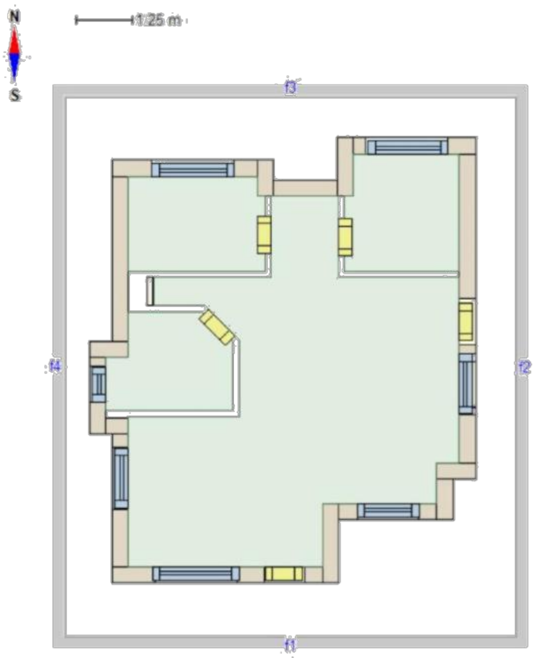


Figure 2. Room and space allocation (IDA-ICE 4.8)

characteristics of the buildings envelope are represented in Table 1.

From the Norwegian TEK.17 standard, heat loss through thermal bridges can be considered satisfactory if the normalized thermal bridge value calculated does not exceed 0.03 W/m^2K for single-family houses. In this case, the study assumes that this value was durable for the apartment building. For the nZEB case, normalized thermal bridge value was set to 0.015 W/m^2K.

Room boundaries and spaces were required in order to simulate the impact of the variation of each parameter in IDA-ICE. The volume computation for space was based on its room- bounding components and was calculated as the area of its base multiplied by the height of the space. The height was set to 2.6 meters, in accordance with the requirements for minimum height (TEK-17).

5. Results

This chapter discusses the simulated results for each simulation and compares the energy consumption. The results was based on the energy balance and delivered energy to the building to reach acceptable temperatures and indoor climate. For the sustainable design, photo voltaic electricity generation on-site was also included in the results. The photo voltaic production was simulated using PVGIS.

Initially, the reference scenario was modelled and analyzed. Secondly, di erent parameters were changed in the system design for mapping the impact on the annual energy use. Lastly, the economic break even for the photo voltaic systems were described. Sensitivity analysis, with respect to the electricity escalation, was carried out based on the simulated annual energy use in the building. The results show the sensible heat balance for the living room and kitchen main area and the total annual energy consumption for the one apartment. The data is presented in

Table 1. Building design envelope

		TEK-17	nZEB
Roof Function	Materials	U-value: 0.13 W/m^{2}K Thickness (mm)	U-value: 0.07 W/m^{2}K Thickness (mm)
Finish (external)	roof tiles (11 tilt)	-	-
Membran layer	EPDM Membrane	20	20
Thermal/air layer	air in ltrating barrier	-	-
Structure	timber (90x315)	315	315
Insulation	mineral wool	260	500
Membran layer	vapor retarder	-	-
Finish (internal)	Gypsum	-	-
External walls Function	Materials	U-value: 0.18 W/m^{2}K Thickness (mm)	U-value: 0.095 W/m^{2}K Thickness (mm)
Finish (external)	horizontal wood panels	-	-
Membran layer	EPDM Membrane	20	20
Thermal/air layer	air in ltrating barrier	-	-
Structure	timber (90x315)	315	315
Insulation	Mineral wool	175	350
Membran layer	vapor retarder	-	-
Finish (internal)	Gypsum	-	-
Floor Function	Materials	U-value: 0.09 W/m^{2}K Thickness (mm)	U-value: 0.069 W/m^{2}K Thickness (mm)
Finish (oor)	wood ooring	-	-
Membran layer	vapor retarder	-	-
Insulation	mineral wool	350	500
Structure	concrete (24.1 mPa)	125	125
Thermal/air layer	damp pro ng	-	-
Membran layer	randon membrane	-	-
Substrate 1	Concrete (24.1 mPa)	300	300
Substrate 2	hardcore	100	100
Windows TEK-17	WWR 6.6% SHGC and ST 0.15 and 0.1	U-value 0.6	Internal/external emissivity 0.837 (default)
Windows nZEB	WWR 6.6% SHGC and ST 0.15 and 0.1	U-value 0.8	Internal/external emissivity 0.837 (default)
Insulation	Thermal conductivity	Density)	Speci c heat
Mineral wool	0.036 W/(mK)	20 kg/m^3	750 J/(kg K)

Table 2. Room and space data

Zones	People	Lightning*	Equipment*	Occupancy	Lightning	Equipment
Main area	2	100 W	3100 W	07-09 17-22	07-09 17-22	07-09 17-22
Bathroom	1	100 W	1750 W	Never present	Always o	07-09 17-22
Bedroom 1	1	40 W	50 W	21-07	Always o	21-07
Bedroom 2	1	40 W	50 W	21-07	Always o	21-07
Zones	Height	Heating	Cooling	Ventilation	ACH	Supply air
All zones	2.6m	21	25	AHU CAV	0.5	2 L/sm^2 height

*Effect (Watt) for equipment and lightning was obtained from [?]

Month	Walls	Roof	Floor	Windows	Doors	Thermal bridges
1	-318.5	-174.9	-19.0	-232.7	-78.3	-126.7
2	-255.6	-147.2	-16.3	-194.1	-62.6	-105.2
3	-228.9	-146.6	-16.9	-190.9	-55.6	-102.8
4	-158.6	-116.6	-15.3	-148.8	-37.5	-79.5
5	-59.3	-80.0	-13.2	-95.2	-12.5	-48.1
6	-27.4	-63.5	-13.2	-74.0	-4.3	-36.8
7	-14.3	-55.9	-14.5	-63.1	-1.4	-30.3
8	-32.2	-57.0	-9.7	-67.5	-7.0	-33.1
9	-95.9	-78.0	-7.9	-96.1	-22.9	-49.4
10	-170.1	-106.8	-10.5	-137.2	-41.7	-72.6
11	-223.2	-126.0	-11.4	-164.8	-54.7	-88.7
12	-276.6	-151.2	-13.8	-200.6	-68.0	-108.6
Total	-1860.5	-1303.6	-161.7	-1665.0	-446.5	-881.9
During heating	-1723.3	-1145.2	-76.3	-1527.3	-421.9	-809.5
During cooling	-9.7	-23.5	-33.4	-17.0	1.2	-7.7
Rest of time	-127.5	-134.9	-52.0	-120.6	-25.8	-64.7

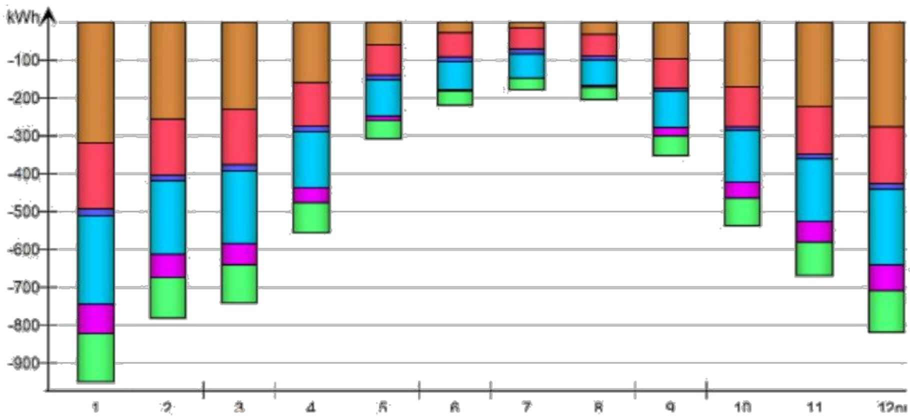


Figure 3.Envelope transmission: Norwegian TEK-17 standard

	Purchased energy		Peak demand
	kWh	kWh/m²	kW
Lighting, facility	308	5.3	0.17
Equipment, facility	1061	18.3	1.9
HVAC aux	272	4.7	0.19
Electric heating	3226	55.7	2.68
Total, Facility electric	4867	84.1	
Total	4867	84.1	

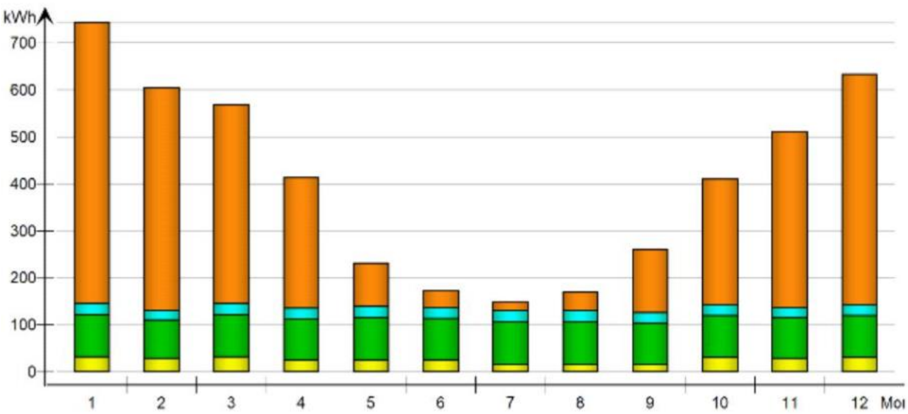


Figure 4.Energy use: Norwegian TEK-17 standard

Figure 3-7.

Month	Walls	Roof	Floor	Windows	Doors	Thermal bridges
1	-204.2	-171.9	-8.9	-179.6	-80.2	-62.5
2	-164.2	-144.6	-9.3	-149.9	-63.9	-52.0
3	-147.0	-143.8	-11.4	-147.6	-56.4	-50.9
4	-102.8	-114.1	-11.9	-115.1	-37.5	-39.6
5	-40.5	-79.3	-14.0	-73.9	-12.2	-24.1
6	-21.0	-63.5	-14.4	-58.0	-4.2	-18.6
7	-12.8	-56.7	-15.7	-50.3	-1.7	-15.6
8	-22.7	-57.5	-10.5	-53.5	-7.1	-17.0
9	-62.6	-76.9	-7.7	-74.4	-22.6	-24.7
10	-108.6	-104.6	-6.9	-106.1	-41.8	-36.1
11	-143.0	-123.5	-6.9	-127.4	-55.2	-44.0
12	-177.5	-148.6	-7.8	-155.0	-69.2	-53.7
Total	-1206.9	-1285.0	-125.3	-1290.9	-451.9	-438.7
During heating	-1150.3	-1166.9	-43.8	-1197.5	-446.1	-409.4
During cooling	-8.4	-23.2	-26.9	-16.8	0.8	-4.7
Rest of time	-48.2	-94.9	-54.6	-76.6	-6.6	-24.6

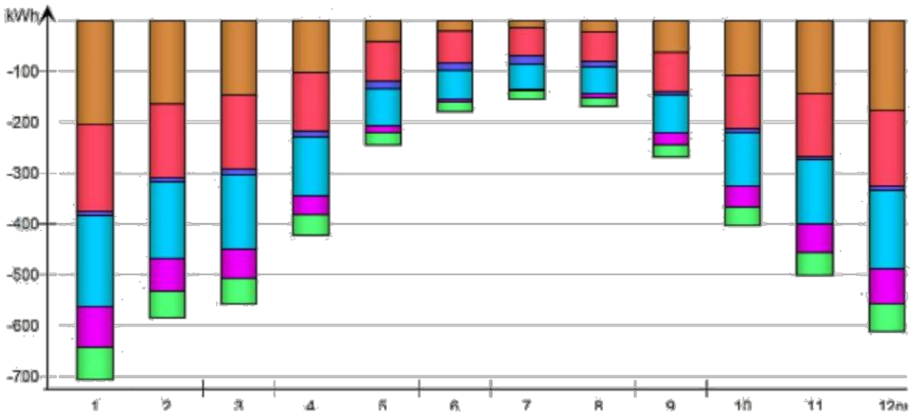


Figure 5. Envelope transmission: ZEB recommendations

		Purchased energy		Peak demand
		kWh	kWh/m²	kW
	Lighting, facility	308	5.3	0.17
	Equipment, facility	1062	18.3	1.9
	HVAC aux	272	4.7	0.19
	Electric heating	2150	37.1	2.28
	Total, Facility electric	3792	65.5	
	Total	3792	65.5	

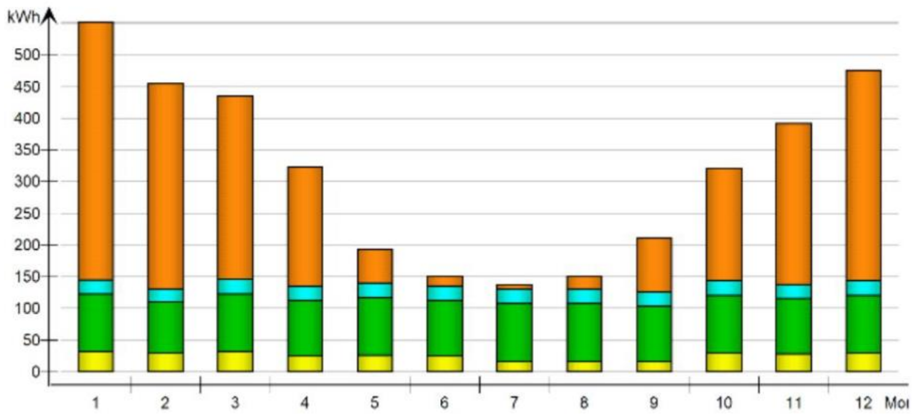


Figure 6. Energy use: ZEB recommendations

The mean and operative temperatures was mapped annually in the main area of the apart-

Table 3. Mean air and operative temperature (electric heating)

	Variables	
	Mean air temperature, Deg-C	Operative temperature, Deg-C
January	21.0	20.72
February	21.0	20.72
March	21.01	20.74
April	21.04	20.79
May	21.32	21.2
June	21.51	21.46
July	22.17	22.15
August	21.99	21.94
September	21.1	20.91
October	21.04	20.79
November	21.01	20.73
December	21.01	20.72
mean	21.27	21.08
mean*8760.0 h	186335.5	184641.1
min	21.0	20.72
max	22.17	22.15

Table 4. Temperature dissatisfaction (electric heating)

Percentage of hours when operative temperature is above 27°C in worst zone	**1 %**
Percentage of hours when operative temperature is above 27°C in average zone	**0 %**
Percentage of total occupant hours with thermal dissatisfaction	**10 %**

ment (kitchen and living room). The maximum temperatures occur in the bathroom, due to the equipment loads in combination with the solar heat gain through the E/W facing windows. The solution to reducing the overheating in this area was to schedule the windows with an hourly opening in the summer months, to allow fresh air into the zones in combination with the HVAC-system.

The oor heating was based on traditional under oor electrical heating, with an emitted power of 70 W/m^2 in the living room, 60 W/m^2 in the bathroom and 40 W/m^2 in the bed-rooms. Due to overheating and thermal comfort, and the size of the building, the only supply heat was placed in the living room area. It consists of an air-to-air heat pump. The total heat power was 6.0kW w/ COP=3.2.

6. Discussion and conclusion

In this study, four electricity price escalations was be considered. The base case scenario (2.8 %) re ects the EU energy price projections to 2030 and was used as a baseline scenario for the present study. Low scenarios (1.3% an.) are often used in the German national context, including by the Federal Government in the elaboration of energy strategies. The high energy prices scenario (4.3% an. assumes a high energy price rise in the future, similar to the latest years observed rises. Due to resent research, there has been a 5% an. real increase in electricity

Figure 7. Design temperatures in main area (electric heating)

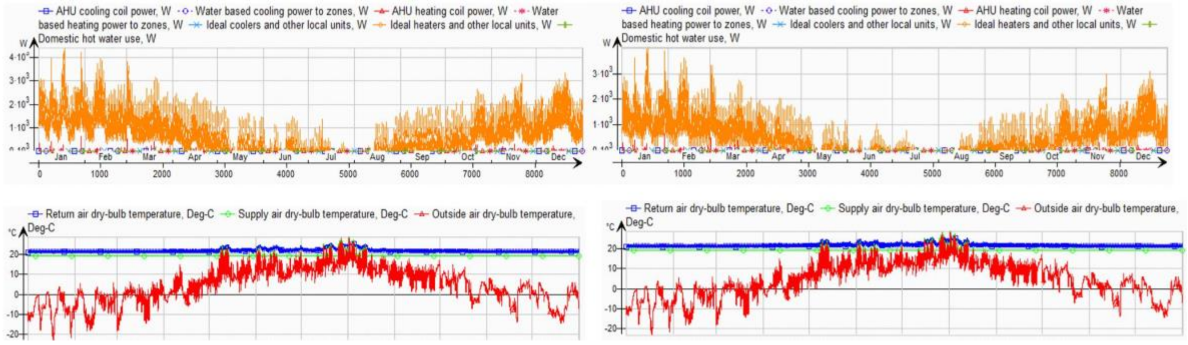


Table 5. Break even (PVGIS)

	PVGIS											
Efficiency	16%				18%				20%			
Escalation	1.30%	2.80%	4.30%	5.00%	1.30%	2.80%	4.30%	5.00%	1.30%	2.80%	4.30%	5.00%
Break even	26	22.8	20.2	19	24.6	21.2	19	18.2	22.9	20	17.9	17

price from 2000-2010. Hence, this optimistic prediction was also presented in the study.

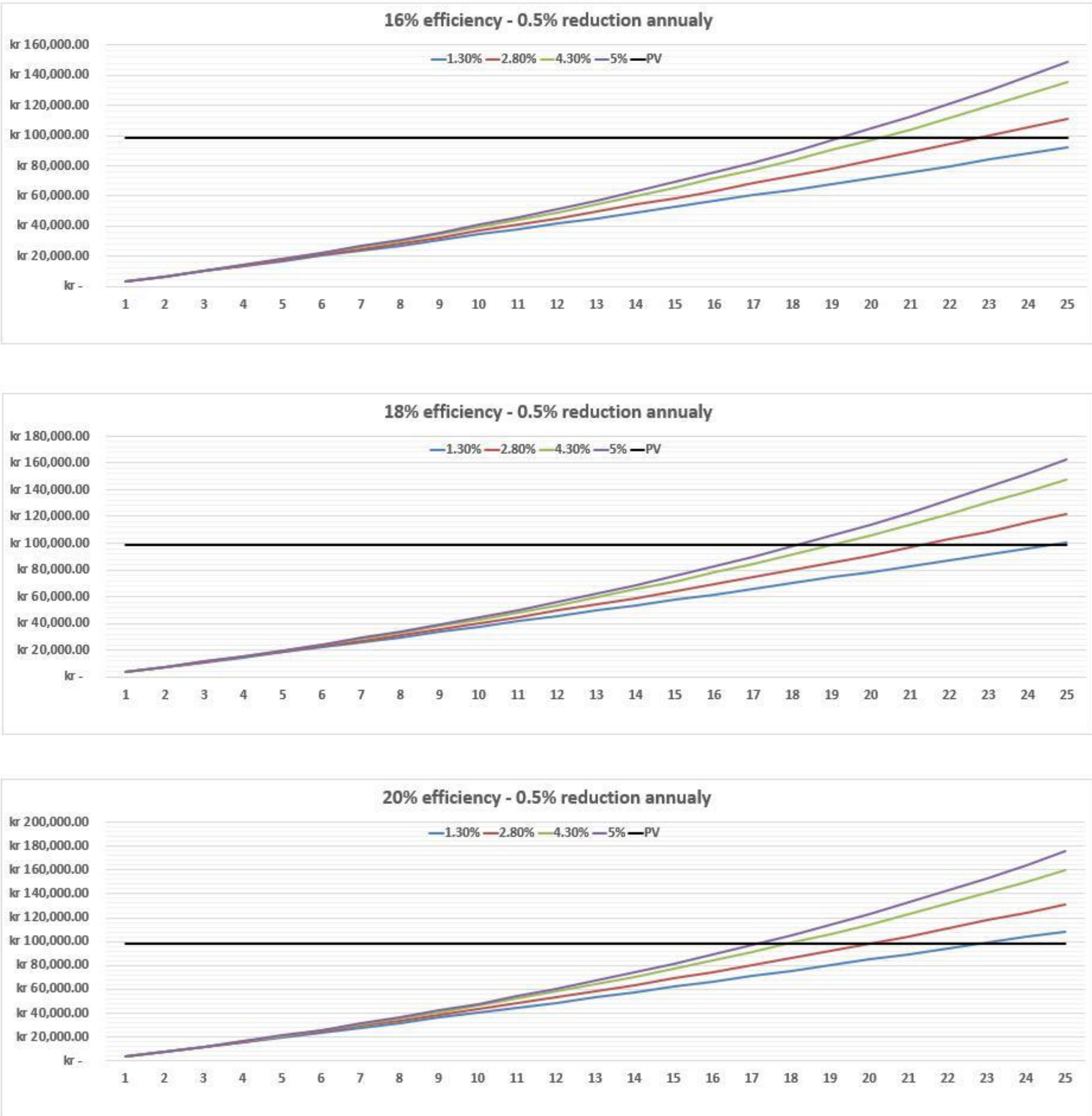
Energy efficiency technologies such as daylight control, thermal insulation, low-emissivity windows and on-site production of energy can be used to decrease energy use in new commercial buildings. Although the increased energy e ciency usually increases the upfront construction costs of a building, the energy savings over the service life of the building often o set these initial higher costs. The results gave a signi cant reduction in energy demend, from 84.1 65.5 kWh/m^2. When considering the displacement from traditional buildings to ZEB, the building type, climate, and study period impact the nancial bene ts from energy e ciency improvements. The longer the study period, the greater the energy savings for the building.

Furthermore, the adaptation of early stage BIM simulation is not a trivial task. This paper nds it prudent to investigate other software tools to evaluate the energy performance of dif-ferent building components. Further research is needed in the areas of software tool integration and selection for establishment of integrated design procedures and optimal criteria.

The results shows that by investing photo voltaic panels in addition to improved building envelope, the building performance reached high levels of performance. However, for the Nor-wegian climate, it is clear that the cost of 22.8 years payback is a high initial investment cost, which was the break even point from the simulations in PVGIS (assuming a 2.8% electricity price escalation). Based on the assumption of escalating electricity prices, specially in Norway, the paper did not nd it recommended from a economical point of view.

Based on the case study and simulations in IDA-ICE, several conclusions can be drawn. The design option with the lowest energy demand was found to be the optional concept building with electric oor heating and a air-to-air heat pump designed according to the ZEB speci cations. By retro tting the design from TEK-17 standard to nZEB, the energy demand reduction was found to be 22%. The cost of retro tting was found to be neglect able, compared to the cost of energy e cient measures, like the photo voltaic system. Furthermore, experimental veri cation of the demonstrated energy demand potential is recommended.

Figure 8. Photo voltaic payback time (PVGIS)



In conclusion, this was a case study of a digital case study building. The work done attempted to establish a fast and precise procedure for optimization of the building envelope using building performance software, which could be applied to di erent case-studies. For further research, this papers nds it necessary to scale the study quantity of di erent building types to be considered in terms of sensitivity analysis based on variation of climatic locations, electricity cost escalation and product costs.

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Application of RecyclingGraphs for the Optimisation of the Recyclability in Building Information Modelling

Schwede D

Institute for Building Energetics, Thermotechnology and Energy Storage (IGTE), University of Stuttgart, Pfaffenwaldring 35, 70569 Stuttgart, Germany

dirk.schwede@igte.uni-stuttgart.de

Abstract. This publication discusses the application of RecyclingGraphs and ConnectionMatrixes in Building Information Modelling (BIM) for the assessment of the ability of structures to be decomposed and their components to be recycled. The assessment of recyclability of designed building parts is a data-rich task which requires expert knowledge and detailed analysis on a small scale, if complete recycling of the material content is desired. Today often only the main content of buildings, such as concrete and steel structures, are recaptured, while components of smaller quantities are lost or in the worst case, if they cannot be separated, lead to deterioration of the main material flows. BIM models will be connected to relevant databases and used in future to support the optimization of building parts for complete recycling through assisted design or even in automated analysis runs and workflows. Structural compositions are described by RecyclingGraphs and ConnectionMatrixes, which's components represent on the one hand material elements and on the other hand the connections between them. Materials are classified in terms of various characteristics, such as their recyclability, their ability to be incinerated and the harmfulness of their deposition. The connections are evaluated regarding their ability to be disassembled and the compatibility of the materials connected. The structures are translated into ConnectionMatrixes and the aspects of the evaluation are assessed individually and in combination. The translation of BIM models of four wall structures into RecyclingGraphs and ConnectionMatrix representations is analysed and potentials of such representations in new BIM-based workflows are discussed.

1. Introduction

The principles of design for recycling have been known for a long time and the stakeholders in the design and construction industry are increasingly aware of the need to preserve resources. In future, resource efficiency of buildings will be required as a necessary quality of building designs, like energy-efficient building today [1]. However, up to now there are still no applicable tools and assessment methods that enables engineers and architects to systematically translate these objectives into constructible designs.

Although there are methods for the evaluation of recyclability, these are often limited to the assessment of the individual material elements in a building structure. If at all, joining techniques and the ability to disassemble are only included in the assessment qualitatively. In product design however methods for the development of recyclable products are now widely applied, also because recycling is more straightforward here due to longer design cycles, higher quantities and more controlled production conditions. With the increasing use of digital planning methods and prefabrication, the development of recyclability is becoming also more feasible in the construction industry. Especially the object-oriented approach in Building Information Modelling (BIM) will give rise to the application of pre-designed elements stored in catalogues of design templates optimized for resource-efficiency, recycling and low life cycle impact. Common to these three new design aspects is that their assessment are highly data-rich tasks that required detailed consideration and a large degree of expertise which is not in the core competence of architects and engineers today. Such new requirements will overwhelm design professionals if not supported by databases and computational tools. The approach presented in this paper will allow the evaluation of resource-efficiency, recyclability and life-cycle impact of structural elements represented in BIM template databases.

As the European Construction Product Regulation (EU-CPR) demands that all new building and building products can be recycled already today, an applicable method for such assessment is needed. Beside the technical, economic and ecological considerations also the assessment of the ability for recycling is required in the development of new materials and structural elements [1].

Akinade, et al. [2] conducted a survey among construction industry stakeholders in the UK how BIM methods can support recycling and resource-efficient design, however most of these approaches address the reduction of construction waste on site ("designing out waste") and the prediction and management of material flows. The authors identified seven key BIM functionalities to be leveraged for design for recycling [3]. These are "Improved stakeholders' collaboration", "Visualization of the deconstruction process", "Identification of recoverable materials", "Deconstruction plan development", "Performance analysis and simulation of end-of-life alternatives", "Improved building whole life management" and "Interoperability with existing BIM software". The utilization of pre-designed and optimized design templates in the object-oriented structure of a BIM model is not listed although such applications will effectively support the introduction of structures optimized for deconstruction and recycling into design practice.

2. Building Information Modelling (BIM)

The term "Building Information Modelling" (BIM) refers to an object-oriented and parametric representation of design objects in the field of building design, construction and building operation. Design elements are represented in digital models as geometric, volumetric objects, which are augmented with relevant numerical and textual parameters. As an object-oriented approach BIM allows nested representations with adapted levels of detail. Through a common modelling standard and aligned workflows BIM facilitates the cooperation of the various disciplines in the design process and between the relevant lifecycle phases. BIM is used for coordination between architectural design, structural engineering and mechanical design. In the building's lifecycle information is passed from design to construction and to facility management.

In the field of resource efficient design BIM models are used for the generation of simulation models for thermal building simulation, load calculations and structural engineering from one common representation. In the context of recycling the application of BIM is often discussed for resource flow management, volumetric waste volume estimation and the prediction of transport and processing requirements [4].

While the main benefit of BIM is often seen in its ability to provide coordination between the disciplines in the design flow, the capacity of the nested object orientation to develop detailed design solutions bottom-up and then to plug them into the top-down design model is not yet utilized for deep analysis of design solutions. Although suppliers of technical installations, such as shading systems or ventilation units, already provide augmented BIM representations of their products to reference to the central BIM model, the detailed representation of for example wall structures with all their constructive and building physical elements and layers is not common today. BIM models are developed to limited level of geometry (LoG) and a limited level of information (LoI) and detailed design information is attached in form of 2D plans and textual descriptions [5,6]. This is partly to reduce the workload of the specialized engineers, who are still reluctant to design, specify and to enter such detailed information into the model [7]. It is also to maintain a workable size of the model since data rich representations become heavy even with today's computer infrastructure [7].

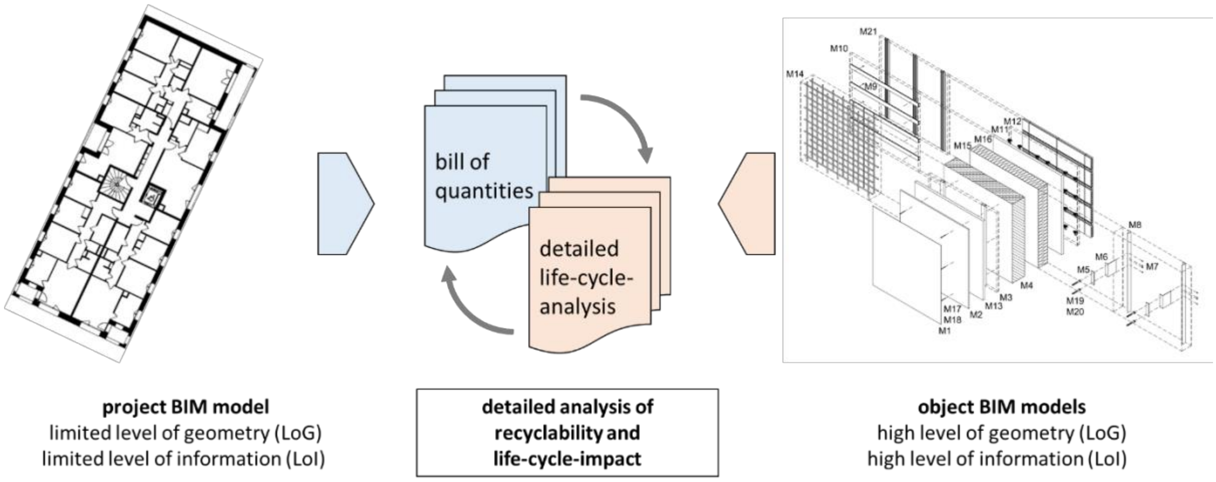

Figure 1. aggregation of detailed analysis results on building level.

3. Description of the method

BIM models contain geometric and volumetric information about the objects in the design. Additional parameters can be attached to these objects, such as material names and properties. However, information on their relationship is usually not included other than through their geometric coordinates and their shape.

Through automatic geometric analysis of the element's geometry and their placing in the model it is possible to identify adjacent elements and to plot a simple recycling graph and connection matrix [8,9] (moving from A to B in Figure 2). Pairs of adjacent elements are then listed as connection datasets. In a next step (moving from B to C in Figure 2) these connections are qualified with relevant parameters indicating the type of connection and other characteristics of the connection such as the ability to be separated and the compatibility of the connected materials [9]. This qualification can be performed by hand or supported by a database of common connection properties of material pairs. However, such information is not yet available in a structured form and will need to be developed to support future design for recycling [10].

Obviously, also the objects in the design can be specified with relevant information on the recyclability and the path of disposal, as well as of other relevant properties for life-cycle assessment and for environmental and economic evaluation. Such information can be retrieved from the available databases and connected to the material elements.

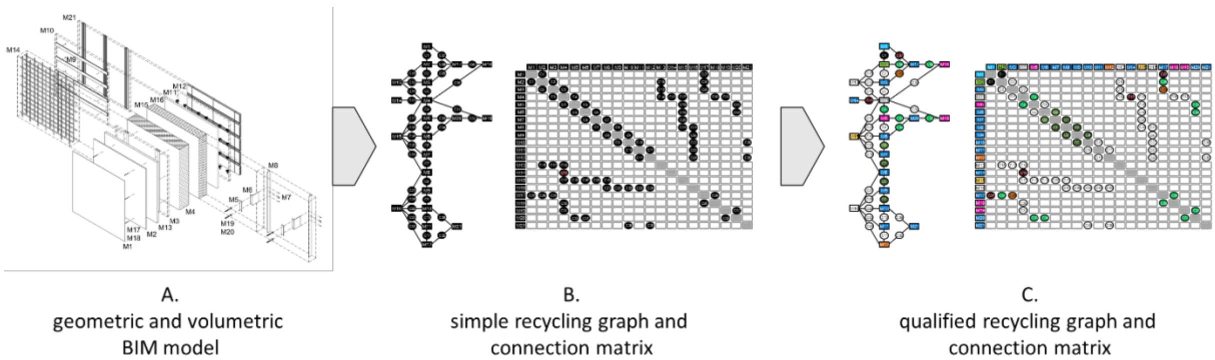

Figure 2. workflow from a BIM model into an analysis model for optimization for disassembly and recyclability. A. geometric and volumetric BIM model, B. simple recycling graph and connection matrix, C. qualified recycling graph and connection matrix.

In first applications of the method the resource demand (e.g. “mass”, “primary energy consumption”) and the environmental impact (e.g. “global warming potential”) were added to the material element data sets [11] as well as the general ability to be recycled [9]. The connection elements have been modelled with information on the “ability to be disassembled” and the “compatibility for processing” of the two connected material elements [9]. Further information can be added to both element categories for detailed assessment and planning as suggested below.

material elements parameters (examples)

- Mass of material
- Environmental impact for LCA
- Resource demand for LCA
- Durability of material
- Classification of hazards for health
- Classification of hazards for environment
- Economic value/burden after recycling
- Specification of applicable ways of processing

connection elements parameters (examples)

- Ability to be disassembled
- Compatibility of elements for processing
- Worktime for disassembly
- Required tools for disassembly

Qualities such as the “ability to be disassembled” can then be rated on a given scale. The rating in a connection element dataset can thereby also differ depending on the direction to indicate that one member will remain intact, while the other member is destroyed in the process of disassembly. Such information can be depicted in the RecyclingGraph and the ConnectionMatrix by numeric values and by colour codes. Related qualities of the design object can be assessed visually and through mathematical evaluation. Integrated evaluations can be produced by overlaying ratings of individual criteria. In [9] it has been demonstrated that the overlay of the rating of “ability to be disassembled” and the rating of “compatibility for processing” can be used to identify the best process for deconstruction to recover the resources in a given structure.

With the translation of a designed structure into a qualified graph and matrix representation its constructive characteristics become accessible for computational evaluation and based on that for processing for optimization. BIM models can be analysed, and related computer aided algorithms can be implemented in BIM design environments.

In a first step the optimization will be performed by the designer based on depicted analysis results as shown below. In future alternative selections of materials and connection types can be suggested by a computer aided system based on information from material and connection databases, as well as based on learning from the analysis of structures with a proven high degree of recyclability stored in element catalogues.

4. Results

The method has been applied to four different wall structures, which are modelled in detail with all required connection elements and fixtures as well as all functional layers to comply with the requirements of the current German energy code (EnEV 2016). The same wall structures have already been analysed regarding their ability to be recycled in [9] and regarding life-cycle impact and resource consumption including all constructive elements in [11].

In Figure 3 the four wall structures and their ConnectionMatrixes are depicted for the “ability to be recycled” (A), “compatibility for processing” (B) and the “integrated assessment of recyclability” (C = SQRT(A x B). For each material element in the four structures simple indicators are determined to analyse the bonding of material elements. The indicator “number of connections to other material elements” (#) indicates if the material element is connected to multiple neighbours. A value of 1 identifies a material element that is either a coating or embedded in another material. A value of 2 indicates a material element which is fitted in sequence with its neighbouring material elements. A further indicator is the “average rating” (∅) in the categories A, B or C. The rules for the analysis depicted in Figure 4 are given in Table 1.

As a result of modelling and optimization of individual design objects the demolition material flows can be predicted as required for management of removal logistics and recycling. In difference to the assessment based on the bill of quantity alone the quality of the material flow can be assessed from the BIM model already in the design. Not only the volume of a material fraction can be determined, but also which combinations of materials are to be expected and which technology would be necessary to process such material fractions into secondary resources.

Table 1. assessment rules for the assessment of disassembly and processing of material elements

number of connections # of a material element M		
1	M is only connected to one other material element. M is either a coating or M is embedded into another material (such as steel in concrete).	
2	M is fitted between two other material elements. M is either a connection or a separation element fitted in sequence with two neighbours. M might also be bridging between two neighbouring elements (coating spanning over different elements).	
>2	the material element is connected to several other material elements. It is possible that the element is locked-in and disassembly is restricted (might require a certain sequence of work steps)	
average rating ∅ of a material element M (A, B or C)		
1	A	material element M can be disassembled from all its direct neighbouring material elements
	B	material element M can be processed together with all its direct neighbouring material elements, the composition is a mono-material system or a material system that can be processed together without reduction of quality.
	C	material element M can either be disassembled from or processed together with all its neighbours

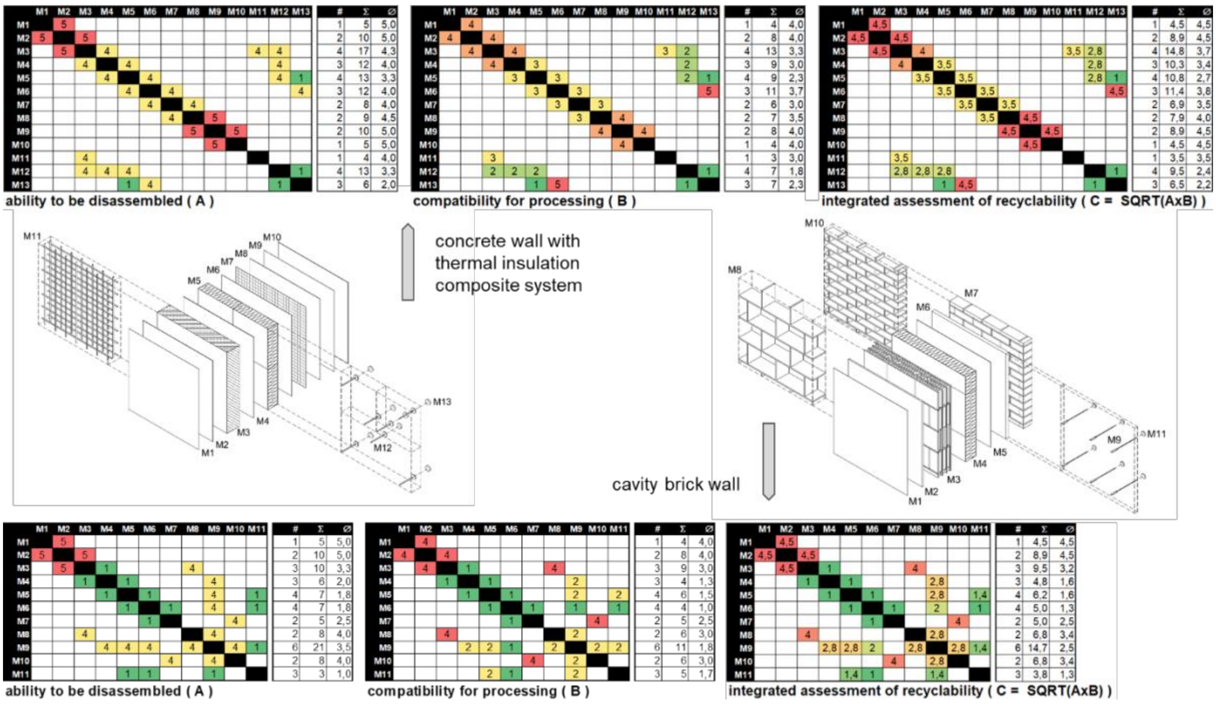

Figure 3. qualified connection matrixes with the properties "ability to be recycled" (A), "compatibility for processing" (B) and the "integrated assessment of recyclability" (C = SQRT(A x B)). (continued next page).

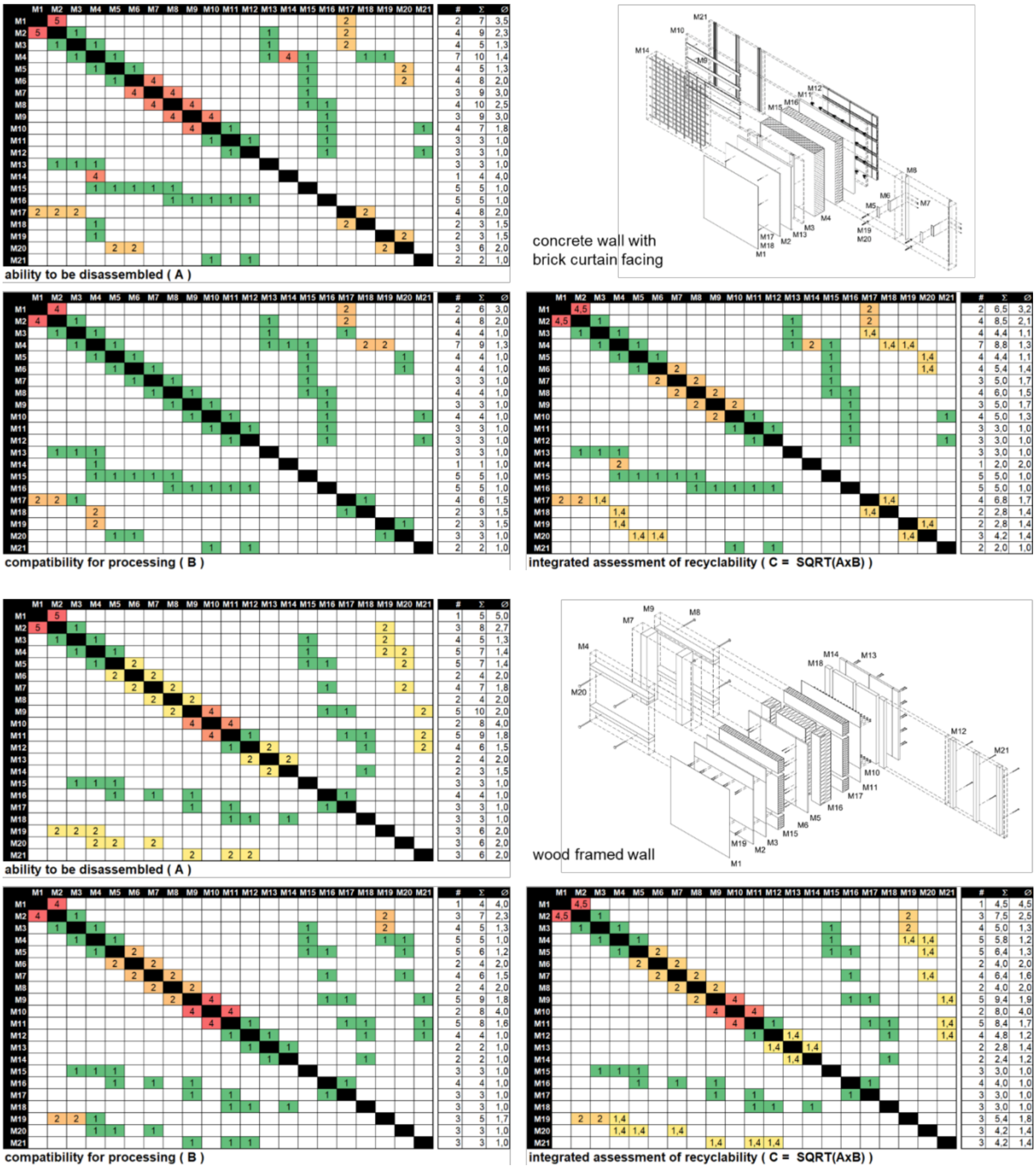

Figure 3 (continued). qualified connection matrixes with the properties "ability to be recycled" (A), "compatibility for processing" (B) and the "integrated assessment of recyclability" (C = SQRT(A x B)).

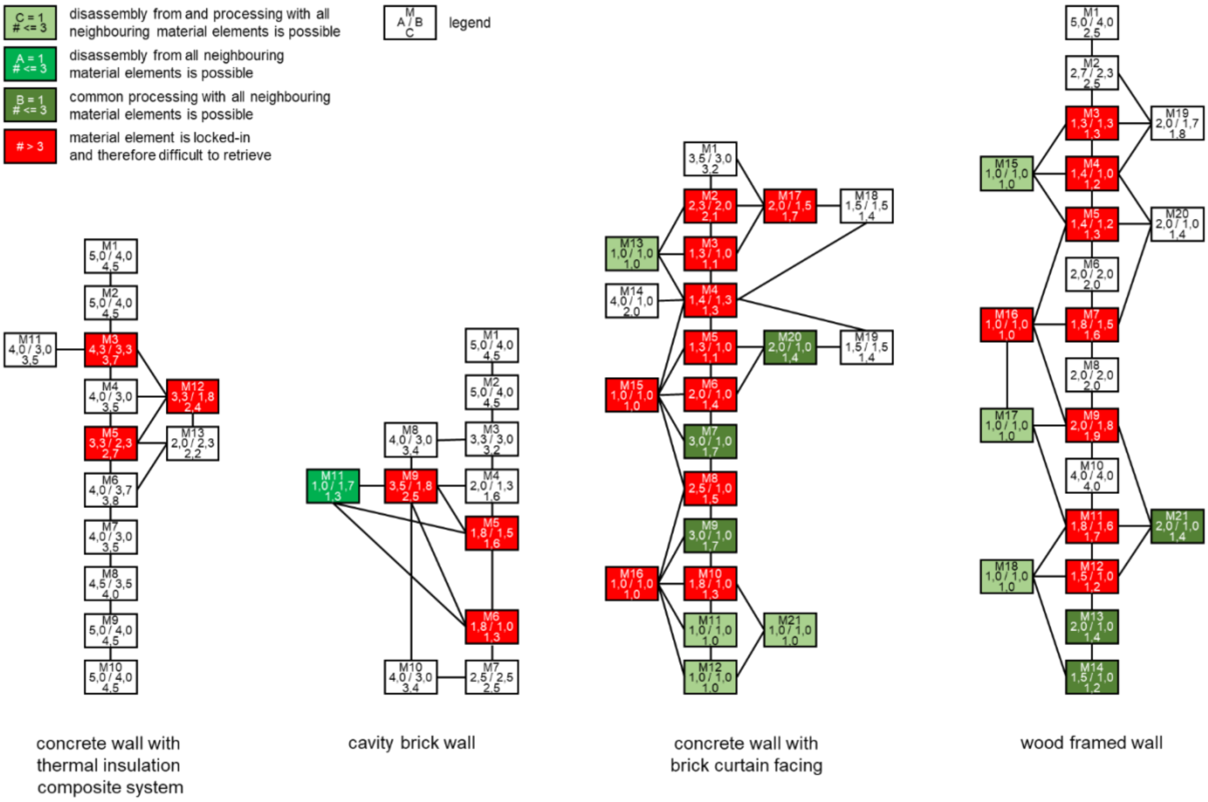

Figure 4. simple rule-based analysis of four wall structures. Colour codes indicate the recyclability of the material elements in the structure.

5. Conclusion

Resource-efficiency, recyclability and a low life-cycle impact are new criteria in building design and construction that require a detailed and data-rich evaluation [9,11]. A detailed analysis of the structural elements, not only of their individual materials but also of their connections and the compatibility of the fitted materials, is required to build truly sustainable structures. The RecyclingGraph approach presented in this paper can be used to translate detailed models of constructive designs into a numerical representation that can be processed by computational algorithms and design tools. This method can be utilized to evaluate designed and pre-designed structures and a catalogue of qualified design templates can be build up to support the BIM-based design development.

The presented RecyclingGraph approach must be developed further and an applicable design tool must be implemented. Research is also needed on the ability of disassembly for common connection principles and especially on the compatibility of material combinations.

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Process model for BIM-based MEP design

Partl R[1], **Hauer S**[2], **Monsberger M**[1]

[1] Institute of Construction Management and Economics, Graz University of Technology, Lessingstraße 27/I, 8010 Graz, Austria
[2] Sustainable Thermal Energy Systems, AIT Austrian Institute of Technology GmbH, Giefinggasse 2, 1210 Vienna, Austria

rainer.partl@tugraz.at

Abstract. Planning quality is a key aspect for the development of sustainable buildings. This particularly applies to mechanical, electrical and plumbing (MEP) systems, which have a high impact on the building performance. The design of these systems considerably affects construction and operational costs. Moreover, it has a substantial impact on the consumption of resources such as energy or water and also on the building quality in terms of user satisfaction. Building information modeling (BIM) is a method capable of substantially improving the quality of MEP design. This requires adequate component models as well as processes describing the proper use of these models in a BIM project. This paper presents a Business Process Model and Notation (BPMN) model which describes the required interactions between project stakeholders during the design phase of a geothermal heat pump system. It describes the roles, tasks and responsibilities of the involved stakeholders and outlines which kind of information is required from whom at which point of time. The specific activities of the stakeholders are linked by information flows. In addition to the process model, a set of parameters describing a heat pump is presented. The parameters can be used as attributes in a BIM model. Each parameter is assigned to the design phase in which it is needed for the first time. This establishes a link between the attributes in the BIM model and the process model. Both, the process model and the parameter set were evaluated by MEP experts.

1. Introduction

The building sector has the highest final energy demand globally representing 31% of the total final energy consumption. Heating accounts for 75% of this energy consumption. The utilization of digital technologies has the potential to save up to 12% of energy for domestic hot water, heating and cooling until 2040 [1].

Building information modeling (BIM) is one of the most promising digital methods in the architecture, engineering and construction (AEC) industry [2]. Hartman et al. [3] pointed out that for a broad implementation of BIM two kinds of languages are required: one language to describe data models for BIM implementation and another one to describe the multidisciplinary BIM work processes [3]. Usually, many stakeholders are involved in the planning process of a construction project. Information management between these stakeholders across the various project phases is an important factor for successful BIM collaboration. A major challenge in project coordination is the question of responsibility for delivering data at the right time in the different project phases [4]. This is especially true for mechanical, electrical and plumbing (MEP) as this domain has many interfaces to other disciplines. One of the reasons why BIM has not yet fully been adopted is that there is a lack of well-defined process models for BIM collaboration. Moreover, there is a need for practicable descriptions of project requirements and BIM components [6].

The objective of this paper is to provide a process model for the BIM-based design of a geothermal heat pump with a vertical closed-loop borehole heat exchanger (BHE). Heat pumps have become an important heating system in Europe with steadily increasing annual sales [7]. BPMN (Business process model and notation) is used to represent the process model in this paper. To facilitate the practical applicability of the process model, a data set with design parameters of a geothermal heat pump is presented. The parameters can be used as attributes in a BIM model of a heat pump. Each parameter is rated according to its importance in the design process and assigned to a design phase. Parameters ranked with a high degree of importance are presented and discussed in detail. The results can be used for setting up and managing BIM projects where a geothermal heat pump system is used as heating system for the building.

2. Methodology

The use of process models is a common way to describe the tasks, responsibilities and workflows in a BIM project. Integrated Definition for Function Modeling (IDEF) [8] [9] as well as BPMN [4] have been used to represent process models for BIM projects. International standards such as EN ISO 29481-1 propose BPMN for generating process diagrams for the development of information delivery manuals (IDMs) [10]. For this reason, BPMN has been chosen to describe the design process of a heat pump system in this paper. The presented process model should support the creation of IDMs or relevant BIM documents in case the building is equipped with a geothermal heat pump system. It should also help to manage and monitor the digital information flow between the project participants in the course of the development of the BIM model. This includes the development of rulesets for automatic BIM model checking.

The IFC4 Add2 (Industry Foundation Classes) data model defines a heat pump as unitary equipment (IfcUnitaryEquipment), which means that the heat pump model consists of models of the individual subcomponents of the heat pump (e.g., evaporator, compressor, throttle or condenser etc.). In practical MEP planning however, it is unusual to consider individual components of a heat pump. It is a common practice to handle a heat pump as a whole device. For this reason, characteristic parameters of a heat pump were collected in order to create the basis for a heat pump data model on device level. The collected parameters were subsequently assigned to different design stages and evaluated by four MEP experts each on having more than 10 years of practical experience. The presented heat pump parameters can be used to set up custom heat pump models in BIM authoring software. It may also be used as a basis for an alternative heat pump model in IFC or to extend the current IFC4 Add2 model with parameters which are not yet implemented.

3. Results

The results are presented in two parts. First, the workflow and data exchange through three design stages of geothermal heat pump planning are illustrated by means of a BPMN process model. In the second part, collected heat pump parameters are presented and categorized, including a rating of their importance in different design stages.

3.1. BPMN model of the BIM-based design of geothermal heat pumps

Figure 1 shows the workflow and information flow during the design process of a geothermal heat pump with a vertical closed-loop BHE using BPMN (based on the ISO 22263 standard [11]). It shows the interactions of project participants from six disciplines: architecture, heating, ventilation and air-conditioning (HVAC), civil engineering, geotechnical engineering (GEO), electrical engineering and building automation (BA).

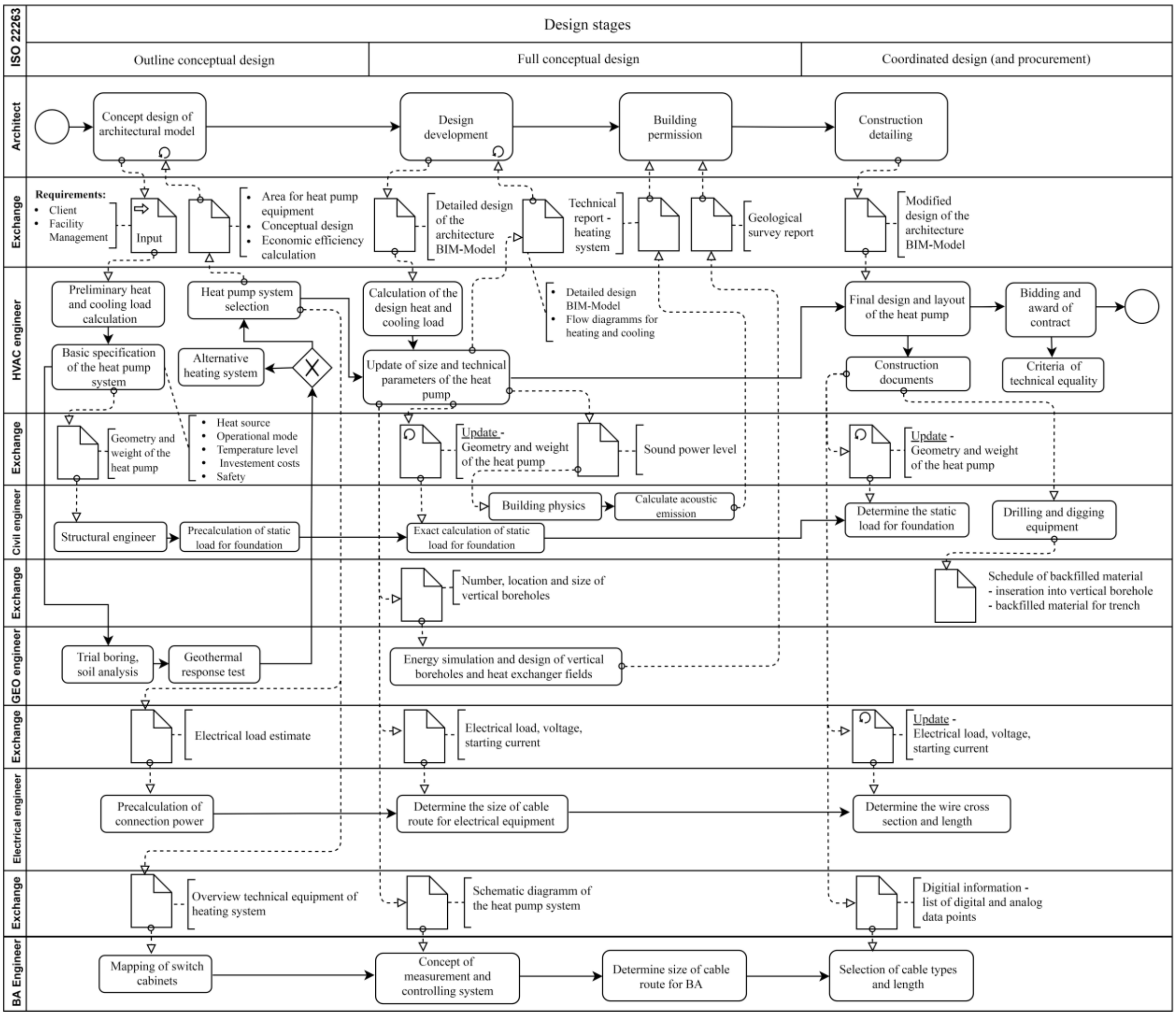

Figure 1. BPMN model of a heat pump for different design stages during the design phase.

At the beginning of the outline conceptual design phase, the architectural model and the requirements of the client and facility managers are analyzed by the HVAC engineer. Based on these requirements and a preliminary heat and cooling load calculation the basic operating conditions of the heating system are specified and main parameters of the heat pump system such as the required heat output, the electric load, dimensions, weight etc. are estimated. The refrigerant type and the basic system configuration are chosen. In large scale projects, the geotechnical engineer plays an important role in the course of system selection: The results of the thermal response test indicate whether the geothermal conductivity of the soil is sufficient or not to provide the required heat output. At the end of the outline conceptual design phase, the architect gets a technical concept of the heat pump system and requirements concerning the space needed for the technical equipment in the building and for the BHE in the surrounding area.

In the full conceptual design stage the parameters specified in the previous stage are extended and refined. The capacity of the heat pump is determined based on a detailed heating and cooling load calculation. This allows for a more precise specification of the dimensions and technical parameters of the heat pump. The results are required for the subsequent building permission process. In the coordinated design phase, the design and layout of the heat pump system is refined and completed and documents for the bidding and negotiation process are prepared. Engineers from all domains should be integrated into the design process as early as possible as shown in the process model.

3.2. Data set of design relevant parameters for geothermal heat pumps

Data was collected from different sources such as national and international standards (e.g., [12]), product data sheets and data schemes such as IFC4 Add 2 in order to compile the following parameter set for a geothermal (brine-to-water) heat pump as described in [13]. Overall, 76 parameters relevant to the design phase were identified. Figure 2 shows different categories to which the individual parameters were assigned.

Each parameter was subsequently assigned to the design phase, in which it is required for the first time. The initial assignment was done by four HVAC experts. In general, the assignments of the experts were in good agreement. In cases of differing opinions, parameters were assigned to the phase with the most entries. The parameters were finally assigned as follows: 30 to the outline conceptual design phase, 28 to the full conceptual design phase and 18 to the coordination design phase.

	Category	Number of parameters	Outline conceptual design	Full conceptual design	Coordinated design
Heat pump (IfcUnitaryEquipment)	Thermal and efficiency parameters	10	4	2	4
	Electrical parameters	9	5	3	1
	Geometry	6	6	0	0
	Refrigerant	6	6	0	0
	Operational parameters	8	3	5	0
	Fluid mechanics	14	0	14	0
	Cost	2	1	1	0
	Temperature range	4	4	0	0
	Machine specific parameters	12	1	3	8
	Building automation	5	0	0	5
Sum of attributes		**76**	**30**	**28**	**18**
Distribution		100%	39%	37%	24%

Figure 2. Categorized parameters of a geothermal pump and distribution among different design stages.

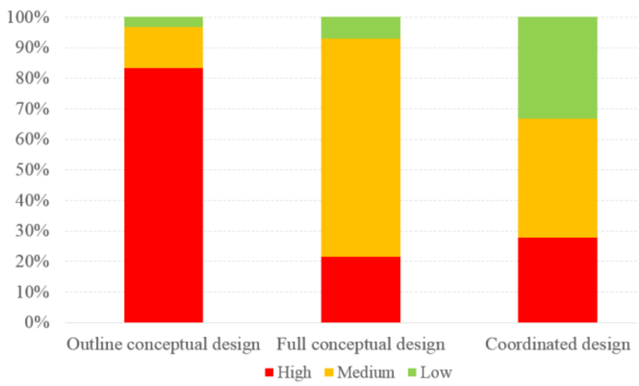

Figure 3. Distribution of the degree of importance of parameters in each design stage.

The four HVAC experts were also asked to rate the relative importance of each parameter. For this purpose, three importance categories ('high', 'medium' and 'low') were defined as outlined in table 1. The rating should help to establish a common sense between all project participants about the priority specific parameters should receive in the course of the development of the BIM model. Particularly for parameters rated with 'high' degree of importance, care must be taken to ensure that they are duly defined, fully incorporated in the digital building model and kept up to date throughout all project phases.

Figure 3 shows the distribution of the parameters according to their degree of importance in each design stage. It can be seen that the parameters with a 'high' degree of importance are predominant in the outline conceptual design phase. This result underlines the importance of early design stages in which requirements and the basic design-relevant parameters are specified. This is especially true for BIM projects as the establishment of BIM triggers a trend towards more detailed planning in early design stages.

Table 1. Categories for rating the degree of importance of the parameters.

Importance category	Criteria
High	• Parameters to be defined together with the client in order to determine the basic requirements for the planning task. • Parameters that are required to fulfil the planning task and which are essential for the work progress of several of the involved project participants. • Parameters needed for the building permit and parameters that represent criteria required to assess technical equality in the tendering and award process.
Medium	• Parameters that are required to fulfil the planning task and which are essential for the work progress of a specific project participant (e.g., parameters required by HVAC engineers to dimension a specific component).
Low	• Parameters which are not required for common planning tasks but which may be required for optional or special tasks (e.g., additional or more detailed simulations, additional documentation etc.).

Table 2 summarizes all parameters rated as 'high'. It also shows the design phases in which the parameters are relevant for the first time. The table reflects the opinion of the four HVAC experts consulted. The following examples illustrate the application of the criteria in table 1.

The heat output and electrical power at specified operating conditions for example are important for estimating the size and capacity of the heat pump. The two parameters are classified 'high' as other important parameters depend on them. The geometric dimensions and the weight of the heat pump depend on the heat pump capacity. This information is required by the architect and the structural engineer (e.g., to determine the location and size of technical rooms). The refrigerant charge is another important parameter derived from the heat pump capacity as pointed out below. Estimating the coefficient of performance (COP) and the energy efficiency ratio (EER) at specified operating conditions is also essential in the outline conceptual design as the granting of subsidies often relies on these parameters. This has a significant impact on cost calculations, which, in turn, are an important basis for decision-making by the client.

Refrigerant parameters (refrigerant type and charge, toxicity, flammability) are highly important because they determine the required extent of safety measures as specified in the EN 378 standard [14]. This concerns for instance the installation site (e.g., permissibility of an indoor installation) or requirements to equip the technical room with additional systems (e.g., additional ventilation, fire protection systems etc.). The parameters thus have an impact on the floor plan and on the scope and configuration of MEP systems. As the refrigerant choice and the refrigerant charge are safety-critical parameters, they also play an important role in the building permit.

Parameters required to assess technical equality of products in the tendering and award process include the nominal heat output, cooling output, COP and EER, the sound power level, the refrigerant type and the refrigerant charge. This justifies the rating 'high' of theses parameters.

Table 2. Geothermal heat pump parameters with a 'high' degree of importance.

Category	Parameter	Unit	Outline conceptual design	Full conceptual design	Coordinated design
Thermal and efficiency parameters	Required heat output at specified operating conditions	kW	•		
	Required Coefficient of Performance (COP) at specified operating conditions	(-)	•		
	Required Energy Efficiency Ratio (EER) at specified operating conditions	(-)	•		
	Nominal heat output	(kW)			•
	Nominal cooling output	(kW)			•
	Nominal Coefficient of Performance (COP)	(-)			•
	Nominal Energy Efficiency Ratio (EER)	(-)			•
Electrical parameters	Required power at specified operating conditions	(kW)	•		
	Starting current	(A)		•	
	Connection voltage	(V)		•	
	Nominal power	(kW)			•
Geometry	Length of unit	(m)	•		
	Width of unit	(m)	•		
	Height of unit	(m)	•		
	Length of required maintenance area	(m)	•		
	Width of required maintenance area	(m)	•		
	Space required for installation	(m^2)	•		
Refrigerant	Type of refrigerant	(-)	•		
	Refrigerant charge	(liter)	•		
	Toxicity	(-)	•		
	Flammability	(-)	•		
Operational parameters	Type of heat source	(-)	•		
	Range of functions (heating / domestic hot water / cooling)	(-)	•		
	Operation mode (monovalent / bivalent)	(-)	•		
	Temperature level of antifreeze	(°C)		•	
	Heat pump with integrated hot water tank	(-)		•	
	Volume of hot water tank	(m^3)		•	
Cost	Capital cost	(€)	•		
	Operational cost	(€)		•	
Temperature range	Maximum flow temperature heating	(°C)	•		
	Minimum flow temperature heating	(°C)	•		
	Maximum flow temperature cooling	(°C)	•		
	Minimum flow temperature cooling	(°C)	•		
Machine-specific parameters	Total weight	(kg)	•		
	Sound power level	(dB)		•	
Building automation	Interface type to automation and control system	(-)			•

4. Conclusion

In this paper, a process model and parameters for a data model for the design of geothermal heat pump systems were presented. BPMN was used to describe a standardized workflow and information flow for the design process. The process model shows that the interaction between different project participants is high. A data set with 76 geothermal heat pump parameters was compiled by analyzing different information sources. These parameters facilitate the design of the heat pump according to the requirements in different design stages. In BIM projects, these parameters can successively be adopted as attributes in the model. All parameters were thus assigned to design stages and rated according to their importance. The result shows that the degree of importance of the majority of parameters assigned to the first design stage (outline conceptual design) is classified as 'high'. This underlines the importance of early design stages in MEP and BIM planning.

The presented process model and parameter set should support the set-up and management of BIM projects in which a geothermal heat pump is used as heating system for the building. This includes the creation of relevant BIM documents (e.g., employer's information requirements, information delivery manuals etc.), the implementation and execution of rules for BIM model checking and the management of attributes in BIM models of geothermal heat pumps.

A next step would be to assign the identified parameters not only to design phases but also to specific use cases such as lifecycle analysis, building simulation, clash detection, BIM-based tenders etc. BuildingSMART Switzerland has recently introduced an online platform where such use cases are comprehensively described and documented. The methodology presented in this paper will subsequently be applied to other MEP components in order to build up a pool of MEP models which can be readily used in BIM projects.

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Criteria catalogue and analysis model to manage complexity in prefabricated timber construction

Geier S, Schwehr P

Lucerne University of Applied Sciences and Arts, Competence Center Typology & Planning in Architecture (CCTP), CH-6048 Horw

sonja.geier@hslu.ch

Abstract. Prefabricated timber construction often comes with demanding planning processes and uncertainties due to higher complexity. Hence, a great potential to optimize design, construction, and economic efficiency is not put to use. In the future, the challenge will be to have project management that is able to handle complexity. The criteria catalogue and the analysis model, developed in my doctoral thesis at TU Munich, are a first step towards the systematic and typological structuring of prefabricated timber construction in terms of complexity. The criteria catalogue makes it possible to describe and record functional and technical specifications as well as the aspects of the design and construction process and implementation, in terms of less or greater complexity. The project-specific system presentation in the analysis model is the basis for a common understanding and a transparent and target-oriented exchange of information among different disciplines, including the client. The application of the model in practice is described by means of a case study. The outlook of this paper describes how the developed analysis model provides a new approach in order to support planning security in Building Information Modeling (BIM).

1. Starting point

1.1 Complexity and planning security in prefabricated timber construction

«Timber Construction is complex», this statement stubbornly persists in practice without any plausible or profound hypothesis in literature. The «Manual for Multi-Storey Timber Construction» (*Atlas mehrgeschossiger Holzbau 2017*) describes timber construction as *«more multi-layered, thus more complex.»*

It says: «*The market offers an almost over-differentiated selection of different materials with many different construction possibilities»* [1]. Published in 2017, this comprehensive manual does not specify, why timber construction shall be «more complex». The question about complexity, however, is relevant, as in practice, it is this alleged complexity that is blamed for many difficulties and deficiencies that might arise in the planning process for prefabricated timber construction. For example:

- <u>Uncertainties</u> in the estimate of costs of alleged «complex» timber constructions in early planning phases. If a project team lacks the experience in early project phases of timber construction, the estimate of costs can be a major challenge: In Switzerland SIA 102:2014 Service Modell demands a cost accuracy of 15% in the Preliminary Project (SIA Phase 3.1) [2]. In Germany it is 10% in the Draft Planning Phase [3]. With the lack of experience and knowledge as to which constructions are simple and uncomplicated to realize and which situations require more effort and/or higher costs, safety margins are the rule. The worst case scenario is significant costs overruns. Both scenarios fail to rebut the widespread prejudice that timber construction is more costly [4] or correct the ratio.

- Concerning the interdisciplinary communication, those involved in the planning process complain about misunderstandings, double or bad planning, which effects the cost and schedule reliability as well as the process and the quality of design and execution [5].
- Concerning the expert-layman communication between the timber company and the developers, people report about the difficulties in transparent communication of context and impact of specific requirements or constructions in timber construction. Non-experts often do not have the understanding for cost-drivers, as these are not «visible» [6].

So although ecological arguments are in favour of wood, many actors raise arguments against it in the planning phase, summarized under the title «timber construction is complex», albeit without giving any reasonable explanation. The aim of my thesis at the Technical University in Munich was to close this gap and to contribute to the planning security in timber construction. The main focus was to determine the reasons for the complexity of timber construction and to derive solution approaches for handling complexity in planning and construction processes.

1.2 Definition complexity in the building construction and prefabricated timber construction

There are various definitions of the term complexity (in general). What is common to all of them is that complex systems are characterized by changing relations and they are unpredictable and cannot be planned ahead. They develop, they change and cannot be broken down into linear chains of cause and effect. If you follow these explanations, (planned) mechanisms and structures (including airplanes) per se are not complex at all, only complicated. Thus a timber construction is not complex but only complicated.

Literature (in general) provides various discussions and definitions of the complexity in building construction: Williams T mentions structural and organizational uncertainties [7], Bertelsen S refers to internal interdependencies, dynamic ambient conditions for the process, fragmented structures of building enterprises and the temporary system of social interactions [8]. That means the term complexity in building practice is used inaccurately. A challenge in construction, technology or design does not necessarily generate complexity (only in exceptional cases).

Within the framework of a situation analysis, my thesis identified and discussed further causes, specifically for timber construction with high levels of prefabrication:

- The lack of standardization of superstructures and over-differentiated variety of products cause uncertainties and the lack of overview within the planning team. [5]
- Functional requirements such as sound protection, fire protection, thermal insulation and moisture protection must be guaranteed in the interdisciplinary, cross-sectional analysis of primary, secondary and tertiary structures. Conflicts of interests and goals must be solved.
- Product specifications/capacities, supply chains, transport and logistics may already influence the design and should be considered early enough – albeit they cannot be controlled by the planning team only, and thus lead to uncertainties. [9]
- Pre-fabrication requires clear and complete execution planning for the production planning. Thus, decisions must be made earlier than with conventional construction methods. Interdisciplinary interaction in order to clarify all (relevant) planning details, takes place in a shorter period of time and with a higher network density. [10]
- The period between a decision (upon planning) and the visible assembly on-site is longer, thus increasing the risk that volatile influences or unforeseen events might thwart the plans. [10]

Thus, the complexity of prefabricated timber construction is not due to construction or architecture but to uncertainties, interdisciplinary interdependencies, conflicts of interests and goals and a higher density of social interaction. A web of manifold «complicated» challenges regarding how to manage interdisciplinary collaboration is thus the reason for any complexity in timber construction with a high level of pre-fabrication.

1.3. Managing complexity in the planning process
Building means deciding – despite all uncertainties, conflicts of interests and goals and the risk of the unforeseen. According to Schwehr P, a project team can only function with a solid base of knowledge and decisions [11]. In line with the interpretation of complexity discussed above, planning security means that it is impossible to foresee everything. Planning security means rather the security to deal with uncertainties, unforeseen events and to solve conflicts of interests and goals during the negotiation processes, through a high level of interdisciplinary interaction. So the management of complexity requires project-specific support through:

- establishment of a common understanding of the project, of terms and language and the priorities during project development (Big Picture).
- transparency and traceability of influential factors, dependencies and possible interactions (internal and external).
- knowledge and understanding of negotiable and not negotiable aspects.
- clarity in the exchange of information in inter-disciplinary communication (expert- and expert-layman-communication).

The conclusion in my thesis was to develop a typological structure of project characteristics and influencing factors in pre-fabricated timber constructions, demonstrating the project specific interaction of all complicated (und thus complexity generating) aspects and criteria in order to support interdisciplinary collaboration in the project team.

2. Criteria catalogue and analysis model

2.1 Methodical procurement and set-up of criteria catalogue
This typological structuring and the «complicated» i.e. complexity-generating criteria are derived from finished projects as part of the WoodWisdomNet research cooperation leanWOOD [12]. A total of 14 projects were investigated. In 45 narrative interviews and 9 interdisciplinary discussion groups criteria, qualified as «difficult» in planning and execution, were discussed from multiple perspectives.

These criteria were classified (less difficult to very difficult), supplemented with all normative and legal references and summarized in a criteria catalogue. Having finished the first version of the criteria catalogue, its validity was tested against the leanWOOD-case studies and other timber construction projects from previous research projects and double checked with practice partners for relevance and practical suitability.

2.2 Structuring of the Criteria Catalogue
Right now, the Criteria Catalogue comprises 35 criteria. The criteria were divided into three categories:

- Criteria that define the «Requirements» relating to task, functionality, surroundings, legal and normative framework conditions and the needs/wishes of the developers.
- Criteria that define the technical and design-related system approaches and details that are developed and/or decided by the project team in «Design + Construction».
- Criteria that influence the «Implementation» in production, logistics and assembly.

Each criteria category is documented in the Criteria Catalogue in a separate chapter. Figure 1 shows screenshots of individual pages of the criteria catalogue.

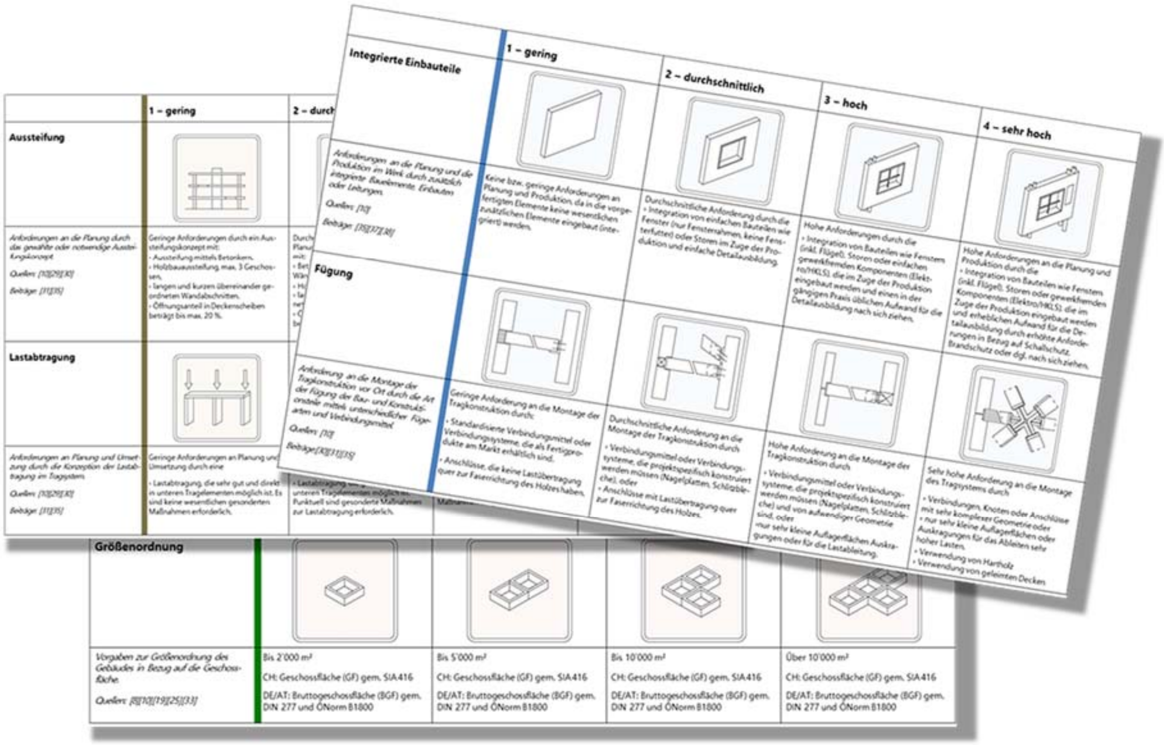

Figure 1: Screenshots of individual pages of the criteria catalogue [13].

As an example for one of these criteria the «Height Limitation» in the chapter «Requirements» shall be explained (see Figure 2):

Buildings in urban areas may be limited in height, because it might have to correspond with the roof line of the neighboring buildings. In order to achieve acceptable room heights, thin ceiling constructions must be applied, which exclude certain ceiling systems a priori, and also have an impact on horizontal cable and pipe ducts in suspended ceilings. This could possibly be compensated with horizontal space resources, where groups of ventilation lines could supply a smaller area and thus have smaller dimensions. If neither applies (level 3 or 4) the choice of ceiling systems is even more limited and/or inevitable crossings of lines and tubes require partial lowering.

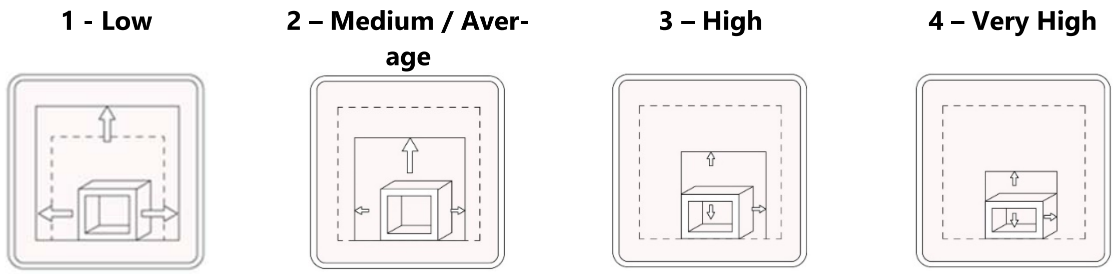

Figure 2. Criteria «Height Limitation» shows four levels of difficulties from level 1, (Low) to 4 (Very High) [14]. Level 1 (Low) shows no limitations in heights and horizontal expansion. Level 4 (Very High) shows a massive limitation in horizontal and vertical expansion.

The criteria «Height Limitation» describes the example as to how architects, timber structural engineers, building technicians and experts in fire and sound protection and structural physics have to tackle the challenges of room and ceiling height as well as cable and pipe ducts. In the case of different interpretations of priorities in the project, such as the priority of system separation, the condition that ducts may only be placed in suspended ceilings, or the question as to whether open ducts are possible, the key players may try to develop solutions on different assumptions.

2.3 Visualisation in the analysis model
The criteria catalogue systematically combines experience and know-how derived from individual, isolated experiences, summarized in a checklist. In order to visualize the assessment of a project and in order to support interdisciplinary communication through Visual Management, a visualization system was developed that generates a project-specific overall profile. In my thesis the Sunburst-Diagram was further developed (see Figure 4). The set-up of an analysis model and the derivable parameters for the planning team are explained below on the basis of real specific case studies.

3. Case study «Top Floor Addition Saumackerstrasse»

3.1 Project description [15]
The case study «Top Floor Addition Saumackerstrasse» describes the refurbishment of a multi-family house (year of construction 1948) in an urban area (Zurich). The total set of 21 apartments on three floors was to be left untouched as far as possible. The facade was insulated, new balconies were added to the facade and a controlled domestic ventilation was installed. The top floor addition replaced the uninsulated roof construction and made room for six new apartments. The element construction method was applied using box beam elements. The developer's goal was to create low-cost housing, thus the project had to be carried out in a tight financial framework.

Number of apartments:	21 + 6	Total construction time:	7 Months
Main usable area	1.970 m^2	Timber elements assembly:	3 Months
Completion	October 2015	Construction costs:	1.227 CHF / m^2 HNF
Architekt	*kämpfen für architektur ag*	Total costs:	1.580 CHF / m^2 HNF

Table 1. *Overview of the basis parameters of the project «Saumackerstrasse» (source see above)*

Figure 3. Installation of the pre-fabriacated roof elements. Photo: *kämpfen für architektur ag*

Figure 4. Interior view loft. Photo: *kämpfen für architektur ag*, Photographer: R. Rötheli

3.2 Assessment by means of the analysis model
Figure 5 shows the case study «Top Floor Addition Saumackerstrasse» in an analysis model. The three categories, Requirements, Design + Construction and Implementation are highlighted in different colors (green/brown/blue) and the difficulty levels (1-4) are graphically displayed with bars of different lengths.

The grey bar in the background shows the so-called «Reference Profile». The Reference Profile makes it possible to display experiences from previous projects and to constantly specify them in the course of future projects.

Figure 5 clearly shows that the «Requirements» in «Saumackerstrasse» were low to average, compared with the Reference Profile. For example fire protection was no big challenge. The required standards for sound protection, energy efficiency and earthquake protection were not unusual. However, Figure 4 shows one challenge. The «Existing Structures» were assessed as level 4. The reason was that the existing apartments had to remain untouched, thus offering little space for ducts in the staircase. The ducts to the new apartments had to be split without any system separation. As a result, the installation along the basement ceilings to the building services had to be solved on-site. In an interview the construction manager admitted that there were no additional costs, but that deadlines has been exceeded. The advantage of a rapid construction progress could not be transferred to the entire construction period. This might have been avoided through better planning during the early planning phase.

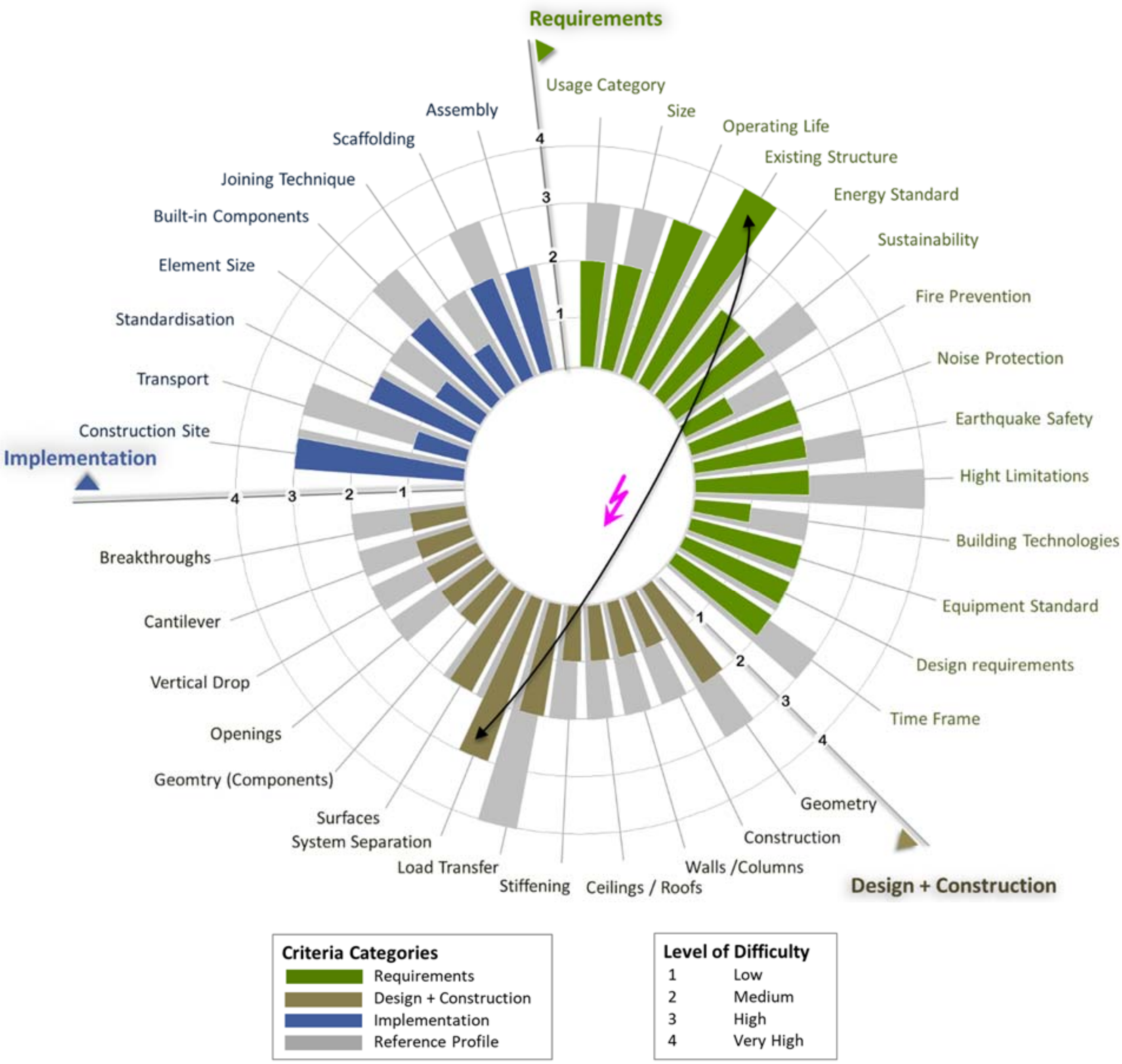

Figure 5. Diagram of the results of the project «Saumackerstrasse» in an analysis model

4. Application and limits

4.1 Use as strategic project support

The main application field of the criteria catalogue and the analysis model is in strategic project support. Complexity-relevant information concerning the project can be scaled gradually and specified in the course of the project. The assessment of the criteria referring to «Requirements» can indicate potential challenges, also in comparison with the Reference Profile. These can be communicated to the developers in a transparent way. Subsequently, a comparison of different designs based on the criteria (mainly concerning the cost estimate) can also be supported.

As an instrument of visual communication the analysis model enhances the exchange of information and knowledge management within the interdisciplinary team and the communication with the developers in the course of the entire planning phase. Dependencies, interactions and the necessary settings of priorities become transparent, thus comprehensible. The clarity of the information transfer and a consistent meaning are supported, so misunderstandings in interdisciplinary collaboration and in expert-layman-communication are avoided. Also, it becomes easier for new team members to get acquainted with the project. Furthermore, the visualized project profile can support the transparency of project descriptions or requirement specifications.

The communication of superior and essential aspects in a project facilitates the handling of uncertainties in the decision-making process. The project leaders have a solid basis for targeted quality, deadline and cost oriented project management. The comprehension of the overriding assumptions enables appropriate project-specific action on the part of everybody involved («Empowerment»).

The assessment of the complexity to be expected and an overview of the project specifications also support the procurement and cooperation model. The relevant disciplines are already being applied in early and subsequent phases. The selection of the contract awarding procedure can take into account specific complexities.

4.2 Conclusion

The assessment by means of a criteria catalogue and the visualization of the analysis model contribute to the typologically structured understanding and communication of causal networks in prefabricated timber construction. The added value is the assessment of possible challenges and the creation of a common understanding for the project within the interdisciplinary team. It is no dogmatic classification.

Flexible criteria can also be supplemented or deleted, depending on the application, without limiting the functionality or significance. The recording of experiences from previous projects in a reference profile supports the people involved and provides a checklist for the project management. However, it does not provide a generally applicable algorithm that can replace expert conclusions.

5. Outlook

The digitalization of the building industry and the successive implementation of the Building Information Modeling BIM initiates a new methodical culture. Model-based automated interdisciplinary collaboration will characterize future planning processes. The understanding of the terms, the interpretation of the meaning, the orientation and the comprehension of the priorities are essential for information management and communication for interdisciplinary collaboration. In this context the analysis model offers a typological approach that has the potential to support the structural transformation into new management and collaboration models in general. In addition a further operationalization of the analysis model may contribute to the following areas:

- The development of a BIM-cost model is challenged by the transfer of parameter-based cost estimates to component-based cost calculations. Today parameter-based models (in early phases) for the assessment of different execution options in timber construction can hardly be verified with cost factors. If reference profiles of previous projects could be set up in an internal data bank, it could provide increased accuracy. Subsequently, the data banks or catalogues could be pooled (e.g. BKI data bank for construction costs [16] or EAK catalogues of elements [17]) making a major contribution to cost security in timber construction.

- In in Switzerland the calculation of fees are on SIA 102:2014 [18], in Austria on LV.VM 2014 [19] and in Germany on HOAI 2013 [20]. What is common to all of them is that the basic services of the architects can be adapted to the increased expenses by means of adjustment factors or categories. However, these factors are rather vague in connection with prefabricated timber construction. The analysis model could enable an adequate assessment and, where appropriate, provide a billing system for architectural and engineer services in timber construction.

Thus, the criteria catalogue and the analysis model are the first important steps towards a typological structuring of prefabricated timber construction. The involvement of the digital planning environment could prove that timber construction is in fact attractive both ecologically and economically.

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Switching to a holistic perspective on semantic component models in building automation – tapping the full potential of automated design approaches

Wollschlaeger B, Eichenberg E and Kabitzsch K

Chair of Technical Information Systems, Technische Universität Dresden, 01062 Dresden, Germany

{bastian.wollschlaeger, elke.eichenberg, klaus.kabitzsch}@tu-dresden.de

Abstract. Building automation systems are vital for reducing both energy consumption and carbon footprint of modern buildings. However, the engineering of such building systems is becoming increasingly complex, such that automating the engineering tasks is inevitable. Therefore, semantic component models of high quality and high expressiveness are required. But, as of today, existing models suffer from focusing on isolated aspects, high effort for component model specification, and low expressiveness in terms of the provided model structures. To close this gap, this paper proposes to adapt a holistic approach for modeling components. Firstly, we investigate different dimensions of component aspects and their interrelations and secondly, we develop BA-GSem, a graph-based semantic component model for building automation. Using a case study of a multi-variant room control unit, we illustrate that the correctness of system design results can be determined more precisely when using the detailed semantic model BA-GSem. The results offer a suitable foundation for improving the quality of automated design approaches for building automation, thus facilitating the creation of modern and sustainable buildings.

1. Introduction

Building automation systems (BAS) facilitate demand-based building operation and are therefore a key concept for reducing both energy consumption and carbon footprint of modern buildings [1–3]. The application areas of smart building technologies are not limited to building automation itself, but they are also important drivers for shaping the digitalization of home health care and customized precision health care by means of smart home and assistance technologies [4]. However, the engineering of smart building systems is highly complex due to a large number of components and component variants to choose from, highly interconnected information flows and interoperability issues among components of the building system [5]. Human engineers are unable to keep up with the pace of component development in the smart building and smart home sectors: they are only familiar with a small number of the available components, which leads to sub-optimal solutions and wasted potential of energy savings [6].

Consequently, automating the engineering tasks is inevitable to cope with the growing complexity of BAS. The major engineering task is the design of the BAS, which, besides for the system development, can also be used in redesign or self-adaption [7] use cases. This component-based design process requires formal component models of high quality and expressiveness, fulfilling the following requirements: They need to offer structures with a high level of detail (*Precise Modeling*) and in order to be usable by engineering algorithms, the effort for creating and using the component models needs to be in an acceptable magnitude (*Ease of Specification and Use*). Furthermore, design algorithms will need to cope with heterogeneous levels of detail in the component database (*Robustness of Use*).

However, state-of-the-art component models suffer from low model expressiveness, focus on isolated aspects or high effort for specification and therefore fail to provide a foundation for successful automated design. This paper addresses these gaps with the following contributions:

1. **Precise Modeling:** Proposal of the *graph-based semantic model BA-GSem* for detailed modeling of component semantics in context of a holistic perspective.
2. **Ease of Specification and Use:** Identification of *important component aspects and their interrelations* as a basic prerequisite towards adopting modularization approaches.
3. **Robustness of Use:** Discussion of *the impact of different levels of detail on specific system design tasks* as foundation to assess feasibility and quality of system design.

The remainder of the paper is structured as follows: Section 2 discusses related work on formal component models for automated engineering approaches. Afterwards, the holistic perspective on component models for building automation (BA) is discussed in Section 3. Subsequently, a case study of a multi-variant generic room control unit is used in Section 4 to validate the applicability and benefits of the holistic perspective and the semantic model *BA-GSem*. Section 5 concludes the paper with a summary and an outlook towards further research.

2. Related Work

The overall task of automated design consists of fulfilling the user requirements by selecting and combining available components. Semantic specification approaches for functionality allow transforming user requirements into an intermediate, neutral and machine-understandable formal representation of required system functionality. Sub-tasks for the design of BAS are [8]: Selection of *suitable components* for system functions ("T1-ComponentSelect"), identification of required *data flow* between components ("T2-DataFlowIdent"), *interoperability*-check of all interconnected components ("T3-CheckInterop"), and ensuring that all components are capable of *providing their functionality* ("T4-CheckOperational"). Following this concept, a multi-stage *automated design approach* for room automation (RA) systems has been proposed [8, 9]. This approach is based on the common functional vocabulary of RA systems standardized by the VDI 3813-2 [10]: The first design step maps the user requirements to a formal semantic model for system functionality. In the second step, this neutral requirement model is transformed into several design suggestions using a component repository that contains formal models of the available RA components.

Existing approaches for formal device modeling include classification approaches [11–13]. These focus on isolated aspects, e. g. eProcurement or eCatalogs. Functional semantics are only annotated on a very coarse level. Several communication technologies for BA provide electronic self-description documents [14, 15]. Such documents contain models of software interfaces as well as basic functional aspects, but are technology-specific and lack detailed semantic information. Finally, Dibowski and colleagues proposed a technology-neutral semantic component model [16], specifying the device interface coarsely on both software and semantic level. Yet, the link between both levels is missing and device models are specified in a non-modularized fashion, creating a high modeling effort for different variants of a product family.

With regard to automated design, especially step *T4* is currently not sufficiently supported by any of the existing component model approaches. A holistic approach for modeling devices is required, taking into account aspects such as hardware, software, functionality, and their interrelations. We will extend the approach of Dibowski [16] to meet the practical needs of automated design approaches.

3. A Holistic Perspective on Component Models for Building Automation

3.1. Important model aspects and their relations

A general model of an automation device is shown in Figure 1. It is focused on the *Device* as the central entity and describes its inner structure as well as its interfaces. Depending on the role of the device, its

Hardware-interfaces may include connections to the process (i. e. the physics of rooms in a building), human-machine-interface elements (operating elements and display functionality), or the communication medium (automation network). The network interface is displayed on the lower right by a connection to a field bus and the appropriate *Network Stack*, which handles wrapping and un-wrapping payload with the bus' telegram structure. On the other hand, *Periphery Drivers* handle the pre-processing and integration of electrical signals received from or sent to the electric terminals (pins) of the device.

The second area of a Device's inner structure is its *Software*, which is modeled in terms of a whole *Device Application*. To allow for better modularization, the general device model allows the Device Application to be composed of individual *Software Modules* that can be managed and used independently of each other. The Device Application may restrict the number of available instances of each Software Module to account for a limited computational or storage capacity. Software Modules can also be modeled according to their interfaces and inner structure. The Software may receive and send information as payload of the communication platform (i. e. field bus). This data is shown as data points of the *Network Interface* (`nwIn` and `nwOut`). In addition, a Software Module may exchange data with the physical process by means of electrical signals, constituting the *Peripheral Interface* with the data points `pIn` and `pOut`. Lastly, a formal *Semantic Model* of a Software Module's functionality processes and generates this information on an abstract level.

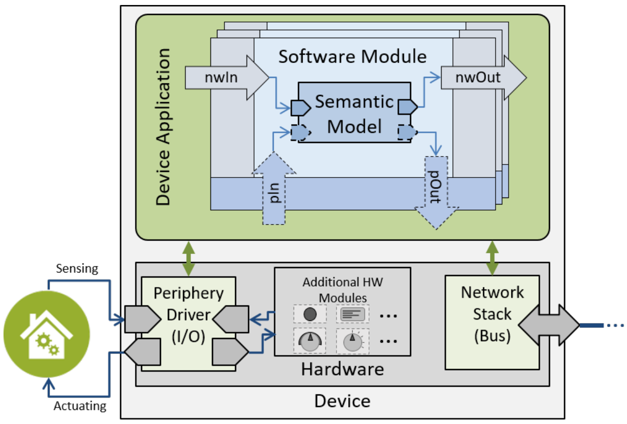

Figure 1. General Device Model of an automation device

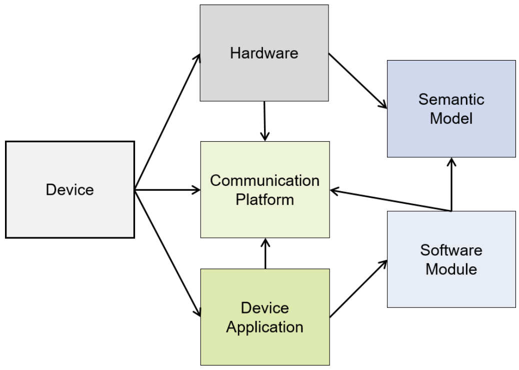

Figure 2. Model aspects and interdependencies

As can be seen from the general device model, there are several key aspects that need to be modeled for an automation device. Decomposing a device model into different aspects proves valuable if product families and therefore a great degree of similarity are involved. Instead of having a monolithic device model, each device aspect can be defined in a modular and reusable way, which makes the specification and use of device models more efficient. As part of our investigation, we examined which model parts would prove suitable for modularization. The identified aspects and their dependencies are depicted in Figure 2. A directed edge in this graph means that model artifacts of the aspect at the origin make use of model artifacts of the aspect at the target end of this edge. Starting from the *Device* as the main entity, several other model aspects are linked: Firstly, a device consists of a specific *Hardware* and a software *Device Application*. Secondly, individual variants of a product may target different communication technologies; thus, another important aspect of a device is its *Communication Platform* (which only needs to be modeled once). The communication platform is again referenced by both hardware and device application, since the first needs to contain a compatible transceiver required for communicating with this particular network and the latter makes use of the communication platform's application layer data types.

Further references can be identified from the general device model: the device application can be

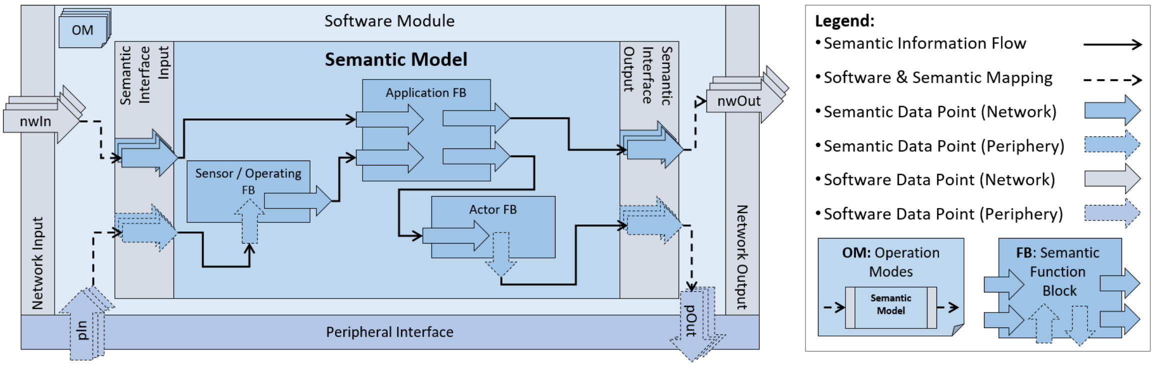

Figure 3. *BA-GSem*: Graph-based semantic model of a software module

made up out of *Software Modules*, which each contain *Semantic Models* and reference types from the communication platform. Finally, the hardware aspect referencing the semantic models is less obvious: It can be inferred from the general device model that a semantic model may only receive information from the network interface (i. e. software aspect) or from the peripheral interface (i. e. hardware aspect). Thus, a specific hardware equipment may determine, which parts of the semantic model can be chosen.

3.2. Conceptualization of BA-GSem – a Graph-based Semantic Model for Building Automation

The related literature analysis in Section 2 shows that the available structures for specifying component functionality are limited to a plain list of functions without taking into account the inner flow of semantic information as well as neglecting the distribution of data from the semantic interface to the semantic functions and vice versa. In order to provide a more fine-grained structure to model device semantics, we developed a *graph-based semantic model* for software modules of BA devices (cf. Figure 3). This model uses the function block (FB) structure proposed by the VDI 3813-2 [10]: a semantic function is represented by a specific block that defines its information flow interface. More specifically, semantic information of a certain type may be provided to the function block by directing the information flow to connectors, so-called data points, on the input side of the block. Information flows generated by the function block originate at data points on the output side of the block and can be directed to other data points. These connectors also have a specific type and the semantic linking is only valid, if the types of data points and information flow match. In case of function blocks connected to the periphery (i. e. sensor, operating, actuator, and display blocks), data points handling information flows from the peripheral interface will be drawn vertically with a dotted outline, whereas all other data points are visualized in a horizontal style with a continuous outline. This distinction is motivated by the physical connectors in [10].

With information flows connecting function blocks, a function block network as a directed graph is created. In order to be able to interact with further semantic models (contained in other devices or software modules), a semantic model also needs an interface. This semantic interface is depicted on the left (semantic input) and right (semantic output) side of the function block network. If a semantic information is created inside the function block network, this information can only be used outside the semantic model if it is represented in the semantic output interface. The semantic model is used as an abstract and formal description of how the software code of a software module processes data. Therefore, data available at the interfaces of software modules need to be mapped to the semantic interface of the semantic model, distinguishing between periphery and network. Since semantic models are more abstract than software modules, this mapping will be an abstraction (software types to abstract semantic types) or a specialization (abstract semantic types to specific software types).

Even after production and programming, automation devices can be adapted to a specific use case by configuring a set of parameters. Usually, data types can be changed and even some functionality

Table 1. Levels of detail (LoD) for model aspects

Aspect	Level	Label	Description	Example
Semantic	0	Sem0	no semantic model	-
	1	Sem1	functions annotated as *plain list*	[13], [11], [12]
	2	Sem2	additional model of *semantic interface*	[16]
	3	Sem3	detailed *graph-based semantic model*	*BA-GSem*
Software	0	SW0	no software model	-
	1	SW1	*software interface* of device application	[15]
	2	SW2	software divided into *individual SW modules*	[14]
	3	SW3	*operation modes* of software modules	*BA-GSem*
Hardware	0	HW0	no model of hardware features	-
	1	HW1	*communication technology* and transceiver	[14], [16]
	2	HW2	*number and type of peripheral connectors*	[13], [11], [12]
	3	HW3	*semantic of peripheral connectors*	*BA-GSem*

can be (de-)activated. The graph-based semantic model accounts for such post-production flexibility by the concept of *Operation Modes* (OM), which possibly alter the semantic graph, the mapping between semantic and software data points as well as their respective types in a pre-defined way. By doing so, an operation mode acts as a wrapper for the semantic model of a software module.

3.3. The impact of the level of expressiveness on the feasibility of automated design

With the proposed graph-based semantic model offering more detailed structures to model components' functional semantics, more fine-grained analyses and consistency checks become available at the level of automated design. However, it has to be expected that the semantic models in a component repository will not always be homogeneously described. The available level of detail (LoD) of semantic component descriptions in a component repository restricts, which analyses and consistency checks can be performed by the automated design algorithms.

We will now define different levels of detail for key aspects of component models (i. e. Semantics, Software, Hardware) and subsequently discuss their impact on typical automated engineering sub-tasks from Section 2. Table 1 defines the different levels of detail for the three main aspects of device models, including a short description and examples.

The first sub-task of automated design – "T1 Component Selection" – benefits from detailed semantic models since components are selected based on neutral functional requirements using the same functional vocabulary as the semantic model. Levels *Sem1* and *Sem2* already allow a proper querying of devices based on functions. *Sem3* adds the ability to query sub-graph-structures, which can be used by sophisticated device selection algorithms to solve the cover problem. The next step, "T2 Data Flow Identification" benefits from detailed models of the software and semantic aspects. The levels *SW1* and *SW2* offer a basic understanding of the software's interface; however, since they – unlike *SW3* – do not include operation modes, they incur a model error when describing the device's flexibility. On the semantic dimension, *Sem2* enables an identification, which semantic data might be communicated on a possible software connection. However, if *Sem3* is not available, there is no way of exactly assessing, what the purpose of the semantic data is and whether it is used at all.

The step that benefits the most from detailed models is step "T3 Check Interoperability". Each data flow connection needs to be investigated for validity on different levels: semantically using information starting from level *Sem2* (*Sem3* allowing more detailed checks), syntactically on software level (feasible

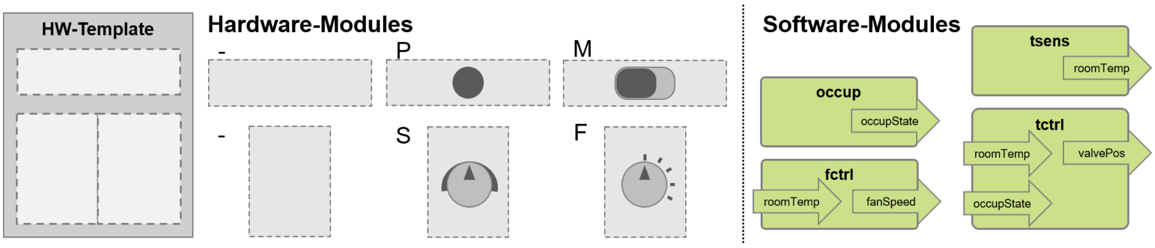

Figure 4. Building blocks of RCU Product Family – Hardware (grey) and Software (green)

at *SW1* and above with *SW3* removing uncertainty even further) and on hardware level (*HW2* and above). Finally, step "T4 Check if Operational" needs to make sure that all devices are delivered the information they require for proper functioning. This can only be assessed, if the interfaces are modeled (*Sem2* and above, *SW1* and above, *HW2* and above). The more information is available, the more accurate the operational state of components can be evaluated. For a device to be operational, it has to be ensured that all information required by semantic models is provided by either the software interface or appropriate hardware modules.

4. Case Study: Product Family "Generic Room Control Unit"

In order to provide a validation for the proposed semantic model *BA-GSem* and to show its applicability for product families in BA, we apply the method of a case study. The core element of the case study is a generic room control unit (RCU) product family, which is inspired by actual products to depict the real complexity of component models in the context of automated design approaches. The RCU product family is made up of eight similar variants that differ in their hardware configuration, which introduces subtle constraints and dependencies with respect to the functionality an RCU variant is able to fulfill.

4.1. Set-up of the Case Study

Figure 4 depicts the building blocks of the case study. All RCU variants are based on a common hardware template, which includes a temperature sensor and a small as well as a large panel for optional extension with hardware modules. There are two small and two large hardware modules: The small modules (P: *Presence button* and M: *Manual presence slider*) offer different interaction mechanisms for manually indicating the presence of persons in the room. Module P contains a button that is pressed when entering the room, while module M contains a slidable presence switch that is usually used for a distinction between day and night mode. Each large module (S: *Set point temperature* and F: *Fan speed*) features a rotary switch. Module S allows a continuous adjustment of the temperature set point (usually with an offset of ±5K), while module F has five distinct levels for the fan speed.

Restrictions regarding the large panel are: Each module can only be used once and if the large panel is equipped, module S must be present. Furthermore, if module F is chosen, the small panel must not be empty. As can be seen, the panels cannot be considered independently from each other. In total, the RCU product family consists of eight product variants.

As can be seen from the green function blocks in Figure 4, the software for the product family has been modularized into four independent software modules: *tsens* (Temperature Sensor), *tctrl* (Temperature Control), *occup* (Occupancy), and *fctrl* (Fan Control). For simplification, the imaginary manufacturer of the RCU product family supplies each product variant with a uniform device application consisting of those four modules.

4.2. Comparison of semantic models

The comparison of different semantic modeling approaches will be presented using the example of the *tctrl* software module, since it offers a degree of complexity to illustrate issues when dealing

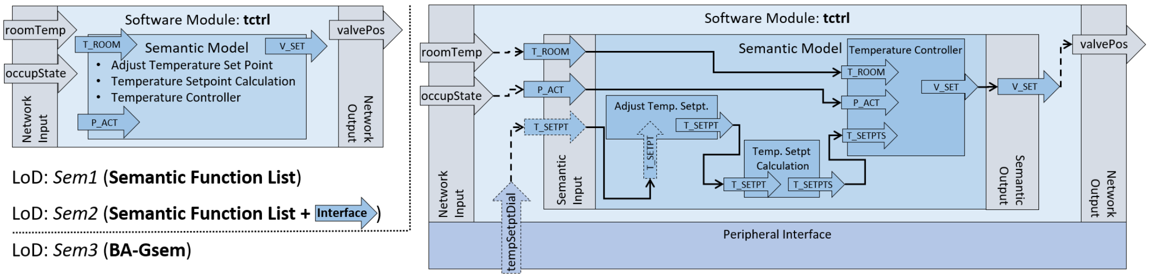

Figure 5. Comparison of Semantic Models with different level of detail (LoD)

with semantic component models. The *tctrl* software module implements a demand-based closed-loop temperature control for room temperature. The temperature controller computes a valve set point, which is transmitted from the software data point "valvePos" to a remote valve actuator using the communication network. The controller requires information about the current room temperature, the chosen temperature set point, and the current occupancy information, which is taken from both the network and the periphery: Network-wise, the room temperature and occupancy information are received by the software data points "roomTemp" and "occupState", respectively. Finally, the temperature set point is calculated from a base set point and a set point offset that can be adjusted using the temperature set point dial of hardware module S. To convert the electrical signal from the peripheral interface, a driver block "Adjust Temperature Set Point" is required. In order to keep the example concise, a simplified notion based on VDI 3813-2 [10] is used for specifying semantics. Usually, temperature control would also involve functionality like *energy mode selection* or *function selection*, which however do not add any relevant information for this case study.

For a validation of the capabilities of *BA-GSem*, different semantic models of the RCU software module *tctrl* have been created as a manual enrichment of the existing ontology component models [16] using the OWL ontology language [17]. They are presented for each LoD from *Sem1* to *Sem3*. Figure 5 depicts these three models: As a base line, model 1 depicted on the left (without the semantic data points in blue) is a semantic model consisting of a list of semantic functions. For semantic aspects, it achieves LoD *Sem1*. The second model is an extension by adding semantic interface information (i. e. data points of semantic model). Model 2 achieves LoD *Sem2*. On the right, the third model following the *BA-GSem* approach is depicted. It consists of a graph of semantic functions and thus achieves the highest ranking *Sem3* in terms of semantic LoD. Since all variants of the RCU product family are supplied with the same device application, implicit constraints on which software modules are usable for a specific variant arise. Variants that do not have the hardware module S cannot use software module *tctrl*, since the set point offset dial is required for a proper functioning of *tctrl*. This static constraint can be evaluated at time of device modeling without need for any context information.

Furthermore, *tctrl* is dependent on a presence information being available. Thus, variants without the P or M hardware modules need to be provided with a presence information from the network. This is a dynamic constraint that needs to be taken into account during step *T4* of the automated design process – it cannot be sufficiently evaluated during device modeling.

As can be seen from Figure 5, the function-list-based semantic models on the left are not sufficient to evaluate both static and dynamic constraints. The static constraint regarding hardware module S cannot be specified at all for both LoDs *Sem1* and *Sem2*. The dynamic constraint requiring an occupancy value is also not modeled appropriately. While the software interface features a data point for an occupancy state, it is not clear for *Sem1* if this information is evaluated by the semantic model and if *tctrl* is operational without a presence information. LoD *Sem2* specifies semantic interfaces, so it is sufficient to assess that presence information "P_ACT" is required, but not if *tctrl* is operational without "P_ACT".

In contrast, the semantic model of *BA-GSem* contains a sufficient level of detail for both constraints to be checked. In the static case, explicit modeling the peripheral interface reveals that the operational state of the semantic model depends on the availability of signals from the set point dial. For a dynamic evaluation of the occupancy constraint, it is explicitly modeled that the temperature controller is not operational without occupancy information.

In general, implicit constraints on provided functionality need to be detected and taken into account when modeling components. However, until now, functionality could not sufficiently be determined by analyzing the device software only, especially not in case of re-used uniform device applications. Using the detailed *BA-GSem* model, relevant constraints can be inferred, which allows to model modularized software components only once and without using error-prone copy-and-paste techniques. As a summary, providing additional levels of detail increases model quality and fosters the reduction of modeling errors induced by implicit constraints and inconsistencies amongst variants of product families.

5. Conclusion and Outlook

Smart building systems play a vital role for sustainable and smart cities in the future. However, the engineering of these building systems is a complex process, which still suffers from available products not being semantically modeled in sufficient detail. In this paper, we proposed *BA-GSem*, an enhanced graph-based semantic model for BA components. This model is part of a holistic perspective on component models, which also takes into account dependencies to hardware and software aspects. Thus, it is a foundation for capturing the real-world complexity of building automation product families, providing input for automated engineering algorithms. To this end, we used a realistic case study to discuss the influence of different model granularity on the steps of the typical engineering process.

Component manufacturers' expertise on product functionality and inner working mechanisms is a most valuable asset and allows for a high component model quality. The level of detail offered by *BA-GSem* implies that manufacturers need to invest more time and effort in modeling their products. While *BA-GSem* provides appropriate structures to capture this knowledge, further research should investigate, how the effort of model specification can be reduced and which quality assurance mechanisms can be put in place. To this end, we intend to provide tooling support for model specification. It is also conceivable to investigate an integration of this component model with already applied solutions for product information modeling as well as using the detailed information from the different model aspects for consistency checking. Finally, further research on how the levels of detail affect further engineering tasks is required to tap the full potential of automated engineering.

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The practical use of module D in a building case study: assumptions, limitations and methodological issues

Laetitia Delem & Lisa Wastiels

Belgian Building Research Institute (BBRI-CSTC-WTCB), Brussels

laetitia.delem@bbri.be

Abstract. According to the EN 15804 and EN 15978, a material or building life cycle consists of three major life cycle stages or so-called modules: Production and Construction (module A), Use (module B) and End-of-life (module C). Potential benefits and loads occurring beyond the building's life cycle as a result of recycling, reuse or energy recovery can be declared in an additional module D. As part of the upcoming amendment of the EN 15804 a formula was developed to facilitate the calculation of module D. This paper provides a critical discussion on the practical use of module D. First of all, the development of the formula revealed specific methodological issues, such as the unequal approach to closed and open loop recycling. Secondly, the consideration of module D in a Belgian building LCA case study provided insights in the different methodological choices, interpretations, and assumptions related to the calculation of module D. This concerns for example the calculation of net output flows of secondary materials, modelling of avoided primary production, definition of the point of functional equivalence, efficiency of incineration, etc. Aspects that are not clearly specified in the standard and therefore can be open to interpretation are illustrated with concrete examples from the building case study. Where possible, recommendations for a harmonized approach are made. In any way, the results from the case study analysis reveal that the methodological choices can have a significant effect on the results and that module D results should therefore be considered with care.

1. Introduction

Probably one of the most controversial issues in building Life Cycle Analysis (LCA) is how to allocate impacts and benefits from recycling and energy recovery of materials at end-of life between the system (building (material) life cycle) that generates the secondary resources (output) and the one that uses them as input. According to the European standards for the environmental evaluation of buildings (EN 15978 [1]) and the environmental product declaration of building products (EN 15804 [2]), the system boundary between both systems shall be set where materials/fuels have reached their end-of-waste (EOW) state. This state is reached when the criteria derived from the European Waste Framework Directive are met (e.g. the recovered material is commonly used for specific purposes and fulfils the technical requirements for that purpose, a market demand exists, and its use will not lead to overall adverse environmental or human health impacts) [3]. All impacts occurring prior to EOW are attributed to the first product system and all impacts occurring after EOW are attributed to the next product system.

Consequently, the first life cycle benefits from the fact that the (demolition) waste is valorized as it does not have to carry the impact of waste disposal (landfill, incineration). The subsequent life cycle benefits from using secondary materials/fuels as it does not have to carry the impact from primary material extraction/production (which is fully attributed to the first life cycle), but only the impact from transport and further processing of the secondary materials after EOW.

Often the highest benefit from secondary material valorization is the avoided impact from substituted primary production. The reason why the European standards keep these avoided impacts outside the system boundaries of the system that generates the secondary output flow is that the uncertainty concerning the potentially avoided impact is very high, given the long life span of a building (e.g. energy mixes and production processes are very likely to evolve, and the demand for recycled products at the time of demolition is uncertain). Moreover, it would be unfair to credit "highly uncertain potential" benefits that will occur in a distant future against consumption today [4].

Nevertheless, information on the potential benefits from recycling, reuse and/or energy recovery of materials after the building life cycle could stimulate planning and design choices that facilitate greater valorization potential at the end of the use period. Therefore, the European standards provide rules to calculate this information and declare it as supplementary information "beyond" the building life cycle, in the so-called module D (modules A, B, and C represent the production stage, the use stage, and the end-of life stages of a building, respectively). Until now, this module was optional and therefore often not included in building (material) LCA. However, with the proposed amendment of the EN 15804+A1+prA2 [5] module D will very likely become mandatory.

2. Module D: the theory

Module D represents the potential benefits and loads from "net" output flows of materials for recycling (e.g. secondary materials), reuse or energy recovery (e.g. secondary fuels), but also from energy exported to the outside of the building system boundaries. The latter can be energy produced during waste disposal (incineration or landfill) of construction materials or energy generated on the building site (during the use-stage) that is exported for other uses (e.g. electricity produced by photovoltaic panels on the roof that is exported to the grid).

The potential benefits reported in module D represent the avoided impact from primary material production/extraction (which is substituted by the secondary materials) and avoided generation of primary energy (heat and/or electricity production substituted by the use of secondary fuels or energy exported from waste disposal and on-site energy production). The potential loads relate to the recycling and recovery processes occurring from beyond the system boundary (point of EOW) up to the point of functional equivalence, where the secondary material, fuel or exported energy substitutes primary production. If the output flow does not reach the functional equivalence of the substituted process a justified value-correction factor has to be applied. Both benefits and loads shall be calculated based on current average technology and practice. If information on current practice is lacking, a conservative approach shall be used [2].

The "net" output flow of materials for recycling or energy recovery represents the difference between the output flows of a specific secondary material or fuel leaving the system at EOW and the amount of this secondary material or fuel initially used as input during the production stage.

3. Objectives and methodology

The objective of the present paper is to provide a critical discussion on the practical implementation of module D based on the insights gained from (1) a Belgian building LCA case study including module D, (2) discussions with LCA experts, and (3) the translation of module D into a formulae as part of the latest amendment proposal of EN 15804+A1+prA2 [5]. The main issues handled in this paper relate to the identification of the point of functional equivalency, the calculation of net output flows and the potential benefits from avoided (primary) production.

3.1. Case study

The environmental performance of a 4-level multi-residential building, with 25 living units and a total net floor area of about 2000 m², was calculated using LCA. Different load bearing structures and material combinations were tested (e.g. wood-skeleton, concrete, cross-laminated timber, and sand-lime bricks) in order to evaluate how and whether results would be influenced by the construction mode. The LCA was performed with SimaPro, using generic data (ecoinvent v3.4, cut-off by classification), and end-of-life scenario's representative for Belgium [6]. More information on the case study, the results on the relative importance of module D on building level (compared to other life cycle modules) and the main materials contributing to module D are presented in a separate publication [7].

An additional goal of the case study was to get a better insight into the practical implementation of module D. For example, can the standard be applied univocally or is it open for interpretation? Is all necessary data readily available to perform the calculations? What kind of hypotheses need to be made? The main methodological issues that were identified through this practical implementation are discussed in the next sections.

4. Results: issues related to the calculation of module D

4.1. Net output flows

In module D, benefits and loads are calculated only for the resulting net output flows (= output minus input) of secondary materials or fuels. The reasoning behind this approach is that secondary materials used as input to the production stage (module A) do not have to carry the impact from primary material extraction/production (which is attributed to the previous life cycle). Consequently, as benefits are already taken into account in the production stage, they cannot be considered again in module D. Moreover, this approach intends to prevent that output flows of secondary materials would be considered to substitute primary materials in a next product system, when the next product system (which is supposed to be identical to the one that generated the waste) is already (partly) using secondary materials in reality. The principle of calculating net output flows is illustrated in **Figure 1**. Case 1 represents the "basic" situation where the secondary material on the input side and the output side are the same (e.g. steel scrap), and the quantity of secondary material at the output side is larger than at the input side.

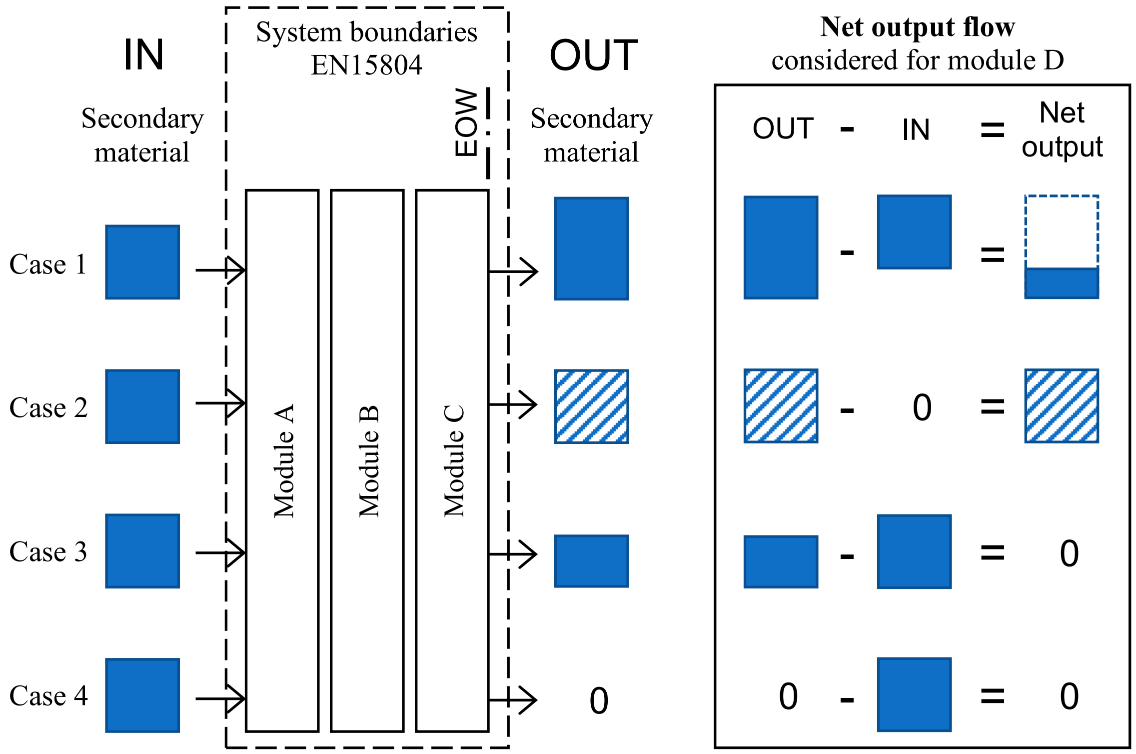

Figure 1. Conceptual representation for the determination of the net output flows depending on the type and quantity of secondary material at input and output side.

This approach for calculating net output flows can however only be applied in closed loop systems. Therefore it leads to an unequal treatment between open and closed loop recycling. Indeed, in open loop systems the secondary materials used as input (e.g. glass cullets for the production of glass wool insulation) are different from the secondary materials exiting the system (e.g. glass wool fibers that can be used as reinforcement for the production of composite materials). Therefore, the amount of secondary materials used as input cannot be subtracted from the output for the calculation of the net output flow (see **Figure 1**, case 2). Consequently, if the impact of the substituted primary material is of the same order of magnitude in open and closed loop recycling, this approach will tend to favor open loop recycling. Indeed, in open loop recycling the amount of net output flow considered for the calculation of module D will be higher since it is not reduced by the input flow of secondary materials.

Apart from clear open and closed loop recycling, there are also many cases where the calculation is open for interpretation. For example, crushed bricks are used as input for the production of a specific type of hollow bricks sold on the Belgian market. At end-of-life those bricks will probably follow the Belgian default scenario for inert waste, namely 95% of recycling into secondary granulates (e.g. for road construction). The nature of the input and output flows are essentially the same (crushed bricks). So in practice a net output flow could be calculated. Nevertheless, the substituted materials (clay in the first system and aggregates in the second system) are different. To our interpretation this should be treated as an open loop (as for case 2).

Another question that can be asked concerning the calculation of the net output flow is what to do in cases where the input of secondary materials is higher than the output (see **Figure 1**, case 3) and therefore the net output flow is negative? One approach would be to multiply the negative flow with the substituted impact from primary production, and therefore report net impacts rather than benefits in module D. However, materials with a recycled content that are disposed of at the end-of-life (e.g. landfill or incineration) could also be considered to have a negative output flow (output = 0, input > 0), but they do not have to report potential impacts from "not" recycling in module D (**Figure 1**, case 4). Moreover, negative output flows are in fact net input flows, while module D is intended to report net output flows of secondary materials (not net input). Therefore, the authors suggest that only positive output flows should be reported in module D.

Table 1. Loads and benefits reported in module D for 1 kg of concrete depending on the point of functional equivalence

Point of functional equivalence	Impacts reported in module D	Benefits reported in module D
OPTION 1 After crushing (recycling plant)	▪ None	▪ 1 kg limestone, crushed
OPTION 2 At (road) construction site	▪ No primary resource ▪ Transport of secondary aggregates to construction site *(30 kgkm by 16ton lorry, EURO5)*	▪ 1 kg Limestone, crushed ▪ Transport of primary aggregates to construction site *(100 kgkm by 16ton lorry, EURO 5)*
OPTION 3 At end-product level (gate of concrete plant)	▪ 1/X[a] m^3 of concrete made with . recycled aggregates (impact of the aggregates = 0 unless some additional crushing is needed) . 385 kg cement /m^3 concrete . 2.11 kg plasticizer /m^3 concrete ▪ Transport of secondary aggregates to concrete plant *(0 kgkm as recycling plant = concrete plant)*	▪ 1/X[a] m^3 of concrete made with . limestone crushed . 380 kg cement /m^3 concrete . 2.08 kg plasticizer /m^3 concrete ▪ Transport of crushed limestone to concrete plant *(100 kgkm by 16 ton lorry, EURO5)*

[a] With X = mass of secondary aggregates /m^3 of concrete

4.2. Point of functional equivalence

Potential loads and benefits reported in module D are calculated from EOW up to the point of functional equivalence where the secondary material/fuel/energy substitutes primary production [2]. Therefore, the determination of the point of the functional equivalence can have a major impact on the loads and benefits reported in module D. A first example is the case of inert materials (e.g. concrete). In Belgium, about 95% of concrete from demolition waste is recycled as aggregates, mainly for use in road construction. EOW is reached after crushing of the demolition waste (at the recycling plant). Once the concrete is crushed it can be used as infill for road construction instead of primary aggregates. For module D, the primary aggregates will thus represent the substituted primary production. However, the determination of the point of functional equivalence is open for discussion. A first option is to set it at the gate of the recycling plant. A second option is to set it at the construction site in order to account for the difference in transport between primary and recycled aggregates (**Table 1**). Indeed, there are many recycling plants in Belgium but only very few quarries. Therefore, primary aggregates are typically transported over larger distances than secondary aggregates. Consequently, although recycled and primary aggregates are technically "equivalent" for use in road construction, one could assume that they are only functionally equivalent once they have reached the new (road) construction site (see option2).

On the other hand, a third option is that the secondary aggregates are to be used as aggregates in concrete (instead of infill in roadbed construction). In this case the point of functional equivalence should be set at end-product level in order to account for variations in concrete mix (e.g. extra cement and superplasticizer) due to the (partial) replacement of primary aggregates by secondary aggregates (see Option 3 in **Table 1**). As can be seen from **Figure 2** the impact from the assumed additional use

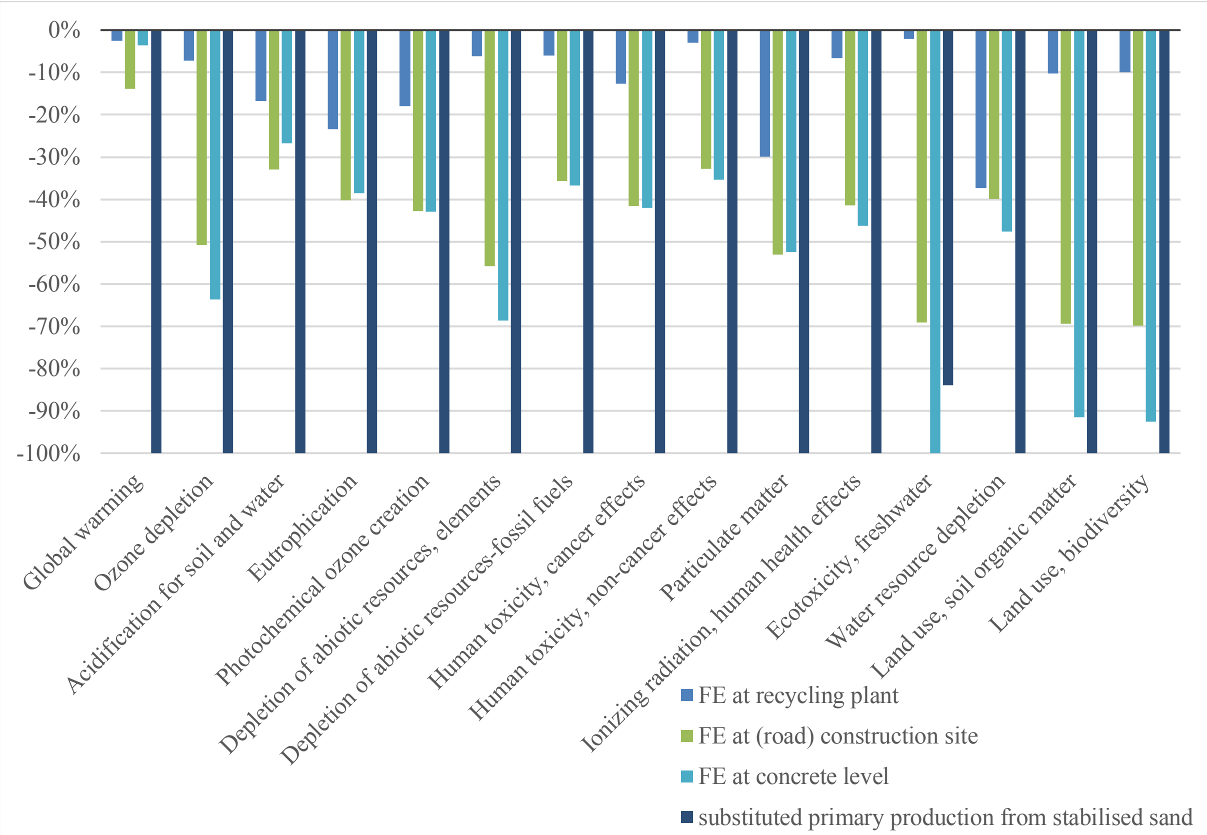

Figure 2. Impacts (net benefits) reported in Module D of concrete when recycled aggregates substitute crushed limestone and the point of functional equivalence (FE) is set at different levels, or when recycled aggregates substitute stabilised sand (MMG v1.05 LCIA model). [8]

of cement leads to a significantly lower net benefit for the impact category Global Warming Potential. Moreover, if the transport of secondary and primary aggregates were equally important, this option could even lead to a net impact instead of a benefit in module D.

Similarly, the case study showed that the outcome of module D of steel products varies significantly depending on whether the point of functional equivalence is set at intermediate product level (sorted steel scrap substitutes pig iron) or at product level (secondary steel substitutes primary steel) in order to account for the lower energy needed to produce steel from steel scrap (with an Electric Arc Furnace (EAF)) than from pig iron (with a Blast Oxygen Furnace (BOF)). Indeed, for most impact categories considered (**Figure 3**) the net benefits reported in module D are higher when the point of functional equivalence is set at the gate of the steel making process. These results are related to the lower energy demand from secondary steel production and in the case of Abiotic Depletion Potential - Elements the possibility to take into account not only the avoided impact from pig iron, but also from alloying elements contained in the steel. However, as the EAF and BOF use different energy mixes (EAF uses mainly electricity, BOF mainly fossil fuels) and produce different types of residues, substituting BOF production by EAF also leads to net impacts for some of the impact categories considered (Ionising Radiation, Ecotoxicity, Human Toxicity, Water Resource Depletion). The small net impacts observed for Abiotic Depletion Potential - Elements for the case where the functional equivalent is set at pig iron level can be explained by the fact that the impact from copper used for the sorting plant is higher than the reported benefit from the substituted pig iron. When the functional equivalent is set at steel level this impact is overruled by the additional benefit from the avoided production of alloying elements (e.g. molybdenite and ferrochromium).

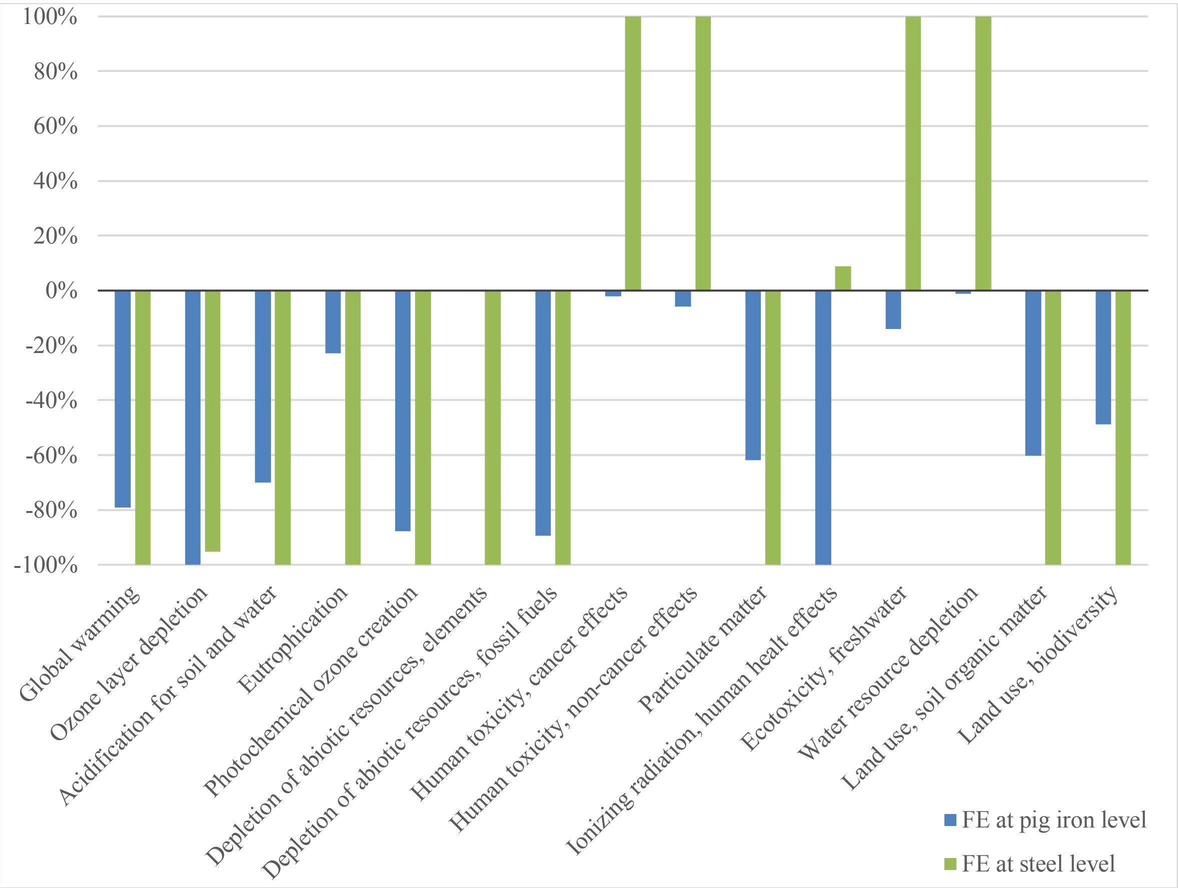

Figure 3. Comparison of module D for 1 kg low alloyed steel with functional equivalency (FE) set before (pig iron level) or after the steel making process (MMG v1.05 LCIA model). [8]

4.3. Avoided "primary" production

The primary production substituted by the use of secondary materials, fuels or exported energy determines which benefits are reported in module D. However, this primary production cannot always be determined univocally: it can be unclear what is actually substituted when the secondary material becomes part of common (usual) practice, the production process based on solely primary resources can be inexistent or the material might be recycled or reused unintentionally as an impurity.

A first example concerns secondary concrete aggregates. The net benefits calculated for module D of concrete in the previous section assumed that the secondary aggregates would substitute primary aggregates. However, in Belgian practice secondary aggregates are always used as infill for road constructions. So, there is some uncertainty related to what they really substitute. Some study suggests that secondary aggregates do not substitute primary aggregates in road construction but stabilized sand [9]. In that case the avoided impact (benefit) reported in module D would no longer be crushed limestone, but a mix of 90% sand and 10% cement. Seen the high impact of cement compared to aggregates, this hypothesis would result in significantly higher net benefits in module D (**Figure 2**).

In some cases, the use of secondary materials affects the production process, or 100% primary production does not exist and therefore needs to be determined artificially. This second example is related to "primary" steel production, where some steel scrap is still used in the BOF. Consequently, the life cycle inventory data of the BOF process have to be manipulated to obtain the (theoretical) impact from a 100% primary production [10]. This could be overcome by allowing the calculation of module D for closed loop systems to be based on the total output flow of secondary materials, provided that the assumed substituted production represents the current average production (with input of secondary materials). Loads reported in module D would in that case also be calculated for the full output flow and in practice this would lead to equivalent results as the net output flow approach with substituted primary production.

A third example concerns the material gypsum installed on inert material (e.g. bricks or concrete). According to the default Belgian scenarios [6], at EOL the gypsum will be crushed together with the inert materials to produce recycled aggregates. Therefore, one could argue that the gypsum (on inert material) substitutes primary aggregates. However, in reality the gypsum reduces the quality of the recycled aggregates and is only tolerated to a certain extent. Consequently, gypsum cannot be considered to be functionally equivalent to primary aggregates and to the author's opinion no benefit from substituted production should be reported in module D.

Finally, the calculation of module D becomes more complex when a waste fraction knows multiple applications (e.g. glass can be recycled as beads for sand-blasting, as secondary aggregates for roadworks, or used as input for glass wool production) and therefore multiple recycling routes have to be modelled and assumptions have to be made concerning the weight for each route. Moreover, although the standard only mentions the benefits from substituted "primary' production, the secondary materials can also substitute other secondary materials in an open loop system (e.g. recycled flat glass cannot only replace sand but also recycled consumption glass in the production of new glass products). Therefore, the benefits reported in module D can also represent the avoided impact from secondary production. This approach is reflected in the formula for module D included in the proposed amendment of the standard [5], which mentions the substituted primary material "or substituted average input material if primary material is not used".

5. Conclusions

"Module D recognises the "design for reuse, recycling and recovery" concept for buildings by indicating the potential benefits of avoided future use of primary materials and fuels while taking into account the loads associated with the recycling and recovery processes beyond the buildings life cycle" [2]. Until now the declaration of module D is optional so there is little experience with the calculation of module D at product or building level. Based on experiences gained from a Belgian building case study including module D as well as from the translation of module D into a formula as part of the EN 15804 amendment, several methodological issues were identified related to the practical implementation and significance of module D. In order to avoid double counting, the potential loads and benefits from secondary materials and fuels are only reported for the net output flows. However, as net output flows can only be calculated for closed loop recycling this leads to an unequal treatment between open and closed loop systems. Results from the study also indicate that assumptions regarding the point of functional equivalence and substituted (primary) production can have a significant impact on the results reported in module D. In addition, the substituted primary production may be difficult to assess when the use of secondary materials is part of the common practice and their use influences the production process. Moreover, in an open loop system, secondary materials/fuels can not only substitute primary materials/fuels but also other secondary materials/fuels.

Uncertainty concerning the potentially avoided impact is not only high because of all underlying assumptions, but also because energy mixes, production processes and demand for secondary materials/fuels are very likely to evolve over the long life span of the building. Consequently, results from module D should always (and especially in comparative LCA) be used with care and interpreted together with the underlying scenarios. Also, in order to avoid unequal treatment within product groups, product technical committees should be encouraged to provide, whenever possible, default scenarios for module D or at least guidance for the identification of the point of end-of-waste, the functional equivalence, and the substituted production.

6. Acknowledgements

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Reconciling recycling at production stage and end of life stage in EN 15804: the case of metal construction products

Leroy C[1], Avery N[2], Tikana L[3], Grund S[4]

[1] METALS FOR BUILDINGS alliance, c/o European Aluminium, Avenue de Tervueren 168, B-1150 Brussels, Belgium, E-mail:
[2] The European Steel Association (EUROFER), Avenue de Cortenbergh, 172, B-1000 Brussels, Belgium
[3] Deutsches Kupferinstitut Berufsverband e.V., Heinrichstraße 24, D- 40239 Düsseldorf, Germany
[4] International Zinc Association, Avenue de Tervueren 168, B-1150 Brussels, Belgium

info@metalsforbuildings.eu

Abstract. With the current political focus on resource efficiency and circular economy, the consideration of all recycling aspects in LCA is becoming increasingly important, especially for metal products which are already recycled for many decades. For such purpose, a complementary module, the so-called Module D, was developed in EN15804 to report the additional environmental aspects resulting from the end of life stage. The metal industry and many LCA practitioners have already used this module for many years. This module D as well as module C (end of life stage) are now mandatory in the agreed amendments to EN15804 that will be published in 2019. This paper explains the methodology used by the metal industry to calculate modules A, C & D for a metal sheet in the light of the equation to be included in the amended EN15804. The calculation is then applied to 3 theoretical examples. Finally, the paper provides guidance on using LCI datasets developed by the steel and aluminium sectors. The collaborating authors have prepared this paper under the auspices of the METALS FOR BUILDINGS alliance that has been established to ensure reliable information on the sustainability of metal building products is available to policy makers and practitioners in sustainability appraisal policies and systems.

1. Introduction

Considering the growing concern regarding resource efficiency and the circular economy, recycling is seen as key enabler to move to a more sustainable European Union. In 2015, the European Commission adopted an ambitious Circular Economy Action Plan [1], which includes measures that will help stimulate Europe's transition towards a circular economy, boost global competitiveness, foster sustainable economic growth and generate new jobs. This action plan has been completed in 2018 by the publication of a circular economy package which includes a Monitoring Framework on progress towards a circular economy at EU and national level.

The waste framework directive [2] [3] is also targeting the building sector in a significant way, since article 11 requires that 70% of EU demolition waste shall be treated beyond 2020. Construction and Demolition Waste (CDW) represents about 30% of the waste flow produced in Europe. Hence, developing a legislation promoting good practices for construction and demolition waste is essential.

As part of its initiative of the single market for green products, the European Commission launched in 2013, the Product Environmental Footprint initiative which aims to harmonise the methodology of assessing environmental performances of products. This PEF methodology was tested during the pilot phase 2013-2018 and it enters now the transition phase where its potential transfer to product policies will be assessed. In particular for the building sector, the European Commission identified the need for closer alignment of CENTC350 standards to the PEF approach before they could be referred to in product policy. The amendment of EN15804, which defines the core rules for environmental product declarations, was a key milestone in this alignment process. The future amended EN 15804 will require calculation of end of life stage and environmental aspects of reuse, recycling and recovery in the context of the circular economy.

In the coming years, the Construction Product Regulation [4] will require in addition to technical information also environmental information related to building products when Basic Work Requirement 7 addressing the “sustainable use of natural resources” will be implemented in harmonised European standards.

All these legal and market developments show that it is of prime importance to properly consider the recycling aspects of building products when assessing life cycle environmental impacts.

2. Metals in buildings: key enabler to circularity

Metals are used in the building and construction sector for structures, reinforcements, cladding, roofing, window frames, plumbing, heating equipment and many other applications. Due to their high strength and high stiffness, metals can bear high loads, be used to reinforce other materials or can span great distances, allowing design freedom. Metal building products are weatherproof, seismic proof, corrosion resistant and immune to UV rays, ensuring a long service life. Most often, metal building products will satisfy the service life of the building itself.

In addition to their technical properties, metal products have also a unique characteristic which is their ability to be efficiently and economically reused or recycled without altering their properties. Already, today, more than 95% of the metal products used in buildings are collected at end-of-life. As an example, a study [5] performed on several demolition sites in Europe has demonstrated that more than 96% of the aluminium-content of these buildings was selectively collected and sent to recycling facilities. A survey carried out among UK demolition contractors [6] has shown that 99% of steel sections are recycled or reused.

High economic value is the main driver for the systematic dismantling, collection and recycling of metal products. As metal recycling provides energy savings of between 60% and 95% compared to primary production [7][8][16], depending on the metal and the metal-bearing product, metal recycling creates a win-win situation for both the environment and the economy.

3. Recycling in LCA and metals products

Today, two contrasting approaches are generally used to tackle recycling aspects: the recycled content approach [100:0] and the end of life recycling approach [0:100].

On one hand, the recycled content approach [100:0] uses a cut-off approach, which only considers the recycled material in the mass fraction of the product issued from recycling. This approach neglects the recycling performances of the product at the end of its life stage. Even though the end of life recycling rate of metal building products is usually high, e.g. around 90%-95%, the average recycled content in metal products does not reach such a level on a global scale. In reality, the recycled content is currently limited by the scrap availability which is the bottle neck of the metal supply from recycled sources. The growth in the use of metals over many years, and the fact that metal building products have a service life of decades, creates a shortage of available metal scrap that has to be supplemented using primary metals to satisfy demand. As an example, the crude steel production in Europe for the year 2017 [9], excluding imports, was 168,1 million tonnes, from which about 93,35 million tonnes were coming from scrap, i.e. from recycling. This shows that on average about 55% of the steel supply comes from recycled steel scrap. Thus, the recycled content metric alone is not adequate to reflect and integrate the recycling performances of metal products in an EPD.

On the other hand, the End-of-Life (EoL) recycling approach [0:100] considers the recycling rate of the studied product as the relevant parameter for tackling the environmental aspects of recycling. For metal products, the recycling rate corresponds to the actual amount of metals obtained from recycling with the amount of metal initially available within the product. The metal industry considers that this end of life recycling approach is the most relevant for metal products in order to maximise and preserve metal availability for future generations as explained in the common Metals Declaration on Recycling [10], published in 2006. This end of life recycling approach is also accepted in the scientific community as UNEP [11] and ILCD [12]. Under PEF, the circular footprint formula considers a contribution of the end of life recycling parameter for metals which is four times more relevant than the recycled content. This ratio demonstrates the higher relevance of the recycling rate metric for metals.

4. Recycling in EN15804: the hybrid approach

The cut-off approach was chosen for the Module A (production), Module B (use) and Module C (End of life stage) of EN15804 [13] meaning that the recycling benefits of building products at end of life cannot be reported in those modules. An additional module, the so-called 'module D', was therefore needed for transparently reporting the additional benefits which result from the recycling or energy recovery at the end of life of the building product. For closed material loop recycling, as in the case of metals, Module D avoids any double crediting or counting since only the net benefits of recycling are reported based on the net flow, i.e. the secondary material exiting the system boundary at the end of life minus the secondary material already considered at the production stage. Module D is not restricted to metal scrap, as it allows reporting the environmental aspects from the net flow resulting from any secondary material or secondary fuel entering and exiting the product system boundary. Description of an exemplative metal sheet case

Fig.1 gives an example of one possible scenario for a metal sheet. It provides the various flows of scrap, metal semi-finished product and product as well as the main processes included in the system boundaries of the various modules. In this example, it is assumed that the unit of analysis is 1 kg of metal sheet with a recycled content of 40%, i.e. 0,4 kg of metal sheet came from recycling, while the recycling rate at end of life corresponds to 90%, i.e. 0,9 kg of recycled metal is produced at end of life. In such a case, Module D shall calculate the environmental benefits resulting from the production of 0,5 kg of recycled metal, i.e. the net difference between both recycled quantities. The next sections explain how the equation reported in Annex D of the new EN15804 shall be interpreted and used to reflect this example and the associated flow sheet.

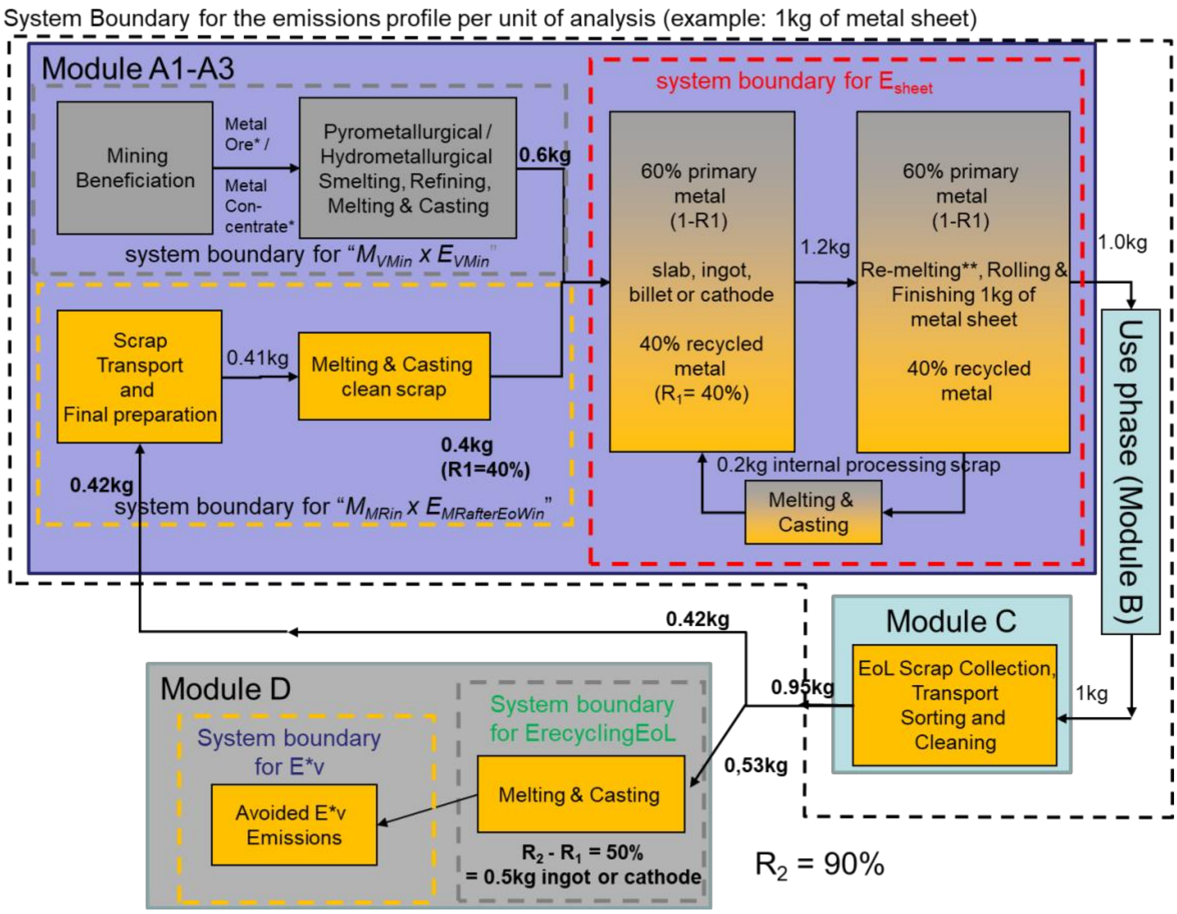

Fig. 1: Illustrative example of a flow diagram for a metal sheet

4.1. Module A1-A3

The applicable formula for the calculation of the emissions and resources consumed related to material resources and energy per unit of analysis for module A is the following:

$$e_{module\ A} = e_{PE} + M_{VM\ in} \cdot E_{VM\ in} + M_{MR\ in} \cdot E_{MR\ after\ EoW\ in} + M_{ER\ in} \cdot E_{ER\ after\ EoW\ in}$$

Where the first term covers the impacts related to primary energy inputs, the second term covers the impacts related to material primary inputs; the third term covers the impacts related to recovered material (recycled and reused) inputs from previous products and the last term covers the impacts related to use of secondary fuels. All terms are calculated per unit of analysis. For metal products, the second and third terms are the 2 most relevant ones.

$M_{MR\ in}$ represents the metal scrap input to the product system at the production stage. In our example, it corresponds to 0,42 kg of metal scrap entering the production stage. After a possible final cleaning and treatment operation, this scrap flow is melted, purified and casted in order to produce a metal ingot. These operations generate small metal losses so that the mass of the recycled ingot is slightly lower than the mass of metal scrap entering the system, i.e. 0,4 kg of recycled ingot in the example. This recycled ingot then needs to be converted into a metal sheet. Hence, "$M_{MR\ in} \cdot E_{MR\ after\ EoW\ in}$" shall cover the specific emissions and resources for producing 0,4 kg of metal sheet issued from recycling. Similarly, "$M_{VM\ in} \cdot E_{VM\ in}$" represents the specific emissions and resources for producing 0,6 kg of metal sheet issued from primary resources.

In practice, the point of substitution, i.e. the location in the production chain where recycled metal substitutes primary metal, is usually at the ingot level or cathode level for the specific case of copper [16]. Hence, often, the LCI datasets developed by the metal industry cover the primary processes or recycling processes up to the ingot level. The manufacturing of the metal sheet from the ingot can then be covered either by a separate LCI dataset (i.e. see aluminium LCI datasets) or aggregated with the ingot production (see steel LCI datasets). In the case of separate LCI datasets, the equation for "Module A1-A3" can be adapted for metal sheet as follows:

$$e_{module\ A} = (1 - R_1) \cdot E_v + R_1 \cdot E_{recycled} + E_{sheet} \text{ where:}$$

- R_1 percentage of recycled content of the metal sheet, i.e. fraction of metal issued from recycling
- E_v specific emissions and resources consumed per unit of analysis arising from acquisition and pre-processing of primary metal in the production of the metal ingot or cathode.
- $E_{recycled}$ specific emissions and resources consumed per unit of analysis arising from sorted metal scrap recycling of the previous system into metal ingot or cathode.
- E_{sheet} specific emissions and resources consumed per unit of analysis arising from the transformation of the metal ingot/cathode into the metal sheet.

For the module A1-A3 calculation, 60% of the metal supply is issued from primary metal and 40% from recycling. Hence, the equation can be simplified as follows for the exemplative case.

$$e_{module\ A} = 0{,}6 \cdot E_v + 0{,}4 \cdot E_{recycled} + E_{sheet}$$

The sheet manufacturing from the metal ingot generates some internal scrap which is re-melted but does not increase the recycled content in the LCA model of the overall product, since the recycled content has already been 'fixed' in the slab production process, and the subsequent scrap generated is an internal flow in the overall product system model.

4.2. Module C

The applicable formula for the calculation of the emissions and resources consumed per unit of analysis for module C is the following:

$$e_{module\ C} = M_{MR\ out} \cdot E_{MR\ before\ EoW\ out} + M_{ER\ out} \cdot E_{ER\ before\ EoW\ out} + M_{INC\ out} \cdot E_{INC} + M_{LF} \cdot E_{LF}$$

For metal sheets, the first term is the most significant since it is almost entirely collected and directed to recycling. At end of life, metal sheets are dismantled and specifically collected for recycling. These operations take place under module C1. The collected metal sheet is directed to specialised companies for shredding and sorting (module C3). In the context of EN15804, it can be considered as most appropriate that sorted metal scrap leave the system boundary and are addressed in Module D. It should be noted that there is no full harmonisation among the European countries regarding the application of the "End of Waste" status to metal scrap. Hence, from a legal perspective, the official "end of waste" status may be located at a different point in the recycling value chain.

In our exemplative case, it will be assumed that 99% of the metal sheet is collected and directed to the scrap preparation treatment from which 0,95 kg of sorted scrap is generated and directed for recycling. Hence, 0,95 kg of sorted scrap exits the product system from module C3. Only a tiny fraction can end up in landfilling from the scrap preparation operations.

4.3. Module D

As described in section 6.4.3.3 of EN15804, Module D aims at assessing the benefits and loads resulting from the net flow of secondary fuels or materials exiting the product system. The environmental aspects of these flows are assessed through system expansion using the so-called "substitution methodology" or "avoided impact" methodology. In such methodology, the secondary material needs to be processed up to the point of functional equivalence where substitution of primary material takes place. In the case of metal sheet, the point of equivalence is the ingot or the cathode for copper. Hence, module D calculation needs to consider on one side the burdens of the recycling processes up to the ingot or cathode level while the benefits are calculated by the burdens of primary metal which is effectively saved. If needed, a correction factor may be applied when full substitution cannot take place, i.e. when properties are not maintained through recycling.

For metal sheet, the applicable formula for the calculation of the loads and benefits beyond the system boundary per unit of output calculated for each output flow leaving the system boundary can be restricted to Module D1 related to secondary materials for recycling: For the metal sheet case, only one metal is considered. Hence the indice "i" is not necessary. A as result, the equation can be simplified as follows:

$$e_{module\ D1} = (M_{MR\ out} - M_{MR\ in})\left(E_{MR\ after\ EoW\ out} - E_{VMSub\ out.} \cdot \frac{Q_{R\ out}}{Q_{Sub}}\right)$$

- "$M_{MR\ out}$" is the quantity of sorted scrap exiting the product system, i.e. 0,95 kg in the example.
- "$M_{MR\ in}$" is the quantity of sorted scrap entering product system, i.e. 0,42 kg in the example.
- "$M_{MR\ out} - M_{MR\ in}$" represents the net quantity of sorted scrap generated by the product system, i.e. 0,53 kg of scrap.
- $E_{MR\ after\ EoW\ out}$ corresponds to the specific emissions and resources arising from the recycling at end of life of the sorted scrap up to the ingot. For the metal sheet case, it will be called $E_{RecyclingEoL}$.
- $E_{VMSub\ out}$ is specific emissions and resources consumed per unit of analysis arising from acquisition and pre-processing of the primary material from cradle to the ingot. For the metal sheet case, it will be called E_v^*.
- $\frac{Q_{R\ out}}{Q_{Sub}}$ is the quality factor between recycled ingot and primary ingot. For metals, the properties are restored through re-melting.. In the building market, only a limited number of metal alloys or grades are used. In addition, collection and scrap preparation routes from end of life metal building products are well developed. These routes generate high quality scrap with low level of contamination. Hence, it can be assumed that recycled metal is of equivalent quality as the primary metal, i.e. that the quality factor is equal to one.

For the metal sheet case, the net quantity of scrap can be substituted by the difference between the recycled metal at end of life and the recycled metal content at production, i.e. (R2 - R1) *1kg = (0,9 – 0,4)*1kg =0,5 kg under the condition that $E_{RecyclingEoL}$ and E_v^* use the mass of produced ingot or cathode as the reference flow, i.e. the process output, and not the scrap input as a reference flow. This assumption will be used for the 3 fictitious examples so that the equation is simplified as follows:

$$e_{module\ D1} = (R_2 - R_1) \cdot (E_{recyclingEoL} - E_v^*) = 0{,}5 \cdot (E_{recyclinEoL} - E_v^*)$$

5. Calculation for 3 theoretical examples

The first example (Product "P1") considers the metal sheet case as described in the previous section, using a recycled content of 40% and an end of life recycling rate of 90%. The second example (Product "P2") considers a generic product, not necessarily a metal product, which is produced mostly from secondary materials (R_1 =80%) but which is not efficiently recycled in closed loop at end of life, i.e. R_2 = 40%. Finally, the third example (Product "P3") corresponds to a product made 80% of recycled material and which is recycled at 80% at end of life according to two scenarios, either in pure closed loop (scenario A) or in an open loop recycling with downcycling (scenario B).

Table I reports fictitious figures expressed in "Units of Indicator" [UoI] for the various processes listed for the previous simplified equations as well as the corresponding results for Module A1-A3, Module C and Module D. For Module C, only the sub-modules C3 and C4 play a differentiating role in the 2 scenarios of P3. Hence, only these 2 sub-modules are addressed in Table I

Table 1: equation parameters and [Unit of Indicators] for the 3 theoretical product examples

Parameters and process	Module A				Module C		Module D		
	R_1	E_v	$E_{recycled}$	E_{sheet}	C3	C4	R_2	$E_{recylingEoL}$	E_v^*
Unit	%	[UoI]	[UoI]	[UoI]	[UoI]	[UoI]	%	[UoI]	[UoI]
P1	40%	40	10	5	2	1	90%	10	40
P2	80%	40	10	5	2	3	40%	10	40
P3 - scenario A - closed loop	80%	30	20	0	4	1	80%	20	30
P3 - scenario B - open loop	80%	30	20	0	2	1	80%	5	10

<table>
<tr><th>Results</th><th>Module A</th><th>Module C</th><th>Module D</th></tr>
<tr><td>Equation</td><td>$(1-R_1).E_v+R_1.E_{recycled}+E_{sheet}$</td><td>C3+C4</td><td>$(R_2-R_1)\cdot(E_{recyclingEoL}\ -E_v^*)$</td></tr>
<tr><td>Unit</td><td>[UoI]</td><td>[UoI]</td><td>[UoI]</td></tr>
<tr><td>P1</td><td>33</td><td>3</td><td>-15</td></tr>
<tr><td>P2</td><td>21</td><td>5</td><td>12</td></tr>
<tr><td>P3 - scenario A</td><td rowspan="3">22</td><td>5</td><td>0</td></tr>
<tr><td>P3 - scenario B-1*</td><td rowspan="2">3</td><td>-4</td></tr>
<tr><td>P3 - scenario B-2**</td><td>4</td></tr>
</table>

*R_1 is not considered for the net flow calculation of module D as allowed in EN15804

**R_1 is considered for the net flow calculation of module D as recommended in ISO14044

P1 - Assuming values of 40 [UoI] for the primary production of 1 kg of ingot, 10 [UoI] for the production of recycled ingot from sorted scrap and 5 [UoI] for the transformation of 1 kg of ingot into sheet, the module A equation gives a result of 33 [UoI] for module A1 to A3 for 1 kg of metal sheet. Module C does not contribute significantly to the overall results. It is assumed that the scrap preparation of 0,95 kg of sorted scrap (module C3) contributes for 2 [UoI]. Landfilling contributes for 1 [UoI]. For the calculation of module D, similarly to the production phase, it is assumed that the recycling of sorted end of life scrap into 1 kg of ingot generates 10 [UoI] and the avoided primary production of 1 kg of metal ingot corresponds to 40 [UoI]. This provides a complementary result of -15 [UoI] for Module D reflecting the additional benefits resulting from the end of life recycling.

P2 –The same [UoI] figures are assumed as for P1, except for Module C, for which the contribution of landfilling is higher than for P1 considering the higher fraction going to landfilling. A value of 3 [UoI] is used for the landfilling impact. The Module A calculation provides 21 [UoI]. It is lower than for P1 due to the higher recycled content. The calculation of Module D provides a positive [UoI] due to a negative net flow of secondary materials entering Module D. The consumption of 40 % of recycled material generates then an additional impact of 12 [UoI] for module D.
Comparing P1 and P2 results, P2 appears as a better when using the recycled content approach, i.e. Module A + Module C, providing 26 [UoI] for P2 against 36 [UoI] for P1. However, from a full life cycle perspective which considers as well the additional benefits from end of life, the conclusions are reversed, i.e. 21 [UoI] for P1 against 36 [UoI] for P2. This shows the importance to consider Module D in the product assessment. It should be noted that EN15804 does not allow aggregation of results across modules. Hence, this aggregation is done for the sake of illustration and explanation but is not according to EN15804.

P3- For the sake of simplicity, E_{sheet} is not considered in this example (i.e. E_{sheet} = 0 [UoI]). For the closed loop case (scenario A), it is assumed that $E_{recycled}$ and $E_{recyclingEoL}$ are identical and correspond to 20 [UoI] while E_v and E_v^* are also the same processes and correspond both to 30 [UoI]. For module C3, i.e. preparation for recycling, a figure of 4 [UoI] is assumed.

For the open loop recycling with downcycling (scenario B), it can be assumed that ErecyclingEoL is less impacting than the closed loop case, i.e. a value of 5 [UoI] is used. Similarly, Ev* is also smaller since the substituted primary material is of lower quality/performances in case of downcycling than in case of closed loop recycling. A figure of 10 [UoI] is used for Ev*. For module C3, the preparation for recycling is less demanding than in case of closed loop recycling. Hence, 2 [UoI] is chosen for C3. For Module A, the calculation gives a figure of 22 [UoI]. For Module C, scenario A gives 5 [UoI] while the open loop with downcycling (scenario B) gives 2 [UoI]. Without considering Module D, the results for Modules A and C provide a lower impact to the open loop recycling with downcycling (scenario B) in comparison to the closed loop. In such a case, not considering Module D, will clearly lead to misleading choices which are against the most environmentally sound end of life practices.

In case of closed loop recycling (Scenario A), the module D is equal to 0 [UoI]. In absence of any recycled materials generated or consumed by the product system, a value of 0 [UoI] is indeed calculated for module D. In such a case, there is indeed no discrepancy between the recycled content and the end of recycling rate.

In case of open loop recycling (scenario B), it can be assumed that the secondary materials entering the system are not similar to those exiting the system. Hence, a net flow calculation via a direct deduction does not make sense. In such a case, the current formulation requires to calculate the net flows only for the secondary materials exiting the system. This means that the secondary materials entering the product system can be neglected in the calculation of Module D if its characteristics are significantly different from the characteristics of the secondary materials exiting the product system.

In the case of Scenario B-1, the entering flow of secondary materials has been neglected. This gives a benefit of - 4 [UoI] which results from a double crediting of the recycling benefits from the recycled content at production and from open loop recycling at end of life. From a calculation perspective, this open-loop recycling scenario B1 appears then as the most relevant for reducing the overall impact of the product life cycle while in reality, it is not the case, since the closed loop recycling provides better environmental results. The current lack of requirements to address all entering flows of secondary materials and fuels generate then results which can be misleading and which create discrimination against closed loop recycling vs. open loop.

In the case of scenario B-2, the calculation is corrected and the benefits from the recycled content are considered, leading to a result to +4 [UoI] for module D reflecting the effective downcycling at end of life. In other words, the product system consumes high quality secondary materials at production stage without generating them back at end of life. This second calculation shall be systematically used for Module D to properly reflect the additional contribution (benefits or burdens) of the end of life stage to the product life cycle assessment and to avoid misleading calculation wrongly promoting downcycling. The equation should then be adapted accordingly in any future revision of EN 15804.

6. Using datasets developed by the metal sector

Table 2 reports the LCI datasets which can be used in the context of EN15804 and building applications. Further explanations are then given for the 2 metal cases: Aluminium and steel.

Table 2. Aluminium and steel LCI datasets for use in EN15804

Module	Formula in EN 15804	Metal datasets corresponding to EN 15804 formula terms assuming 1kg sheet product	
		Aluminium	Steel
A	$M_{VM\,in} \cdot E_{VM\,in}$ + $M_{MR\,in} \cdot E_{MR\,after\,EoW\,in}$	R_1 x [wrought ingot from pre-consumer scrap or clean post-consumer scrap] + (1-R_1) x [primary ingot produced (or used) in Europe - cradle to gate] + [sheet produced from wrought ingot]	Aggregated cradle to gate LCI for 1kg steel sheet containing recycled and primary steel e.g. "Cold rolled coil" or "Continuous Hot Dip Galvanised coil"
D	$(M_{MR\,out} - M_{MR\,in})\left(E_{MR\,after\,EoW\,out} - E_{VMSub\,out} \cdot \frac{Q_{R\,out}}{Q_{Sub}}\right)$	(R_2-R_1) * ([ingot from post-consumer scrap] - [primary ingot produced (or used) in Europe - cradle to gate])	$(M_{MR\,out} - M_{MR\,in})$ * [Value of scrap LCI], i.e. LCI result using 100% scrap based EAF slab minus theoretical 100% primary slab.

6.1. Aluminium sheet

Every 5 years, *European Aluminium* develops average datasets representative for the European production or market. The latest datasets published in Feb 2018 refer to data collected for the year 2015 [8]. The datasets listed in Table 2 are included in this report, i.e.

- [primary ingot produced in Europe - cradle to gate] (A) corresponds to the production of 1 tonne of ingot from primary aluminium, i.e. from bauxite mining up to the sawn aluminium ingot ready for delivery. This dataset includes all the environmental aspects of the various process steps and raw materials used to deliver 1 tonne of sawn primary ingot produced by the European smelters.
- [primary ingot used in Europe - cradle to gate] (B) is similar to the previous dataset but considers as well the primary aluminium which is imported into Europe and which represent 49% of the primary aluminium used in Europe in 2015. Global data from the International Aluminium institute [14] have been used for modelling the primary aluminium produced outside Europe.

  If the use of average European LCI datasets is appropriate, these two datasets can be used for assessing E_v or E_v^*. The choice between both datasets should then be based on the sourcing of the primary aluminium. In case of evidence of domestic European production, the dataset (A) should be used. If not, the dataset (B) should be used.
- [sheet produced from wrought ingot] This dataset corresponds to the transformation of a sawn aluminium ingot into a sheet ready for delivery to the user. This dataset includes the recycling of the scrap and chips generated during the sheet production stage and corresponds to the production of 1 tonne of aluminium sheet. This dataset can be used to assess E_{sheet}
- [wrought ingot from pre-consumer scrap or clean post-consumer scrap] corresponds to the production of 1 tonne of recycled wrought ingot, i.e. slabs or billet, from process scrap or clean sorted post-consumer aluminium scrap like big aluminium pieces in the building sector or aluminium beverage cans collected through specific collection networks.
- [ingot from post-consumer scrap] corresponds to the production of 1 tonne of casting ingot from pre- or post-consumer scrap

6.2. Steel sheet

The World Steel Association, *worldsteel*, provide global and regional average data for up to 16 different semi-finished steel products [15]. The *worldsteel* modelling approach employs vertical averaging incorporating the slab and sheet production emissions specific to the individual product supply chains. For this reason, it is not necessary to split the data into slab and sheet, since the datasets already correspond to the result of:

$$(1 - R_1) \cdot E_v + R_1 \cdot \ E_{recycled} + E_{sheet}$$

The construction related sheet LCI products available, depending on the region, include: plate, hot rolled coil, cold rolled coil, hot dip galvanised, organic coated coil, and welded tube. Long products, such as sections and rebar are also available, similarly including further rolling and processing as for sheet production. The value for R1 is specific to the product supply chain and steel production process and provided in the datasets as a scrap input flow (external scrap). This excludes scrap recycled internally within the product supply chain and any re-melting losses, and so is no equivalent to the recycled content as such. The scrap input flow can be used to calculate the net scrap flow to avoid double accounting in Module D.

Due to the fact that all steel slab production includes some scrap, it is necessary to make a theoretical 100% primary slab without any scrap input. This has been modelled and calculated by worldsteel and is used with the corresponding 100% secondary slab to calculate the net environmental benefit of recycling 1kg of pre and post-consumer scrap, called the ['Value of scrap' LCI]. A yield factor is used to account for any scrap input or output that is lost during the re-melting due to the presence of non-target material in the scrap and metallic re-melting losses in e.g. fume dust. This means that the EN 15804 formula for Module D can be directly applied since on one side $(M_{MR\ out} - M_{MR\ in})$ corresponds to the next flow of scrap generated by the product system and on the other side $\left(E_{MR\ after\ EoW\ out} - E_{VMSub\ out.} \cdot \frac{Q_{R\ out}}{Q_{Sub}}\right)$ corresponds to ['Value of scrap' LCI],

i.e. = $yield \cdot \left(100\%\ secondary\ slab - 100\%\ theoretical\ primary\ slab \cdot \frac{1}{1}\right)$

Module D = $(M_{MR\ out} - M_{MR\ in})$ * ['Value of scrap' LCI]

7. Conclusion

In 2016, the European Commission requested an amendment to EN 15804 in order to ensure a convergence with the Environmental Footprint methodology, and in particular to make mandatory Modules C and D, which address the end of life stage. This development will bring renewed focus on recycling aspects of construction materials, which is an important aspect if the construction industry is to reduce waste, increase resource efficiency and become more circular. This paper shows the importance of considering the quantity and quality of recycling at end of life, and why the only focus on recycled content is insufficient. End of life recycling is not only relevant for metals, due to the increasing demand for materials and a limited supply of available secondary materials, but also other materials. The new proposed formula for Module D in the future amended EN 15804 has been applied to a series of 3 examples, to demonstrate the way both recycled content and end of life recycling are reconciled in a hybrid approach, thus ensuring a full picture of circularity over the lifecycle. The paper also highlights potential pitfalls in the interpretation of the wording of EN 15804, and so users of the standards should play particular attention to situations where net losses of valuable material resources from the system occur, or where changes in the quality of materials take place. This is important in order to avoiding double accounting recycling benefits at the beginning and end of the lifecycle, especially in open loop recycling situations. The paper also offers guidance to users in applying the available steel or aluminium average LCI datasets for the calculation of Modules A1-A3 and Module D.

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Declaration of the End-of-Life for Building Products

Trinius W, Goerke J

Ingenieurbüro Trinius GmbH, Barmbeker Str. 9a, 22303 Hamburg, Germany

thinkstep AG, Hauptstraße 111 – 113, 70771 Leinfelden-Echterdingen, Germany

trinius@trinius.de

Abstract. Increasing energy efficiency and related environmental performance improvements of buildings direct stronger focus on the environmental impacts related to building products. For product manufacturers, the provision of information in terms of environmental product declarations (EPD) is a market tool of continuously rising importance.
The increasing concern related to environmental and resource efficiency promotes the concept of circular economy, especially reuse and recycling procedures at the end-of-life (EoL) play an increasing role in decision making. Manufacturers are often unsure how to include late life cycle stages in their product declarations. At the same time users of the information are confused as to what provided information really refers to.
The concept of modular EoL-declarations with clearly identified and described scenarios aims to facilitate the inclusion of the full life cycle in EPDs based on reliable and realistic data. At the same time EoL-declarations promote the communication between the production and EoL-actors and enhance understanding of provided information, including judgements on potential demand and procedures for adaptation of provided information.

1. Introduction

Buildings account for 36% of global final energy consumption and nearly 40% of total carbon emissions [1] [2]. Construction and demolition waste accounts for 25 to 30% of all waste generated in the EU [3] an equally large share of the overall figures. The savings potential in the building sector is therefore considered to be high, according to government and industry.

In recent years, certification systems for sustainable buildings have been established, including DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen e.V.) [4] and LEED (Leadership in Energy and Environmental Design) [5], providing a framework for improving sustainability in the construction sector. Within these certification schemes, a building Life Cycle Assessment (LCA) can be conducted as a means to evaluate the environmental performance of the building over its life cycle. To enable the architect or planer to calculate such a building LCA, it is essential to have access to environmental information for specific construction products. The concept of Environmental Product Declaration (EPD) in accordance with EN 15804 [6] has been established as an important instrument for declaring and communicating the environmental performance of the different building products in the context of a building LCA.

Furthermore, product manufacturers use EPDs in order to communicate environmental product information both internally and externally. With the increasing recognition of resource efficiency, end-of-life information is becoming more frequently requested and provided, leading to the clear demand to strengthen common practice in providing and applying such information.

2. Environmental Product Declaration (EPD)

An EPD is a document that communicates verifiable, accurate, non-misleading environmental information about products and their applications, thereby supporting scientifically based, fair choices and stimulating the potential for market-driven continuous environmental improvement. The results of a life cycle assessment (LCA) in accordance with ISO 14040/44 [7] [8] are declared in an EPD as impact (category) indicators, such as: global warming potential, acidification potential, primary energy and water consumption.

EPD information is expressed in life cycle stages and subdivided into information modules, which facilitates a coherent structure and expression of data packages throughout the life cycle of the product [6]. The modular structure groups significant life cycle stages into product stage (A1-A3), delivery and installation in the construction stage (A4-A5), use stage (B1-B7) and end of life stage (C1-C4). Additionally, benefits and loads from, for example, recycling or thermal treatment, can optionally be declared in module D. Figure 1 gives an overview of the stages and modules covered by an EPD according to EN15804 [6].

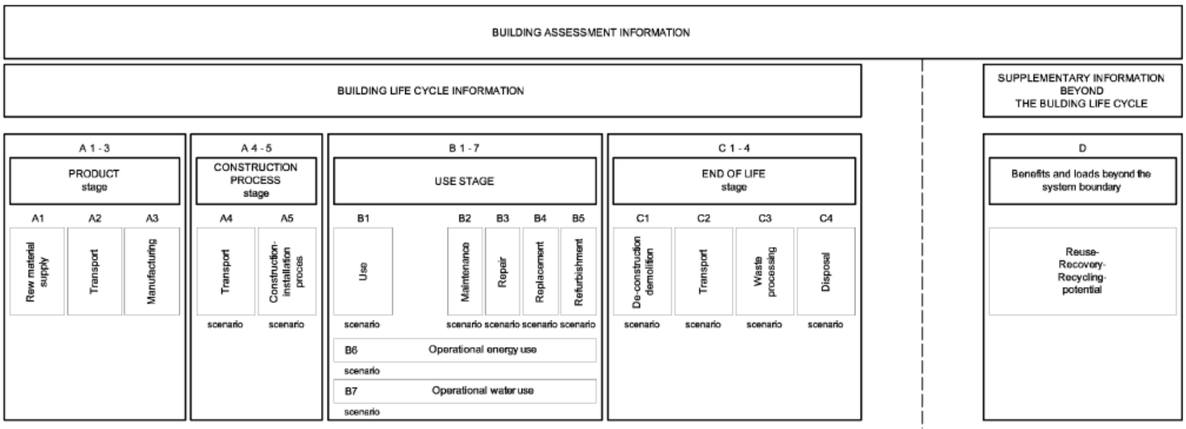

Figure 1 Life cycle stages and modules according to EN 15804

Today, most EPDs focus on the production stage (modules A1-A3 according to EN 15804 – "cradle to gate"); the subsequent modules are included less frequently. Frequently mentioned reasons for focusing on the initial life cycle stages include aspects such as the manufacturers direct involvement and responsibility through to the hesitance to include scenario-based information about later life cycle stages in a declaration for which the manufactures may be held liable. The declared environmental product performance may as well depend significantly on aspects well outside the influence of the manufacturer. Instead user-related aspects (e.g. frequency of product application) or contextual systems (e.g. changes in the energy supply system, or technologies being replaced in situations of changing demand) may have a significant or even decisive influence on the declared information. Consequently, the content of such an EPD may vary between scenarios.

While the loss of the generic value of the presented information may be considered a drawback, scenario-based information can also strengthen the quality of the information provided in an EPD, as the information may be adapted to case-specific boundary conditions, and scenario parameter variations may demonstrate the dependency and sensitivity of declared information to selected parameters.

3. Scenarios in Environmental Product Declarations

One way to declare the subsequent life cycle stages to A1-A3 in an EPD is to use a scenario. Scenarios support the calculation of information modules covering processes that deal with any one or all of the life cycle stages of the construction product, including the end-of-life. In order to define such a scenario, EN 15804 does not give further specifications but generally states that a scenario shall be realistic and representative of one of the most probable alternatives. Thus, currently it is the responsibility of the owner of an EPD to specify the scenario and declare these modules. To make informed decisions about scenarios, EPD owners need access to reliable and realistic data.

For the modules of the product stage (A1-A3) and installation (A4 - A5), manufacturers rely on their own data or generic data. Generic data describe processes that could, in principle, be traced back to the provision of raw materials and thus, for example, reflect the entire upstream chain of raw material or energy generation.

For the end-of-life, there are two processes/scenarios commonly included/described in EPDs: landfill and waste incineration (for production and post-consumer waste). For recycling, generic datasets for common recycling processes – e.g. steel or aluminum recycling – are available. But if a specific recycling process is to be declared in an EPD, then appropriate information for the recycling scenario must be available – often, this is not the case. In the context of circular economy and the promotion of recycling, it is important to close that gap and to enable manufacturers to address the complete life cycle in their declarations. Consequently, to enable manufacturers, they need to have access to robust data to develop reliable partly scenario-based EPDs. Such data, however, can only be obtained from the waste management and recycling industry. There is, thus, an information gap between the manufacturer at the beginning of the product's life cycle and the actors at the end-of-life of the building. The situation is complicated further by the necessity to identify substances and boundary conditions that might have an influence on the applicability or the efficiency of the processes involved in an end-of-life route such as the impurities or harmful components that might influence choice and applicability of an EoL route.

4. End-of-Life Declarations (EoLD)

With the aim of supporting the modelling of the entire life cycle in the context of a (real/true) circularity of buildings the research project: Resource efficient buildings - EPD for construction products: dismantling and recycling information (Module C and D) including hazardous substances funded by the German Federal Environment Agency (Umweltbundesamt, UBA) has started in 2017. Within this research project, the idea of an End-of-Life Declaration has been developed in order to close the information gap between manufacturer and the stakeholders at the end-of-life of the building.

An End-of-Life Declaration (EoLD) calls for the recycling and disposal industry to provide specific data in a form and format that can be integrated in a building product EPD according to EN 15804, which provides the modularity needed for the building LCA. In this way, all actors for production, use and disposal can be liaised. For waste collectors or recyclers, one benefit of declaring environmental information for the end-of-life procedure in an EoLD is the ability to present the environmental quality of their processes in a "readable" and EPD-compliant manner to the manufacturer. Recyclers can thus also describe the input conditions for the respective recycling process in terms of pollutants and impurities. Such information is essential for the correct choice of a scenario and can also be very helpful for producers by enabling the optimization of the product content in the context of better recyclability.

Within the research project, the format of the EoLD has been defined and aligned with the EPD format and content. The EoLD contains company specific, technical and LCA relevant information. It gives a description of the EoL route and the materials and conditions in which the material is accepted by the waste treatment companies. The LCA results are declared in the same systematic as in an EPD in order to link both documents in a consistent way.

The aim of the EoLD is mainly to promote information exchange between stakeholders over the life cycle of a product. By opening lines of communication during the creation of a product EoLD, actors are presented with opportunities to improve their stage of the product life cycle: from design to installation, disassembly, and waste treatment at the product end-of-life.

An EoLD should include a realistic selection of waste treatment at the end-of-life stage of a building or product, enabeling comparing recycling processes with landfill and incineration on the basis of reliable and specific information. To define the end-of-life treatment process for a product, producers must communicate with waste processors to find out which treatment processes are proven to be economically and technically feasible. On the other end, producers must decide, when defining an EoL scenario scope for a product, how the product is (designed/intended) to be installed and disassembled. Information about installation requirements for products, insofar as they enable the proposed EoL scenario, should be verified as realistic common scenarios.

Through the process of learning about how their products are, in practice, installed, maintained, disassembled, and processed at EoL, manufacturers gain valuable information for making improvements within their main sphere of influence: the product design phase. By exchanging information with a recycler, a manufacturer may learn how to improve product's recyclability, for example, regarding separability of materials, and can then make informed changes in the product design. The EoLD includes prerequisites for achieving high-quality recycling at the product EoL. Here, the planning and installation phases are significant. Manufacturers must provide targeted supporting information on the proper application and installation of products to enable the achievement of higher recycling rates.

For waste processors, the EoLD creation process presents the opportunity to learn about manufacturers' intentions for their products and, through access to LCA data and improved information exchange, to improve to their own processes. For example, as recycling companies learn more from the manufacturers about specific product properties and ingredients, they may be able to improve recycling rates by avoiding contamination and impurities, or by improving separability. Better understanding of the product may also lead to innovations in the recycling process. With strong communication pathways, recyclers can communicate with manufacturers about both established and new treatment processes in a way that meets the requirements of sustainable certification systems.

As EoLDs become established through the manufacturing industry, the EoL modules in EPDs will become much less sparse. And while, initially, the bulk of EoLDs will be issued by product manufacturers, once created, EoLDs can also provide a basis for associations or product TCs in international harmonization and standardization to establish reference scenarios for a product group. Based on robust EoLD data, such reference scenarios can then improve the comparability of EPDs. Over time, robust, reliable data on the environmental information about the end-of-life of construction products will become readily available. A larger dataset of EPDs covering the product end-of-life (/all periods of a product's life cycle) will provide reliable data to be used by planers on the building level.

5. Conclusion

As interest in improving the environmental performance of buildings continues to grow – and expand beyond energy efficiency – a stronger focus is directed towards environmental impacts related to building products. For product manufacturers, environmental product declarations (EPD) are a market tool of continuously rising importance, providing a way for producers to share information about the environmental impacts of their products.

The increasing concern related to environmental performance and resource efficiency promotes the concept of circular economy. Reuse and recycling procedures at the end-of-life (EoL) play an increasingly important role in decision making. Manufacturers, however, are often unsure how to include late life cycle stages in their product declarations. At the same time, users of the information are confused as to what provided information really refers to.

The concept of modular EoL-declarations with clearly identified and described scenarios aims to facilitate the inclusion of the full life cycle in EPDs based on reliable and realistic data. At the same time, EoL-declarations promote the communication between the production and EoL-actors and enhance understanding of provided information, including judgements on potential demand and procedures for adaptation of provided information.

While acknowledging that continued use or reuse of products is presumed to be a preferred option, the upcoming standards for environmental product declarations will require the inclusion of the complete life cycle, especially the inclusion of the end-of-life stages. The underlying research aims to identify a transparent procedure enabling actors along a product's life cycle to make well informed decisions, and to potentially adapt provided information to his or her current decision making context and the associated conception of reasonable scenarios for information relating to future situations.

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The Reporting of End of Life and Module D Data and Scenarios in EPD for Building level Life Cycle Assessment

Anderson J[1], Rønning A[2], Moncaster A[1]

1 Open University, Walton Hall, Milton Keynes, UK
2 Østfold Research, Norway

Jane.anderson@open.ac.uk

Abstract. This paper identifies the need for Environmental Product Declarations (EPD) to provide End of Life (EoL) and Module D data for products for use in building level Life Cycle Assessment (LCA). Although the provision of data for EN 15804 Modules A4-D is not currently mandatory for EPD, many currently report some or all of these. This paper provides an overview of the existing reporting of the end of life (Modules C1-4) and Module D and the types of scenarios used in European EPD. Using examples from existing EPD for two product groups, this paper examines the variation in approaches to scenarios for Module C and D. It explores the difficulties brought by this variation and discusses benefits from using default national scenarios at end of life, but additionally considers the advantages of providing alternative EoL scenarios for products to promote the circular economy.

1. Introduction

Life cycle assessment (LCA), as defined in ISO 14044 (1) addresses "the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave)." For construction products, the European Standardisation body, CEN's Technical Committee TC350 responsible for Sustainable Construction has developed a framework and standards to address the assessment of environmental aspects and impacts for both products and construction works. The life cycle for construction works and for construction products are set out in the framework standard, (2) and used in the building level environmental assessment standard, (3) and the construction product level environmental assessment standard, (4).

This framework clearly separates the end of life stage from the other life cycle stages, and breaks it down into four information modules, C1 (deconstruction), C2 (transport to waste processing), C3 (waste processing for reuse, recovery and recycling), and C4 (Disposal). In addition, another module, Module D is included to show the benefits and loads beyond the system boundary from the net output of recovered material, fuel and energy from the product system.

This framework allows Environmental Product Declarations (EPD) as described in EN 15804 (CEN/TC 350, 2013) to provide information for the various life cycle stages and modules, and for this information to be used, if appropriate, within a building level assessment according to EN 15978 (CEN/TC350/WG1, 2007). EN 15804:2012+A1:2013 only requires the mandatory provision of data for Modules A1-A3 (covering cradle to gate for the product stage), other modules and stages are voluntary. The current amendment of this standard, EN 15804+FprA2:2019 (5) will require Module C and D to be provided for all products except a very small number of exceptions, however it does not describe any scenarios which should be assessed for products, other than the requirement already set out in EN 15804:2012+A1:2013, "A scenario shall be realistic and representative of one of the most probable alternatives." (CEN/TC 350, 2013, 6.3.8).

This paper builds on the work of Silvestre, Brito and Pinheiro (2014) (6) which demonstrated that EoL data provided in EPD can be an important source of data for decision-making at the end-of-life of building materials, especially to ascertain whether the minimization of waste flows, the maximization of their reuse or recycling operations, or the increase of the recycled content maximises their C2C environmental performance. At the time of their paper however, few EPD were available and they provided limited data on EoL scenarios. This paper demonstrates that many European product EPD now report some or all of the voluntary modules, including the end of life (C1-4) and beyond end of life (D). Using examples from existing EPD for two product groups, this paper examines the variation in approaches to scenarios for Modules C and D, and highlights some of the difficulties this causes. It discusses the benefits that can be gained from using default national scenarios at end of life, and also considers the advantages of providing alternative EoL scenarios for products to enable specific building LCAs. It also stresses the need for specific product scenarios at EoL to promote the circular economy within the manufacturing industry.

2. The purpose of EPD and use of data for Module C and module D data from EPD

2.1. Purpose of EPD and scenarios

EN 15804:2012+A1:2013 states "The purpose of an EPD in the construction sector is to provide the basis for assessing buildings and other construction works, and identifying those, which cause less stress to the environment.". EN 15804, which provides the core Product Category Rules (PCR) for construction product EPD, therefore states it has the objective to ensure:

- *"the provision of verifiable and consistent product related technical data or scenarios for the assessment of the environmental performance of buildings;".*

CEN TR16790:2017, the guidance document for EN 15804 describes the approach for scenarios,

> *"as soon as a construction product leaves the factory gate the assessment is based on scenarios and assumptions: the fate of the product in the building chain will depend on locations, types of transport, installation and constructing methodologies, building type, use of the building, maintenance, repair and waste handling. The manufacturer cannot control these processes completely. An assessment thus requires scenarios to be specified for each module, i.e. for modules A4, A5, all B-modules, all C-modules and for information module D."*

2.2. Purpose of EPD for Building Level Assessment

EN 15978, 8.1 describes how building level LCA assessment needs to evaluate the end of life of the building. "This requires the development and use of appropriate scenarios representing assumptions (or, where known, real information) that can be applied to models for construction, use, and end-of-life stages (modules A4 to C4) of the object of assessment. If information on module D is communicated in a building assessment, scenarios are required to be defined at the building level." As described in the TC 350 Framework, EPD to EN 15804 are the first source of LCA data for construction products to be used at the building level. EN 15978 8.1 states, "Information modules available from EPD shall be reviewed in order to determine if they are representative of the assessed building". This is reiterated in clause 10.2.3, *"Any scenarios incorporated in the EPD and/or other information used for the assessment should be checked for consistency with the scenarios for the building. Where differences occur, it is still possible to take consistent information from an EPD (e.g. cradle to gate information from a cradle to grave EPD) and apply other appropriate scenarios at the building level (e.g. gate to grave)."*

This means that if the building has been "designed for deconstruction" to minimise landfill and to maximise reuse at end of life, that EoL data provided in EPD should only be used if they are representative of this "design for deconstruction" approach; if the EPD provides EoL data based on a scenario for landfill or incineration without energy recovery for example, then it will not be representative of the assessed building and should not be used.

Similarly, if an EPD provides EoL data for Energy Recovery in C3 and its Module D shows the benefit of the exported electricity and heat in the UK with substituted UK grid mix, then this Module D data will not be representative for the end of life of a building located in France, where the French grid mix should be substituted if the product is used for Energy Recovery at end of life.

2.3. EPD for Product Comparison

For comparisons of EPD, EN 15804 states, "comparison of the environmental performance of construction products using the EPD information shall be based on the product's use in and its impacts on the building, and shall consider the complete life cycle (all information modules)."

As described above, products can therefore only be compared in a specific building context over the full life cycle. This means that data for the products end of life will need to be used, and will need to be representative of the chosen building context. It will therefore be necessary to ensure that end of life scenarios in particular reflect the same context – this does not mean that the end of life scenarios have to be the same however – they need to be equivalent; if the context is the typical building in the Netherlands, then it would be appropriate to reflect the typical Dutch end of life for different products – this could be recycling for metals and energy recovery for biomass for example.

3. The end of life stage

3.1. Benefits of assessing the end of life stage

The assessment of the end of life of the building (Modules C1-C4), and for Module D allows a number of mitigation strategies to be considered to reduce the impact of the building. This is described in Pomponi & Moncaster (2016) which classified various mitigation strategies (MS) found in the literature, including the following with direct relevance to Modules C1-C4 and Module D of EPD:

- MS1: use of materials with lower embodied energy and carbon;
- MS3: reduction, re-use and recovery of EE/EC intensive construction materials; and
- MS17: demolition and rebuild.

Many materials such as plastics or biogenic materials have high impacts at end of life as their feedstock carbon is emitted through incineration or transferred to future product systems. Other materials (e.g. reinforced concrete) can require recycling processes at the end of life to achieve the "end of waste" state meaning they have crossed the system boundary. The provision of data showing the impacts of end of life, allows the identification of products will lower life cycle impacts (MS1).

Provision of information in the EPD covering the impacts of reuse and/or recovery (Module C1-C4) and its potential benefits in the next product system (Module D) enables the reuse and recovery strategy (MS3) to be evaluated.

MS17 suggests that by demolishing existing buildings and rebuilding them with significantly increased energy efficiency we can make reductions in the whole life impacts of our built environment compared with refurbishment. The data provided in Modules C and D of EPD for products used in the building and EPD for new products can be used to assess refurbishment and redevelopment options and provide the information to assess the validity of this controversial proposal.

3.2. Assessment of end of life in Building Level studies

Despite the potential use of data from Modules C and D to mitigate the impacts of the built environment, these are seldom assessed in whole building LCAs. Wallhagen, Glaumann, & Malmqvist (2011) (7) point out that these stages are not addressed by Adalberth et al. (8), Chen et al. (9), Peuportier (10), Blengini (11) and Ortiz et al. (12). Silvestre, De Brito, & Pinheiro (13) also find that "*…the LCA results from more than 10 years of international research studies on the environmental impact of a building's external walls has shown that … just a third (21 out of 63) include the end-of-life of the building assembly.*"

This may be partly because end of life impacts are often considered small as for example found by Nemry et al. (2010) (14) though aggregating Module C and D together may have reduced the impact shown at end of life. Other studies show the impact of the EoL stage is greater. Pomponi, Moncaster, & De Wolf (2018) reviewed the assessment of five buildings undertaken by different consultants using different tools and found the impacts of the End of life module C averaged around 6 to 8% of the whole life carbon, but in some cases were as high as 15%.

It is also the case that the end of life stage varies in importance for different product types. For metals for example, the end of life stage is often assumed to have no impact, as the metal is assumed to reach the end of waste state on collection in C1. For masonry, many EPD only include collection as demolition rubble in C1 to be the end of waste state. However, for products such as those based on biomass or fossil feedstocks, the end of life stage can have significant impacts due to emission or transfer of feedstock carbon. The authors suggest that for buildings with higher proportions of bio-based products, the end of life stage impacts may be significantly greater than those provided in the literature above.

4. Reporting End of life in EPD

4.1. Approach to the Review of End of life Data in EPD

While reporting of Module C is not mandatory, many EPD from European EPD Programs do report Module C and D scenarios, as shown below. In some EPD Programs such as the French National EPD Program (15), it is a requirement to evaluate and report Module C as French EPD must cover cradle to grave.

The authors have reviewed over half (2464) of the EPD compliant with EN 15804 and registered by ECO Platform members (ECO Platform, 2018) over the period December 2018-January 2019. The study excludes all EPD from the IBU and EPD Norge Programs which are still being evaluated. 784 PEP EcoPassport EPD for electrical products used in buildings have also been excluded as although they are cradle to grave EPD, they do not report modules C1-C4 separately. The EPD were assessed and classified as to whether each module was “Reported” or “Not Reported”. If it was marked “not relevant” this was classified as “Not Reported”.

4.2. Results of the Analysis

The analysis showed that 72% of these EPDs report Module C1 (Demolition/deconstruction), 77% report Module C2 (Transport to waste processing), 76% report Module C3 (Recovery), 82% report module C4 (disposal) and 51% report Module D.

There was wide variation between EPD Programs in relation to reporting of end of life (EoL) modules (C3 and C4). For example, within the ITB Program in Poland, the DapHabitat Program in Portugal, EPD Global in Spain, EPD Danmark (Denmark) EPD Norge in Norway and EPD Ireland, less than 50% of all EPD provide EoL modules. However in RT EPD (Finland), MRPI (the Netherlands) and Bau EPD (Austria), over 75% provide EoL modules. The FDES and PEP Ecopassport programs (France) require all EPD to cover cradle to grave.

5. Analysis of declaration of Module C and Module D and scenarios for two product groups

5.1. Overview

A more detailed analysis was undertaken of the reporting and description of scenarios for two particular product/material groups, namely polystyrene insulation, including expanded and extruded polystyrene (EPS and XPS) insulation, and wood panel products, including medium density fibreboard (MDF), orientated strand board (OSB), particleboard and plywood. The end of life impacts of these product groups are likely to be significant due to the emission or transfer of feedstock carbon.

5.2. Classification of reporting of Modules:

For these EPD, the authors propose the classification of Module C1-C4 and Module D reporting as to whether modules were "**declared**" with an impact, declared with "**zero"** impact, "**not declared**" (MND), or declared "**not relevant**" (MNR).

5.3. Types of Scenario used in EPD

Additionally, the types of scenario declaration for module C1-C4 and Module D were analysed. The authors propose four separate types of scenarios used for gate to grave and Module D in EN 15804 EPD:

- **"100%"** scenario: where only one approach is reported for the module or modules in the EPD, eg 100% of the product is sent to landfill. These scenarios can also include consecutive processes, for example, where 100% of the product is used for energy recovery in C3 and then the incinerator ash is landfilled in C4, or where the waste is transported by road and then by sea to waste treatment.
- **"Mixed"** scenario: where a combination of two or more approaches is considered in a single scenario reported for the module in the EPD, with a proportion using each approach – e,g. 50% of the EoL product is sent to landfill (C4) and 50% used for energy recovery (C3), or 25% is sent to landfill (C4) and 75% sent to incineration without energy recovery (C4). These scenarios are often typical of a national situation;
- **"Multiple"** 100% scenarios: where two or more 100% scenarios are reported for the module in the EPD.
- **"Mixed+100%"** scenario: where a mixed scenario is reported for the module in the EPD together with 100% scenarios for the contributing approaches, as described in CEN/TR 15970 clause 6.3.8.

5.3.1. 100% scenarios: It should be noted that EN 15804, and more specifically the guidance document to the standard, CEN/TR 16970:2016 6.3.8(16), states that 100% scenarios should also be declared if a mixed scenario is provided:

> *"When different scenarios are developed for information modules C1-C4 the most relevant scenarios are provided as 100 % versions. For example when 20 % of a product is recycled, 50 % is incinerated and 30 % is deposited, scenarios for 100 % of incineration, 100 % of recycling and 100 % of deposition are declared. This allows the building assessor to choose and calculate the correct scenario on building level as actual waste management practices vary in different member states".*

5.4. Analysis of Description of Scenarios

The description of the scenarios provided in the EPD were also analysed considering the level of detail provided and the type of processes included in each module.

5.5. EPS and XPS Polystyrene Insulation

20 EPD from nine EPD programmes were identified and analysed under the product category "polystyrene insulation" and the results described in Table 1. Where several EPD for different but very similar specific products were produced using the same scenarios, only one was assessed.

10 EPD provided 100% scenarios, four provided two separate 100% scenarios and five EPD provided a "mixed" scenario. There were also some differences in the way in which EPD reporting a 100% scenario for C3 declared module C4 and vice versa. As Module C and Module D are intended to become mandatory requirements in EN15804+FprA2 then consistency in considering this situation would be useful.

Only four EPD declared C1, with 3 declaring the impact to be zero. 16 declared C2 with quite varied scenarios. Distances range from 10 km, 50 km, 200 km, and one Norwegian EPD used 1000 km by road to a recycling plant. For such a lightweight product as polystyrene insulation, it would be expected that the volume capacity might be considered in the transport scenarios, but few EPD mention it: two used

Table 1. Scenario data for Polystyrene Insulation EPD.

Product	Scenario type	Stated scenario for Module C1	Stated scenario for Module C2	Stated scenario for Module C3	Stated scenario for Module C4	Stated scenario for Module D	Programme/ Location of Manufacture
EPS	100%	Collection, no impact	10 km, 5% capacity	Energy recovery	MNR	Substitution exported energy	DK / DK
EPS	100%	Collection, no impact	10 km, 5% capacity	Energy recovery	MNR	Substitution exported energy	DK/ DK
EPS	100%	Deconstruction	Zero impact	Energy recovery	Zero impact	Substitution exported heat (district heat)	RT / FI
EPS	mixed	Collection, no impact	10 km	44% recycling, 53% energy recovery	2% landfill	Substitution exported heat + electricity and virgin product	EPD-Norge/ NO, SE
EPS	multiple 100%	MND	No info	Recycling	related disposal	Substitution of virgin product	EPD Italy/ IT
				Energy recovery	related disposal	Substitution of exported energy	
EPS	100%	Collection, no impact	25 km	Zero impact	Landfill	MND	Inies/ FR
EPS	multiple 100%	MNR	50 km	Recycling		Substitution of virgin EPS	IBU/ EU
				Zero impact	Incineration eff.<60%	Substitution exported energy	
EPS	100%	MND	MND	MND	Incineration eff.<60%	Substitution exported heat +electricity	IBU/ DE
EPS	MND	MND	MND	MND	MND	MND	EPD Ireland/ IE
XPS	mixed	INA	INA	50% reaches EoW on collection	50% landfill	50% processed to substitute of virgin product	BRE/ PO, CZ
XPS	mixed	MND	50 km, 21% capacity	MND	10% incineration, 90% landfill	MND	BRE/ UK
XPS	100%	Collection, no impact	50 km	no recycling	Landfill	MND	International EPD/ ES, PT
XPS	100%	MND	MND	MND	Landfill	MND	International EPD/ TU
XPS	multiple 100%	MND	no info	MND	Landfill	MND	IBU/ EU
				MND	Incineration eff.<60%	Substitution exported heat (nat. gas) + electricity (EU)	
XPS	100%	Collection, no impact	not info	Energy recovery	Zero impact	Substitution exported heat (district heat)	RT/ FI, LI, ES
XPS	multiple 100%	MNR	no info	MND	Landfill		IBU/ DE
					Incineration eff<60%	Substitution exported electricity (EU) + heat (natural gas)	
XPS	multiple 100%	MNR	no info	MND	Landfill		IBU/ DE
					Incineration eff.<60%	Substitution exported electricity (EU) + heat (natural gas)	
XPS	mixed	MND	18% capacity, 10 km to ER, 1000 km to recycling	28% recycling, 63% energy recovery	9% landfill	Substitution of virgin polystyrene, exported electricity + heat (oil)	EPD Norge/ NO, SE
XPS	mixed	MND	10 km	44% recycling, 53% Energy recovery	3% landfill	Substitution of virgin polystyrene, exported electricity + heat (oil)	EPD Norge/ NO
XPS	100%	Mixed waste collection	200 km	Zero impact	Landfill	MND	Inies/ FR

Table 2. Scenario data for wood panel product EPD.

Product description	Scenario type	Stated scenario for C1	Stated scenario for C2	Stated scenario for C3	Stated scenario for C4	Stated scenario for Module D	Programme/ Location of Manufacture
MDF	MND	MND	MND	MND	MND	MND	BRE / Ireland
MDF	multiple 100%	MND	MND	Shredding + energy recovery	MND	Substitution exported heat (natural gas)	EPD Australasia / Australia
				Recycling to wood chip	MND	Substitution (virgin wood chip)	
				MND	Landfill DOCF 0.7%	Substitution electricity ER of landfill gas	
				MND	Landfill DOCF 10%	Substitution electricity ER of landfill gas	
MDF	mixed	Mixed wood waste	85km in NO. % to SE	90% Energy Recovery	2% landfill, 7% incineration	Substitution exported electricity + heat (NO + SE)	EPD Norge /Norway
MDF	100%	not given	85km	Energy recovery	MND	Substitution exported electricity + heat	EPD Norge /Norway
MDF*	100%	MND	MND	Chipping to secondary fuel	MND	Substitution exported electricity + heat	IBU / Germany
MDF	100%	MND	MND	processing to secondary fuel	MND	Secondary fuel use, EU average substitution	IBU/ Germany
MDF	100%	Removal	MND	Zero impact	MND	Secondary fuel use	IBU / Germany
MDF	100%	Removal	20km	Crushing	Incineration eff. 35%	Substitution of exported heat + electricity	IBU / Germany
MDF	100%	MND	MND	Chipping to secondary fuel	MND	Substitution of exported heat + electricity	IBU / Germany, Portugal, South Africa, Spain
MDF	100%	MND	MND	Energy recovery	MND	substitution of exported heat + electricity	IBU / Poland
MDF	100%	MND	MND	Chipping to secondary fuel	MND	Secondary fuel use, Substitution heat (natural gas), electricity (ES)	International EPD /Spain and Portugal
OSB	MND	MND	MND	MND	MND	MND	EPD Ireland / Ireland
OSB	100%	MND	MND	Chipping to secondary fuel	MND	Secondary fuel use, EU average substitution	IBU /Germany, Romania
OSB	100%	MND	MND	Chipping to secondary fuel	MND	Substitution exported heat & electricity	IBU /Germany
OSB	100%	MND	MND	Energy recovery	MND	Substitution exported heat & electricity	IBU /German, Poland
Particleboard	mixed	Mixed construction waste	33% 85km (NO), 67% by road and sea (SE)	91% Energy Recovery	2% Landfill 7% incineration	Substitution exported electricity & heat (NO + SE)	EPD Norge /Norway
Particleboard	100%	MND	MND	Only bioCO2 transfer	MND	Substitution exported heat	IBU / Austria
Particleboard	100%	MND	MND		MND	Substitution exported heat	IBU / Austria
Particleboard	100%	MND	MND	Only bioCO2 transfer	Zero impact	Secondary fuel use	IBU / Belgium
Plywood	100%	Mixed construction waste	85km	Only bioCO2 transfer	Energy recovery eff. <60%	Substitution exported electricity + heat	EPD Norge / Norway
Plywood	mixed	not given	85km	Energy recovery	Landfill of ER ash	Substitution exported electricity + heat (NO)	EPD Norge / Sweden
Plywood	multiple 100%	MND	MND	Chipping to secondary fuel	Zero impact	Secondary fuel use, substitution heat (natural gas)	International EPD /Australia
		MND	MND	Recycling to wood chip	Zero impact	Substitution of virgin woodchip	
		MND	MND	Reuse	Zero impact	Substitution of virgin product	
		MND	MND	Zero impact	Landfill DOCF 0.7%	Substitution exported heat & electricity from landfill gas	
		MND	MND	Zero impact	Landfill DOCF 10%	Substitution exported heat & electricity from landfill gas	
Plywood	MND	MND	MND	MND	MND	MND	International EPD /Italy
Plywood	MND	MND	MND	MND	MND	MND	International EPD /Spain
Wood panel	100%	not given	100km	Energy Recovery	MND	MND	FDES /France

a 5% capacity including empty returns, one 18% capacity and one 21%. Fuel consumption for the trucks was reported variously as 0.2 l/km, 0.38 l/km, 25 l/km, 0.173 l/tkm, 0.4 l/tkm, and 0.026 l/tkm for the large capacity trucks travelling 1000km.

There was a wide range of end of life options, including recycling, energy recovery in C3 and incineration with energy recovery in C4. 14 EPD declared Module D showing the benefit of energy and material recovery, though few stated what electricity or energy was substituted.

5.6. Wood panel products: OSB, MDF, particleboard/chipboard and plywood

Twenty five EPD from five EPD programs were considered within this product group and details of the modules reported and scenarios used are provided in Table 2. Again, there are a range of mixed, 100% and multiple 100% types of scenarios declared.As for polystyrene, very few declared C1. Reporting for C2 (transport to waste processing) was also varied with distances varying from 20 to 100 km. Although almost all EPD declaring end of life modelled use of the waste timber for energy, there was a big variation with some processing and using the waste for energy recovery in C3, some incinerating in C4, and some considering the use of secondary fuels in Module D with some also reporting processing in C3.

6. The Role of Product TCs and c-PCR

CEN/TR 16970:2016 (16) provides guidance to CEN Product Technical Committees on developing complementary PCR (c-PCR) to EN 15804. It says in the development of c-PCR, the following are considered, in 5.1.2, "inclusion of default scenarios related to a specific application of the product including guidance on:

i) The specific content of all information modules of the life cycle and information module D, for default scenarios;
ii) The definition of the end-of-waste status;
iii) The technical scenario information for all information modules of the product system and information module D".

It also states in 6.3.8, that "when different scenarios are developed for information modules C1-C4 the most relevant scenarios are provided as 100% versions. For example, when 20% of a product is recycled, 50% is incinerated and 30% is deposited, scenarios for 100% of 100% of incineration, 100% of recycling and 100% of deposition are declared. This allows the building assessor to choose and calculate the correct scenario on building level as actual waste management practices vary in different member states."

6.1. EoL scenarios in c-PCR in practice

Unfortunately, few of the c-PCR developed to align with EN 15804 provide detailed technical scenario information for the end of life and only one provides an assumption for the end-of-waste status if product specific information is not available. One states that geography will affect the EoL routes used.

6.1.1. EN 16783:2017 is the c-PCR for insulation. This does not provide any default scenarios or specific guidance on the End-of-Waste state for insulation products, but states in clause 6.3.4.5 that the products can be sorted and separated for recycling or for energy recovery and scenarios can vary with the application and with geographical location (17).

6.1.2. EN 16485:2013, the PCR for round and sawn timber (the raw material for use in board products), provides an assumption on the end of waste state for timber where product specific information is not available, which is after sorting and chipping for untreated timber, and gives some guidance on the types of process to include in modules C1-C4 for different end of life options depending on when the end of waste state is reached (18).

6.1.3. Other c-PCR: The c-PCR for Glass (EN 17074:2018, clause 9.8.4) states that "End-of-life scenarios and routes can vary according to national and regional legislation, de-construction schemes and requirements, collection and sorting schemes in place and end-of-life treatments available"(19). The c-PCR for concrete (EN 16757:2017) gives detailed technical scenarios for possible EoL options for concrete. It does state, as a note, that "The legal interpretation of End-of-Waste can differ significantly at national level. At some regions, crushed concrete stored indefinitely at demolition sites over long periods will revert to being waste. In such case, certainty over the legal End-of-Waste status is only confirmed when demand exists and a certain market is allocated and the crushed concrete is removed from site"(20). Again, this emphasises the differences that geography plays in determining EoL scenarios for EPD and highlights the difficulty in European c-PCR providing relevant default EoL scenarios when practice varies so widely geographically, due to differences in national and regional legislation, the recycling schemes in place and the EoL treatments available.

7. Discussion

7.1. Variation in reporting

The detailed analysis of end of life scenarios and reporting undertaken for this paper highlights the wide variation in end of life routes assumed within EPD. The authors are also concerned by possible errors in modelling or reporting of fuel consumption and vehicle capacity, differences in assumptions for transport distances, and the differences in the "end of waste state" used. The "end of waste state" can vary regionally as markets and demand may vary, the secondary material may not be commonly used in some regions and the legal definition of end of waste may also vary. But even for MDF EPD for the German Market, there is not consistency regarding the end of waste state – with one assuming the end of waste before chipping. Analysis shows these differences in scenarios also lead to differences in impact reported in Module C and Module D. The wide variation in scenarios also means that there is a general level of distrust with gate to grave data with many Building LCA tool providers telling the authors they do not use gate to grave data from EPD in their tools.

Provision of a national default scenario, such as that for the Netherlands (21) reduces the effort to produce gate to grave EPD data for that market as manufacturers and LCA practitioners do not need to individually research and develop representative end of life scenarios, and this is likely to be associated with reduced costs.

7.2. Insufficient description of scenarios

The authors note that many EPD provide insufficient information on scenarios for those using EPD for Building LCA to ensure "*Any scenarios incorporated in the EPD and/or other information used for the assessment should be checked for consistency with the scenarios for the building"* as suggested by EN 15978 10.2.3. If the type of heat or electricity substituted in Module D is not provided for example, then the module cannot be checked for consistency with building level scenarios for substitution.

7.3. Provision of multiple 100% scenarios

Very few of the EPD provided more than one 100% scenario for different end of life options, although there were several different end of life routes given across the product groups. EPD providing mixed scenarios did not provide any 100% scenarios for the individual processes despite the text in CEN/TR 16970:2016 6.3.8 recommending this. C-PCR also fail to recommend this option, although it would help to deal with the different EoL options available in different locations due to variations in legislation, recycling schemes and treatments available. Providing 100% scenarios for recycling, energy recovery, landfill and incineration (potentially with different end-of-waste states if relevant) gives an understanding of the different impacts of these end of life options and can be used for buildings currently being demolished, wherever they are, to assess the most advantageous options. Where 100% scenarios are reported for re-use and/or recycling in addition to energy recovery, they also enable use of the data for different building level scenarios, such as design for deconstruction, providing encouragement for the circular economy.

8. Conclusion

The authors have provided several new approaches to classifying the scenarios reported in EPD, and identified that a significant proportion of EN 15804 EPD already report Modules C1-C4 and Module D. However, the authors are concerned that their analysis of existing EPD has highlighted such wide variation in the modelling, description and reporting of these modules. With reporting of Module C and Module D likely to become mandatory for all EPD based on FprEN15804+A2:2019, the authors recommend that EPD programmes provide more guidance on modelling, description and reporting to ensure that EPD data can be checked for consistency with building level scenarios and used with confidence. It is also clear that Product TCs find it difficult to develop c-PCR with default EoL scenarios due to the geographical differences in real EoL routes. To address the differences in different locations, and encourage the circular economy, the authors also highlight the benefit for c-PCR and EPD of providing multiple 100% scenarios so the impact of different end of life options can be considered and circular economy approaches to building design can be evaluated in many locations. The authors also recommend that building level assessment schemes together with EPD program consider developing and publishing default national scenarios to enable consistent assessment for benchmarking.

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Modelling options for module C and D: Experiences from 50 EPD for wood-based products in Norway

Tellnes L G F[1], Rønning A R[2]

[1] Research Scientist, Ostfold Research, Kråkerøy, Norway
[2] Senior Research Scientist, Ostfold Research, Kråkerøy, Norway

lars@ostfoldforskning.no

Abstract. Introducing the EN 15804 standard as a core PCR for building products included several specifications for LCA end-of-life and benefits beyond the life cycle. There are however several issues that the LCA practitioner need to interpret during the modelling and generic data needs to be adjusted for being representative and in accordance to EN 15804.The modelling of module C and D has been developed in three different stages during making 50 EPDs over several years. First the model was mainly based on generic data from ELCD database. The second was a statistics-based mix of different treatment options, where the substation of other energy sources in module D was a representative mix of district heating mix, electricity, coal in cement production, wood chips in wood industry and ELCD for exported waste. The third represented a 100 % scenario for energy recovery in municipal waste incineration and substituting statistical mix of electricity and district heating. The objective of the study is to present the experiences from developing and implementing the module C and D in the 50 EPD that where verified at EPD-Norway and discuss in relation to requirements in standards and usability in a building context.

1. Introduction

The environmental product declarations (EPD) for wood products was first introduced in 1996 for some generic products from the Nordic countries. The second generation wood EPDs came in 2009 and was based on the ISO 21930 (1). Several of these where representative for the most common products from the members of the Norwegian Wood Industry Federation. These EPDs was also third party verified and published through the Norwegian EPD Foundation. The use of EPD was however limited, but in 2012 the Norwegian Green Building council (NGBC) released a Norwegian adaption of building environmental certification scheme BREEAM. Known as BREEAM-NOR [2], it included credits for provided EPDs for the most used products and made a sudden increase in demand for EPDs. In 2013 the revision of product category rules (PCR) for wood products was released, NPCR015 [3], and was based on the EN 15804. The launch of BREEAM-NOR made EPDs requested for many more specific products, such as claddings, windows and engineered wood products.

Prior to EN 15804, end-of-life was assumed as energy recovery and that the emissions were allocated to the energy user. However, with EN 15804 it was required that emissions until end-of-waste state was included, but also optioned for including the benefits of energy recovery. The procedure was however not very specific, and the approach was improved in mainly three steps in making about 50 EPD over four years. The aim of this paper is to present this development in procedures with discussion to the relation to standards and practice.

2. Materials and methods

The review has focused on two main issues in modelling of end-of-life modelling:

- Development of scenarios
- Development of life cycle inventories for incineration of materials

2.1. Materials

Three EPDs are selected to represent the three stages of development in scenario modelling module C and D according to EN 15804 and NPCR015 [3]. The EPDs are listed in table 1.

Table 1. List of EPD that represent the different stages of developing the scenario model for module C and D

	Product	Year	EPD number	*Description*
First model	Pine moulding	2013	NEPD00232	Statistical mix of end-of-life treatment and generic data for benefits
Second model	Pine panelling	2015	NEPD-309-179	Statistical mix for end-of-life treatments and market mix of benefits
Third model	Cross laminated timber	2017	NEPD-1269-410	Most common end-of-life treatment and average benefit

One crucial aspect discovered over the years for EPD development was the LCI of incineration of resin in the wood products. This model was also developed in three different stages and EPDs representative for these are listed in table 2.

Table 2. List of EPD that represent the different stages of developing the LCI model for resin incineration in module C

	Product	Year	EPD number	*Description*
First model	Glulam beam	2014	NEPD00263	ELCD dataset for whole product
Second model	Standard glulam	2015	NEPD-336-222	Ecoinvent dataset for each material component
Third model	Glulam for custom projects	2018	NEPD-1577-605	Ecoinvent dataset adjusted to carbon content

2.1.1. Methods

The EPDs are reviewed based on the scenario information and the life cycle inventory is remodelled according to the writer's experiences. The exact LCI is however not publicly available.

3. Results and discussion

3.1. Scenario modelling

3.1.1. First model: Statistical mix of end-of-life treatment and generic data for benefits

The first model for end-of-life of pine moulding coated with paint. In the PCR applied, a reference was give to CEN/TR 15941 (2010) for the use of generic data. This states that generic data for scenarios in end-ofe-life stage should among others reflect: “today’s average practice an dmix of different end-of-life treatment of the product group in the location where the process takes place”. Hence, this was interpreted as that the Norwegian mix of treatment of wood waste should be used for the end-of-life modelling. The most recent statistics at the time of publishing the EPD was from the year 2011 and where about 91 % of wood waste was sent to incineration with energy recovery, 7 % to incineration without energy recovery and 2 % to landfilling.

The module D was based on generic data for energy substitution in ELCD datasets for wood incineration. The ELCD dataset had two versions, one with only emission from incineration and one with also the benefits of energy recovery. Hence, one dataset corresponded to C3 and the other to C3+D. In order to model module D, the first was subtracted to the second.

3.1.2. Second model: Statistical mix for end-of-life treatments and market mix of benefits

The mix of waste treatment was the same in the first and second model for C3, but the substitutions in module D was quite different and because of this also some differences in transport scenario, module C2. The new substitution model aimed at reflecting the current average substitution, hence taking into account that the wood was treated in both municipal incineration and industrial, in addition to a quite large export to Sweden. Based on several sources, a bottom-up approach was applied to estimate the amount to different treatments and what they substituted. The mix of treatment are listed in table 3.

Table 3. List mix of treatments in C3 and substitutions in module D

Treatment in C3	Share [%]	*Substitution*
Municipal incineration	25	District heating mix and electricity consumption mix
Cement plant	5	Heat from coal
Chipping to industrial fuel for sawmill and particleboard industry	10	Wood chip fuel
Pulp and paper industry	14	Heat from fuel oil
Export to Sweden	46	ELCD dataset substitution mix

3.1.3. Third model: Most common end-of-life treatment and average benefit

The third model was a result of more understanding of the EN 15804, but also more recent data understanding. The Norwegian EPD Foundation gathered LCA-practitioners from different research institutes in Norway to work together on a study to harmonize the scenarios in EPDs. This work revealed that EN 15804 requires to use one or more of the most common scenarios. Hence, the requirement for scenarios implies that it should not be a mix. The work also shows how disposal of ashes from incineration could be included in module C4 [4]. The situation in Norway had also changed and in statistics no wood waste was disposed in landfill or incinerated without energy recovery. The third model assumed then that municipal incineration with energy recovery was the one of the most common end-of-life treatments in Norway for waste wood. The amount of energy recovered was based on national statistics of district heating and which also included the amount of electricity generated. The substitution was the mix of heating sources in the district heating in Norway.

There are currently work on PCR in Norway, but also EN 15804 in Europe. The Norwegian PCR for wood products has included several reference scenarios that shall be include, but more can be included if relevant. For update of the EN 15804, it is included an informative appendix with formulas for calculating the module C and D. There is also a requirement to include module C, with some exceptions.

3.2. Inventory modelling for incineration of glulam

3.2.1. First model: ELCD dataset for whole product

European reference life cycle database (ELCD) was established by the European Commission's Joint Research Centre (JRC). It consists of LCI data on a system process type, which means that each dataset only includes elementary flows. This makes the dataset easier for exchange between different users, but not possible to adjust the data and quality control is difficult. The data for wood products incineration is representative for a European technology mix of incineration. For the waste composition, the products OSB and particleboard are mentioned. An example of LCI are performed as shown in table 4.

Table 4. Life cycle inventory from example of first model for module C3

Waste specification			
Name	Amount	Unit	Comment
C3, incineration glulam	1	m^3	
Outputs to technosphere. Waste and emissions to treatment			
Name	Amount	Unit	Comment
Waste incineration of wood products (OSB, particle board), EU-27	470	kg	Weight of product according to product standard

3.2.2. Second model: Ecoinvent dataset for each material component

In the second inventory model used for glulam, ecoinvent database was used instead of ELCD. Ecoinvent is available both as system and unit processes. The unit processes include technosphere flows, like energy use, transport, etc. In addition, the elementary flows are specific to the relevant activity and not aggregated as in system processes. The inventory for incineration of glulam was based on a dataset for untreated wood and one for incineration of polyurethane. Polyurethane was then chosen as a proxy for the resin, as it was also used for treatment of waste resin in manufacturing of glulam in an ecoinvent unit processes for glulam manufacturing. The total weight of the product was the same as in the first model, but divided between wood part and resin part. The LCI modelling is shown in table 5.

Table 5. Life cycle inventory from example of second model for module C3

Waste specification			
Name	Amount	Unit	Comment
C3, incineration glulam	1	p	per functional unit
Outputs to technosphere. Waste and emissions to treatment			
Name	Amount	Unit	Comment
Waste wood, untreated {CH} | treatment of, municipal incineration | Alloc Rec, S	461.22	kg	Wood weight
Waste polyurethane {CH} | treatment of, municipal incineration | Alloc Rec, S	8.78	kg	Resin weight

3.2.3. Third model: Ecoinvent dataset adjusted to carbon content

The third model is based on an update of the EPD in the second model. The company owning the EPD was interested in how they could reduce their carbon footprint and a contribution analysis was performed. The incineration of resin was found to be an important part of the life cycle greenhouse gas emissions and was therefore reviewed. The inventory for incineration was then adjusted to correct for the actual dry content of resin in the final product and the carbon content of the resin. The polyurethane

LCI has a carbon content of about 63 %, while melamine urea formaldehyde (MUF) resin has a carbon content of about 30 %. Hence, the carbon dioxide emissions from combustion of the resin is about half per kg. An simplified example of this inventory is shown in table 6.

Table 6. Life cycle inventory from example of third model for module C3

Waste specification			
Name	Amount	Unit	Comment
C3, incineration of glulam	1	p	per functional unit
Outputs to technosphere. Waste and emissions to treatment			
Name	Amount	Unit	Comment
Waste wood, untreated {CH}| treatment of, municipal incineration | Cut-off, S	375/(1-0,17408)	kg	Dry weight of wood, adjustment, LCI adjustment to dry
Waste polyurethane {Europe without Switzerland}| treatment of waste polyurethane, municipal incineration | Cut-off, S	4.85*0.5	kg	Dry weight of resin, adjustment to actual carbon content

The implication of the three models on the results on carbon is that the first model is actually not including the emissions from incineration of the resin in wood products. The second model overestimates these emissions of more than double when MUF resin is applied. The third model aims at modelling the emission as correctly as possible, but is more complicated to perform. The importance of the modelling to the total results are on a medium level for glulam, but for wood-based panels, like particleboard, these models would have a dominating effect on the total carbon footprint results. The modelling of the production of resin is usually based on specific data from the manufacturers of resin. In the future, it would be beneficial that all upstream LCI data for EPD also is supported with downstream specific LCI for waste treatment. At least for combustible materials.

The modelling of biogenic carbon has been another important issue with wood EPDs and in the future modelling of end-of-life scenarios and inventory of incineration it could have a crucial part. So far, biogenic carbon has been assumed by many of being climate neutral over the life cycle, as the end-of-life scenario of wood will lead to emission of the same amount of carbon dioxide as has been sequestrated during forest growth. Hence, as long as the climate impacts are not time-adjusted, the different approaches for biogenic carbon has the same climate impacts over the life cycle [5]. However, plans for establishing carbon capture and storage (CCS) in Norway at waste incinerator that treat a notable share of the wood waste will lead to new methodological challenges. A case study has been performed on this for treated wood and which leads to climate negative results over the life cycle [6]. This would probably lead to discussions as many believe that biogenic carbon is always neutral over the life cycle.

4. Conclusions

This study has presented modelling principles for modelling end-of-life practiced in a selection of EPDs published between 2014 and 2018. The modelling has been improved on a mainly three step development, both for scenario and for life cycle inventory. These experiences should be utilized in future development of EPD requirements in PCR, but is also in important message for the importance of transparency in LCI datasets in databases and during verification.

For PCR development, these experiences have been included in the revision of the PCR for wood products applied in Norway. The proposal for PCR now includes conservative reference scenarios for the end-of-waste scenario. For wood products, the end-of-life scenarios can be quite different dependent on the country. Hence, the references scenarios are separated between different markets.

For the LCI datasets applied, it is important that they are specific for each material composition of the product. The LCI data should also be available on a unit process type in both databases and during verification. Future methodological challenges will be climate negative situations when biogenic carbon will have final storage when CCS is practiced at end-of-life of wood products.

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A typology of digital building technologies: Implications for policy and industry

Meuer J, Toetzke M, Nakhle C, Windeck S

ETH Zurich, Department of Management, Technology and Economics, Group for Sustainability and Technology, Weinbergstrasse 56/58, CH-8092 Zurich

jmeuer@ethz.ch

Abstract. Digitalization and digital technologies are buzzwords in today's building industry. Because of their promising opportunities to improve (among others) the sustainability footprint of the built environment, they have emerged as an important topic for policymakers, managers, and researchers. Yet, the debate is dominated by references to Building Information Modelling (BIM) and to the success of digital businesses in other industries; it thereby fails to consider other promising digital building technologies and ignores that—in the building industry—many digital technologies require alignment with buildings' physical components. For these reasons, it is unclear how the implications of digital transformation of the building industry for policy and business. In this paper, we develop a typology of digital building technologies, and categorize and assess 29 important building technologies. The substantive differences among different types of building technologies provide valuable insights into how digital building technologies affect the functioning, structure, and competition in the building industry and where digital building technologies offer opportunities to remedy the industry's sustainability footprint. Based on our findings, we offer recommendations to policy makers, companies, and researchers interested in digital building technologies.

1. Introduction

Until the late 1990s, digital technologies appeared as basic software or "the internet." This "first wave" of digital technologies allowed for simple levels of automation, analytics, and digital communication improving the efficiency of processes [1]. Yet, the digital technologies that concern people nowadays are part of a "second wave" of digital technologies of which Big Data analytics, cloud computing, Artificial Intelligence (AI), or the Internet of things (IoT) are only examples [2]. Some industries, such as retail or media, have already encountered the disruptive impact of the second wave of digitalization. New market players and business models have changed prevailing industry practices [3]. As these changes suggest, this "second wave" of digital technologies is a key enabler for disruptive innovations and the creation of new business models that not merely complement but fundamentally transforms how companies create, deliver, and capture value.

The building industry, too, has benefitted from digital technologies. In the past, digital technologies, such as e-mail, simulation software, or Enterprise-Resource-Planning (ERPs) systems have helped to adjust and improve existing processes. More recently, digital technologies of the second wave are also developed and adopted across the building industry and promise to transform prevailing processes and business models. This second digital transformation thus promises many opportunities to increase efficiency, productivity, and transparency across the building industry.

For business leaders and policymakers, understanding the digital transformation of the building industry is relevant for several reasons. The emergence of digital building technologies may change the competitive dynamics in the industry. Companies that successfully employ digital technologies may benefit from substantive efficiency gains that will allow them to offer similar services at lower prices. A company's IT capabilities may eventually determine whether it qualifies for joining building projects—digital technologies may thus emerge as the new entry barrier in the building industry. The enhanced transparency introduced by data-driven building technologies may oust companies that rely on opaque pricing and offer others opportunities to develop new business models.

The digital transformation also raises questions concerning the industry's labor market. In particular, trends in the area of prefabrication or robotics may drastically reduce the number of workplace in the building industry. Companies may need to transition from a large workforce of manual labor to a small one trained in handling IT or IT specialists. For policy, alleviating the industry's dependency on manual labor may lead to large-scale unemployment but may also offer a solution to the lack of skilled personnel—depending on the current situation of the labor market. Either way, policymakers will face questions of how to retrain the current and train the future workforce for a digital building industry.

The digital transformation of the building industry may also offer opportunities to policy makers to address sustainability and energy-related concerns associated with the building industry. Currently, the industry is one of the most energy-intensive ones with 40% of the primary energy consumption globally and about 36% of global CO_2 emissions [4]. Digital technologies offer several solutions to minimize the ecological footprint of the industry and help streamline processes across the entire building lifecycle in a more efficient, transparent, and safer way.

Yet significant barriers to digitalization remain. First, the adoption of new digital technologies in the building industry has been slower than in other industries. This is not necessarily surprising given the structural characteristics of the industry. Highly fragmented, with low margins, and low investments in R&D, building companies either have had no time (during construction booms) or no money (during building industry crises) to develop and adopt new technologies. Second, the current debate on digitalizing the building industry tends to focus on one digital technology, Building Information Modelling (BIM). A debate dominated by the promises of BIM not only risks neglecting the substantive challenges of successfully commercializing BIM solutions but, more importantly, risks neglecting other digital building technologies that may offer a more direct route to transforming the industry.

Third, the building industry differs from other industries affected by second wave digital technologies in one important aspect: the central role of the physical built environment. Successfully developing and commercializing second wave digital technologies is in itself challenging [5], integrating digital technologies with physical building components creates an additional complexity that has yet to be fully understood. A better understanding of how digital technologies will transform the building industry may thus provide important insights into other applications of digital technologies that require consideration of the physical world.

This article serves to develop a better understanding of the promises and pitfalls of digital trends in the building industry and is structured along two interrelated questions: What digital technologies influence the building industry and how will they transform the structure of the building industry?

2. Methodology

We focus on the intersection between digitalization and the building industry. We use the term *digitalization* to refer to the integration of digital technologies into everyday life [6]. Digital technologies are all technologies that comprise data or execute algorithms in digital form [1, 7]. The *building industry* refers to a specific segment of the construction industry, namely the one that includes all actors involved in, and activities related to, residential, commercial, and industrial buildings [8-10]. Thus, we consider digital building technologies as those applied by actors involved in activities related to, residential, commercial, and industrial buildings throughout the building's life cycle.

To address our research question we followed a three-step procedure. First, to identify digital technologies in the building industry, we conducted an exploratory literature review, complemented this review with expert interviews, and surveyed additional 20 industry experts asking them “What are the most important digital trends that have emerged in the building industry the in past years?” Through this process, we identified 29 digital building technologies frequently discussed in both the academic and practitioner literature.

Second, to understand the technological, managerial, and regulatory challenges associated with digital trends in the building industry, we distinguish *complementary* from *platform* technologies and *software-based* from *cyber-physical* digital building technologies [5, 11]. Whereas complementary technologies directly execute specific tasks without coordinating detached subsystems, platform technologies integrate multiple complementary technologies and peer-users via shared databases and standardized interfaces. Additionally, software-based technologies have no direct link to the physical infrastructure. In contrast, cyber-physical technologies [9] combine digital and physical properties and carry out specific tasks by either using digital data as input to execute a physical task, or generating digital data as output of a physical environment [11, 12].

Third, to provide insights into the technological features and implications for industry of digital trends in the building sector, we assessed each of the 29 digital technologies along five dimensions: two technology-related dimensions and three industry-related ones: (1) the maturity level of each digital building technology (i.e., technology in development, emerging technology, state-of-the art technology, or industry-wide standard); (2) the *general-purpose digital technologies* a building technology draws on (i.e., cloud computing, IoT, Big Data, AI, mobile technology, mixed reality, Blockchain); (3) the primary impact area (i.e., efficiency, productivity, safety, quality, transparency, convenience, sustainability); (4) the building life-cycle phase in which a technology is primarily applied (i.e., planning phase; construction phase; use/ operations phase, or end-of-life phase); and (5) the primary industry actors affected by a technology (i.e., investors, planning offices, architects, construction companies, suppliers, utilities, or end-customers).

To ensure the robustness of our findings we pre-tested all dimensions (including the labels and parameter values) for clarity and consistency, asked several experts to assess and code each technology along the five dimensions, and compared their answers for levels of agreement/ disagreement and discussed diverging perspectives to converge and agree on a common understanding of the dimensions.

3. Digital building technologies

Among the 29 digital building technologies, we find a variety of digital technologies currently penetrating the industry. Table 1 draws a typology of four distinct types of digital building technologies and categorizes the 29 digital building technologies. The specific digital building technologies differ markedly in technology- and industry-related aspects. We first provide an overview of the four types of digital building technologies and subsequently discuss important aspects for each type separately.

Software-based complementary technologies are apparently more mature than any other type of digital building technology. In fact, both types of complementary technologies have a lower variance in maturity levels between the technologies in each category, suggesting that technology development and commercialization of complementary technologies follows a more coherent pattern. In contrast, the high variance among platform technologies reflects the substantive challenges in developing and commercializing digital platform technologies. The four types also differ in how extensively they draw on general-purpose digital technologies. Software-based technologies only rarely draw on general-purpose digital technologies. In contrast, nearly all cyber-physical building technologies involve underlying digital technologies, in particular automation, IoT and cloud computing. These differences in technology-related factors directly translated into challenges associated with R&D and with successfully commercializing technologies. Software-based complementary technologies are comparably easy to develop and commercialize. Yet, as reflected in the reliance on general-purpose technologies, technological complexity increases with the shift from software-based technologies to cyber-physical technologies and from complementary to platform technologies.

Table 1. Types of Digital Building Technologies, incl. the number of technologies in each type.

	Complementary technologies	Platform technologies
Cyber-physical technologies	**Cyber-physical complementary technologies (#9)** (1) Laser scanning; (2) automated prefabrication; (3) radio tracking devices in operation; (4) on-site drones (construction) (5) on-site robotics (construction); (6) predictive maintenance; (7) 3D printing (on-site); (8) 3D printing (off-site); (9) augmented reality (operations)	**Cyber-physical platform technologies (#7)** (1) Cloud-based logistic platforms; (2) sensors/ monitoring building data; (3) building automation; (4) optimization of building functions; (5) smart-building systems; (6) connectivity of building to infrastructure; (7) automated building condition analysis
Software-based technologies	**Software-based complementary technologies (#5)** (1) Computer-aided design; (2) logistic management software; (3) parametric design; (4) building performance simulation; (5) virtual reality in design and planning	**Software-based platform technologies (#8)** (1) Digital documentation; (2) Enterprise-Resource Planning; (3) Closed BIM 3; (4) E-Business & tendering; (5) mobile technology in project coordination; (6) customer service automation; (7) block chain in project documentation; (8) open BIM

Regarding industry-related aspects, digital building technologies primarily improve transparency, quality, and productivity; and although their potential to improve energy- and sustainability of the built environment, these improvements occur only indirectly. Moreover, the impact of cyber-physical building technologies appears to be more evenly distributed than that of software-based building technologies. Moreover, whereas software-based platform technologies are applied across all building life-cycle phases, from planning to end-of-life, cyber-physical technologies are used almost exclusively during construction (complementary ones) and use (platform ones) phases. Relatedly, while architects mainly focus on software technologies, construction companies and planning offices deploy both software and cyber-physical technologies. Investors primarily use software-based platform technologies, while end-customers and utilities cyber-physical platform technologies.

Overall, digital trends in the building industry appear in a variety of technologies that differ in maturity levels, underlying general-purpose technologies, impact areas, building lifecycle phase and affected industry actors. As the following subchapters will show, distinguishing complementary from platform technologies and software-based from cyber physical ones helps outline important differences in the technological and managerial challenges associated with digital building technologies and understand the disruptive impact these technologies may have on the structure of the building industry.

3.1. Software-based complementary technologies

Software-based complementary technologies account for the highest maturity levels among all types of digital building technologies. Most technologies are state-of-the art technologies or have already become a standard across the industry. Software-based complementary technologies also account for a comparably low technological complexity as they do not rely on large database architectures and rarely draw on general-purpose digital technologies. For many years, R&D among software-based complementary technologies has been rather incremental as technology providers have primarily focused on developing updates, adding new features, and have only recently drawn on cloud services and developed platforms to connect complementary technologies (e.g., see Microsoft 365 [13]).

For technology providers, key success factors are a detailed understanding of the working processes in which their technology will be used and development of intuitive user experiences and design [14]. Key users in the building industry are architects and planning offices, occasionally construction companies, to facilitate the designing of buildings (elements) and to improve the process efficiency during planning and construction (e.g., facilitating transactions, supporting design, visualizing tasks). Because software-based complementary technologies are stand-alone and task-specific, they rarely require substantive changes to the organization and are thus easily implemented and do not require alignment with partners, suppliers, or customers. Moreover, the economic benefits are readily apparent and explain why these technologies are already widely applied in the building industry.

Yet, despite the maturity of software-based complementary technologies, many industry actors still lack the expertise in handling and using them [15]. The implementation of software-based complementary technologies requires adequate training of employees. Frequently, developers offer trainings to support the transformative process of implementing software in daily working routines. Ultimately, software-based complementary technologies help actors in the building industry develop first IT capabilities and are thus an important route for companies to remain competitive in the market.

3.2. Software-based platform technologies

In contrast, the maturity of software-based platform technologies varies substantially. Whereas some digital building technologies (e.g., ERPs) are already widely dispersed, others (e.g., block chain in project documentation) remain in development. Software-based platform technologies can be found in all life-cycle phases of a building and all industry actors are potential technology users. They primarily foster transparency, thus directly addressing a major barrier for modernization in the building industry.

Platform size primarily explains differences in technological complexity, market penetration, and experimentation with new general-purpose technologies. Complexity increases with volume and heterogeneity of data and users; the more users, the more attractive for technology developers to experiment with general-purpose technologies [16]. Additionally, software-based platform technologies offer opportunities to collect valuable data to generate additional revenue streams, and thus offer substantive indirect benefits to platform owners.

Yet, successfully commercializing software-based platform technologies is subject to network effects, i.e., the value for one peer in the network increases with the number of peers. These network effects are particularly strong in market place platforms and can lead to two problems: a “cold start” problem (i.e., early adopters enjoy only few benefits and have little incentives to join) and a winner-takes-all markets that while highly beneficial to platform developers pose risks to early adopters.

These challenges may also explain the rather reluctant and uncoordinated adoption of software-based platform technologies. Improvements in transparency may require adopters to disclose valuable information (e.g., sub-contractors, technical processes). Moreover, the new role of the network operators may also give substantive powers to individual companies. Finally, the competitive dynamics around software-based platform technologies, as for example among BIM solutions [17], may drastically change the building industry as increased transparency may oust certain industry actors and competences in handling platforms may qualify for joining building projects. Notwithstanding these barriers, software-based platform technologies are key to a more sustainable built environment. Not only do the offer direct contributions through increased transparency. More importantly, by digitalizing processes, structures, and plans, software-based platform technologies often constitute the first step towards enabling sustainability contribution of other digital building technologies.

3.3. Cyber-physical complementary technologies

Cyber-physical complementary technologies are highly sophisticated technologies as they are designed to intervene and adapt to a building’s physical properties [7]. These technologies frequently draw on general-purpose technologies (e.g., IoT, cloud computing, AI) to connect multiple devices and recognize their physical environment. Because of the technological complexity and the need to account for the physical built environment, developing such technologies involves substantive R&D investments.

Cyber-physical complementary technologies are mainly used during the construction phase by construction companies and suppliers. Users primarily benefit because from increasing productivity in the production and construction process, improving the quality of building components, and reducing the risk of accidents because dangerous tasks can be allocated to autonomously machines.

Yet, although many cyber-physical complementary technologies are technologically ready for the market, they still account for low market dispersion [18]. One barrier may related to the substantive upfront investment for the user. Other barriers include the challenges that users face when integrating cyber-physical complementary technologies into their operations as it requires significant adjustment to established operational processes and structures. Furthermore, overcoming the communication and skill gap between technology providers and users requires significant investments in training, re-training, and hiring efforts.

Notwithstanding these barriers, cyber-physical complementary technologies promise several opportunities for new market developments. For technology providers, they offer avenues for new business models, such as product-service systems (e.g., leasing contracts based on usage), data-driven services (e.g., analyze user behavior to improve safety and efficiency in processes), or financial models (e.g., leasing, co-financing, etc.).

Overall, although the industry has only reluctantly adopted cyber-physical complementary technologies, these technologies offer opportunities for new market players to transform the building industry through new business models. By shifting investment patterns and workforce composition, they may significantly disrupt the industry with technology developers gaining prominence while threating small and medium sized companies. Most importantly, cyber-physical complementary technologies offer significant sustainability contributions in a, thus far, labor-intensive and error-prone life-cycle stage (i.e., construction) and thus deserve particular attention from policymakers.

3.4. Cyber-physical platform technologies

Cyber-physical platform technologies, such as smart building systems, require substantive sensor technologies in and around building to coordinate user behavior with building components. They also heavily draw on general-purpose technology, such as cloud computing, IoT, and AI. R&D in cyber-physical platform technologies faces both the challenges of cyber-physical technologies and those of platform technologies. R&D challenges pertain to the real-time processing of data to and to the level of process automation and sensors necessary for cyber-physical platforms. Possibly for these challenges, they remain in development and are nowadays mainly used in large public and commercial buildings.

Technology developers of cyber-physical platform technologies usually maintain ownership over platforms. However, because of the technological complexity and substantive development costs, they strongly incentivize external technology providers to develop complementary technologies, both software-based and cyber-physical ones, compatible with their platform ecosystem. Clearly, as developers seek to reach a critical mass of users to join their platforms and to create a lock-in effect, competition among developers intensifies.

Cyber-physical platform technologies appear particularly attractive entry technologies for new market players from adjacent industries, in particular technology engineering companies with experience in IoT. In fact, many non-traditional industry players with stronger ties to other sectors, such as Siemens or WAGO, entered the building industry with cyber-physical platform technologies. Similarly, many technology component manufacturers begin digitalizing their components by equipping these with IoT sensors, APIs, and smart metering technologies. Thus, cyber-physical platform technologies traditionally serve as an entry point for new market players into the building industry.

This merging of building industry with companies from adjacent industries also lead to changes in existing business models. Cyber-physical platforms also produce different revenue models depending on the service type over the building lifecycle and offer opportunities to monetize data through additional services (e.g., energy optimization, predictive maintenance, and customer / tenants services).

Overall, cyber-physical platform technologies appear particularly valuable for more efficiently managing buildings during their use phase. These technologies offer opportunities for cost savings and new revenue streams. Yet, given the challenges associated with R&D, the severe competition for platform leadership, and their limited potential to realize efficiency and productivity gains during the planning and construction phase, it remains unclear if, and if so how, cyber-physical platforms may transform the building industry.

4. Discussion

The diversity of digital building technologies is immense and although most digital building technologies are still under development, they are already beginning to fundamentally change principles of the industry. Digital building technologies offer substantive opportunities to create positive impacts across the entire lifecycle of a building. Major impact areas of digital building technologies strongly vary within the four types of digital technologies, introduced in this paper. Undoubtedly, digital building technologies help address important energy and sustainability related factors in that they offer several paths to reducing energy and material consumption, increasing energy efficiency, reduce planning errors and facilitate retrofitting and demolishing of buildings and recycling or reuse of materials. However, business models of digital building technologies only rarely address energy- or sustainability-related concerns directly, as value propositions of the four types primarily tackle the areas productivity, efficiency, transparency, and convenience. Hence, most of the benefits to sustainability accrue indirectly as secondary effects. Business models that primarily promise contributions to sustainability and energy seem to struggle in succeeding. Thus, policymakers designing incentives to move towards a more sustainable built environment require an understanding of how primary (non-sustainability) benefits translate into secondary (sustainability) impacts. Thus, although digital building technologies offer several opportunities to move towards a sustainable built environment, designing policy instruments and business models to realize these opportunities remains challenging.

To better understand the promises and pitfalls of digital building technologies, we argue it is useful to distinguish four types of technologies: (1) software-based complementary technologies, (2) software-based platform technologies; (3) cyber physical complementary technologies; and (4) cyber physical platform technologies. This typology is valuable because it illustrates differences in adoption barriers, opportunities for new business models, and the transformative capacity of digital building technologies.

In particular, software-based platform technologies and cyber physical complementary technologies offer promising new business opportunities and may fundamentally disrupt the industry. Software based platform technologies do so by increasing transparency and inducing a stronger focus on the planning phase thereby shifting the traditional distribution of roles and responsibilities in the industry. By promising to reduce planning errors, software-based platform technologies offer vast secondary sustainability effects. They will also raise the entry barriers for traditional building companies while offering an attractive entry point for new industry players. Overall, software-based platform technologies may lead to a significant consolidation in the building industry.

In contrast, cyber physical complementary technologies, primarily applied during construction of buildings, promise significant improvements in productivity and safety, and, as a side-effect, reductions in resource and material consumption. Additionally, for design and aesthetic purposes, cyber physical complementary technologies offer many opportunities to provide large-scale customized buildings, thereby offering an attractive path towards a modular built environment. However, these major benefits come along with at least one major challenge for policymakers. The immediate automation of production and construction processes renders futile many traditional employments and occupations in the building industry. Prefabrication and on-site robotics may eventually replace many workplaces in the industry and shift demand for labor-intensive work to assisting, controlling, and supervising machines.

Thus, digital technologies in the building industry have important implications for business models and the industry structure. First, future business models draw more heavily on services and data analytics, especially in the case of cyber-physical technologies. Furthermore, owners of platform technologies may monetize platform-based market access for 3rd parties [19]. This shift will clearly change the business models of companies in the industry. Moreover, the deployment of platform technologies may disrupt the underlying structure of the building industry by developing stronger linkages to other, adjacent industries (e.g., energy, mobility) and by changing the composition of the building industry. Thus, digitalization will not only lead to more digital building technologies but also, more importantly, will help integrate buildings into a broader, cross-sectoral environment.

Second, the increasing concentration in market power and the changes in the skills necessary to continue participating in building projects should lead to a strong consolidation in the building industry. Larger corporations with the ability to establish platform technologies and to invest in cyber-physical capital will have an advantage over small and medium-sized companies (SMEs) with fewer resources. As a result, SMEs might not only lose market power but also be outdistanced in terms of experience with digital technologies. Thus, digitalization poses a severe challenge in particular to SMEs.

Third, digital building technologies will have a strong influence on the employment conditions and the labor market of the building industry. Especially cyber-physical technologies significantly reduce labor intensity of construction sites. On the other hand, skill requirements for the effective deployment of digital building technologies constantly increase. Digitalization of the building industry will thus most likely lead to a substantial reduction and upskilling of labor force in the building industry. This trend will challenge companies (e.g., construction companies) to find ways to smoothly transition from a company with many employees to one with only few, highly skilled ones. Additionally, given that the building industry is major employer for low-skilled jobs, the labor market effects of digital building technologies should be more pronounced in the building industry than in other industries. Thus, policymakers should not only consider how to support the digitalization of the building industry but should also devise approaches for absorbing the negative side effects on the labor market.

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Life Cycle Assessment applied to construction and demolition waste treatment: proposal of a Brazilian scenario

Hackenhaar I C[1], Waskow R P[2], Tubino R[2], Passuello A[1]

[1] Postgraduate Program in Civil Engineering: Construction and Infrastructure - PPGCI. Federal University of Rio Grande do Sul – UFRGS. 90035-190 Porto Alegre – RS, Brazil
[2]Postgraduate Program in Mining, Metallurgical and Materials Engineering - PPG3M. Federal University of Rio Grande do Sul – UFRGS. 90035-190 Porto Alegre – RS, Brazil

ana.passuello@ufrgs.br

Abstract. Important amounts of construction and demolition wastes (CDW) are currently generated in several countries. Considering the correct management of this kind of residue, and the search for its noblest use, several studies have focused on the environmental potential impacts from CDW management. Life Cycle Assessment (LCA) is often used to investigate the potential environmental impacts over the life cycle of a product, thus becoming an important tool to support decision-making. CDW recycling process produces coarse, fine and mix aggregate as outputs, characterizing a multifunctional process. But, how CDW's LCA should be run, considering a circular and more sustainable built environment? Thus, the objective of this work is to explore the basic premises in proposing a product system for the CDW recycling process in Brazil. For this, data available in the literature on the recycling process in Brazil and in other countries support the definition of the product system. The complexity of this management option is explored, considering how the use of the recycled materials interfere in the scope, objective, unit function and other modelling choices, as well as reliability of CDW studies. Finally, the datasets provided by Ecoinvent are examined in order to promote debate on data adaptation, followed by remarks on the most appropriate choices on allocation in the CDW LCA. The cut-off system modelling associated with the new perspective on the avoided burden approach is concluded by the authors to be the most suitable for this waste recycling multifunctional processes. Understanding system models is key. When no inventory adaptation is intended, available inventory datasets are more advisable to be used when performing end of life scenarios only, once burdens differ according to countries management scenarios, as well as life cycle inventory approaches.

1. Introduction

The construction industry plays an important role in society. The processes of urban expansion or connection between cities demand the construction of buildings, residences, paving and urban maintenance, roads, train lines, among others.

The execution of engineering works requires the use of natural resources, such as coarse aggregates. Brazilian aggregate consumption in 2014 was 741 million tons, of which 302 million tons correspond to the consumption of natural coarse aggregates (NA), from 4.74 -19.1 mm. The potential per capita demand for aggregates for Brazil in 2014 was 3.7 tons, still lower than European Community (5.2 tons), USA (9 tons), China (12 tons) and Finland (17 tons). The Brazilian regions that consume the most natural aggregates are Southeast (47%) and Northeast (21%), followed by South (16%), Central West (9%) and North (7%) [1].

Associated with this large amount of natural resources extracted, there are potential environmental impacts that must be considered. The assessment of potential environmental impacts should serve as a basis for decision-making in actions to make building processes more sustainable.

The aggregates from construction, maintenance and/or demolition stages of construction works, called recycled aggregates (RA) from construction and demolition wastes (CDW), can be considered as potential surrogates for NA, observing their environmental viability, in addition to performance and costs.

The use of the Life Cycle Assessment (LCA) in a study of CDW recycling scenarios has gained attention, with growth in the number of publications in recent years [9] [21]. The definition of the product system in these studies, however, lack the application of concepts, such as allocation, multifunctionality of processes, system models and among others.

Thus, the objective of this paper is to explore the basic premises in proposing a product system for the CDW recycling process in Brazil. For this, data available in the literature on the recycling process in Brazil and in other countries support the definition of the product system. The system models proposed by Ecoinvent and background data available by the database are observed. Available data in the Ecoinvent are suggested as background data, considering the cut-off system modeling associated with the new perspective on the avoided burden approach, suitable for the multifunctional process.

2. Method

A literature review on the topics was conducted in other to add information into the product system definition, as well as system modeling choice to conduct LCA studies for CDW management. The first stage consists of a literature review on the existing research models. Secondly, an analysis of the CDW market in Brazil is presented as a case study. The product system is then defined. Finally, the datasets provided by Ecoinvent are examined in order to promote debate on data adaptation, followed by remarks on the most appropriate choices on system model and allocation in the CDW LCA.

3. Life Cycle Assessment and Construction and Demolition Waste

Bovea and Powell [21] showed growth in researches of LCA of CDW between 1999 and 2015, in consequence of European directives and ISO 14040 series standards. Yet, most CDW LCA studies present a lack of information about the system model adopted in the calculations, among others [22][23][24].

In a recent literature review [22], the authors identified a total of 91 published researches on LCA of CDW. Most of the reviewed researches focus on the cradle-to-grave analysis of buildings, considering the waste management into the EoL scenarios after demolition. Although the analysis are reasonable for EoL scenarios, there is a misinterpretation of the term “construction and demolition waste” management once most papers assess only demolition wastes. Moreover, the majority of the research papers assess the EoL for a variety of materials, as a result of the entire building demolition. The EoL inventory and processes are rarely detailed, however, several scenarios were assessed, as re-use, recycle, landfilling, incineration and composting for wood material.
Only 5% of the researches informed the life cycle inventory (LCI) analysis’ modeling approach. Considering that the recycling of CDW for RA production is a growing market for substitution of NA, the modeling approach could reflect a significant difference in the impact results, e.g. for natural resources depletion. Systems with high recycling rates have the choice of the system model adopted as a key factor [25].

Besides the studies, the treatment in waste management is strongly addressed in an update of the System Models carried out by one of the most worldwide used databases, Ecoinvent. In its version 3, in addition to the introduction of the Consequential approach, the attributional approach is presented in two system models, allocation at the point of substitution (APOS) and Cut-Off. In the cut-off model, for example, all intermediate exchanges (i.e., exchanges within the technosphere) are classified into either “allocatable by-products”, “recyclable materials” or “wastes”. The classification is based on the expert judgment of an exchange’s value, use potential, and predicted fate [25][26]. Depending on this classification, byproducts (i.e., products that are not the reference flow) in multi-functional activities are handled differently [25][27][28][29][30].

4. Brazilian CDW Market

The literature review showed that most of the LCA application to CDW management is connected to the building's LCA. However, the market for this kind of waste still developing and information is needed to support decisions related to CDW recycling.

4.1. Source and composition of the Brazilian CDW

CDW is a generic term that defines the waste generated by the economic activities involving the construction, maintenance, demolition and deconstruction of buildings and civil works [2]. The CDW can be generated in activities like construction and demolition of buildings and infrastructures, roads and their maintenance, disaster debris, among others. Data available from Brazil suggest a higher generation of new reforms and repairs, followed by new constructions, reaching 76% and 67%, respectively, of the total CDW in some important Brazilian cities [3][4][5][6][7]. According to the same sources, another significant source of CDW in Brazil is demolition, although this does not represent 50% of the CDW in any evaluated city.

In a previous work [9], a systematic review identified that in the average composition of Brazilian CDW, the most representative materials are concrete, ceramics and mortar (Figure 1). However, the amount (in %) of each material may vary considerably.

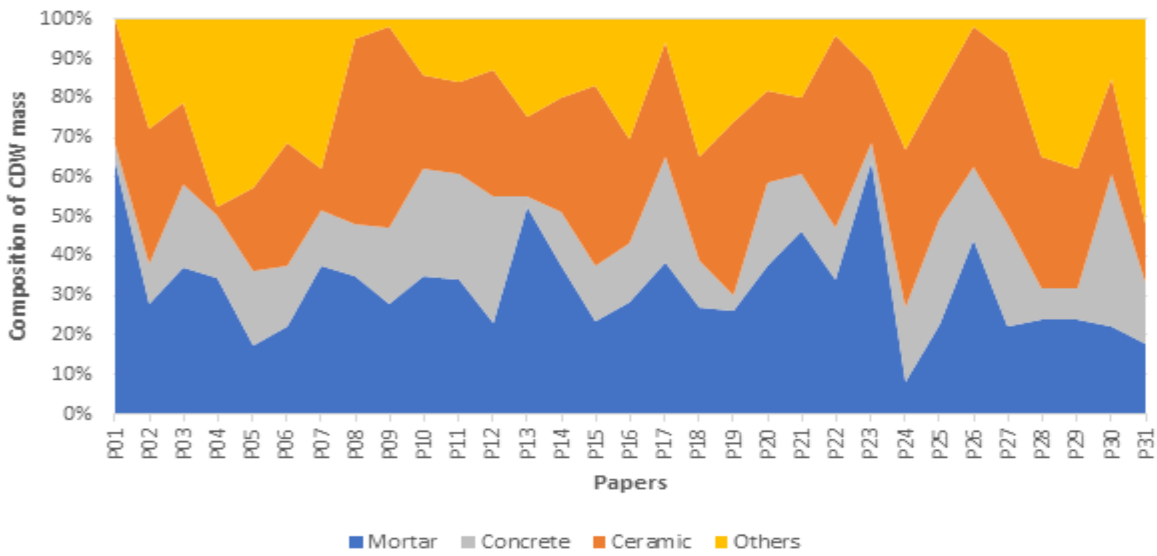

Figure 1. The composition of Brazilian CDW from 31 papers published available in a systematic review realized [9].

4.2. Future use and RA performance

RA is a coarse material derived from the beneficiation of CDW. The use of RA in concrete has still some technical limitations since their performance varies depending on the source material and its properties, such as compressive strength, shape, abrasion resistance, presence of cement incompatible materials, among others. Associated to this, there is a low level of confidence on the mechanical performance of the concrete with RA when compared to the concrete composed by NA, a commonly used material with known properties.

Although concrete applications are the noblest, the use of RA as sub-base materials for roads, backfilling and maintenance for unpaved roads, and higher grade applications (e.g. aggregate for new structural and non-structural aggregate) also has a high potential. However, assuming that the product complies with high-quality standards, the use of RA in structural concrete manufacture is widely accepted in the scientific community as an alternative to replace NA [10][11][12][13].

According to Gálvez-Martos et al. [15], RA from mixed wastes, usually with a minimum of 50% concrete content, can be used for buildings and other civil works, for non-structural concrete.

Cabral [11] generated a series of models to simulate properties such as compressive strength (fc) and demonstrated that the partial replacement of NA by RA can achieve the same compressive strength of concrete composed in 100% of NA, when adjusting water/cement ratios.

Figure 2 shows the main impediments in the reuse of the Brazilian CDW, mainly related to composition and quality, available technology and market of RA. Positive issues that need to be highlighted for the purpose of expanding recycling of Brazilian RCDs are also described in the same figure.

STRENGHTS	WEAKNESSES
❑ Reuse of an inert material; ❑ Reduction of landfill / uneven disposal; ❑ Reduction of natural resource consumption (NA); ❑ National Policy on Solid Waste; ❑ Seek for nobler uses; ❑ New marking opportunity.	❑ Residue of very diverse composition; ❑ Existence of impurities of other materials with the CDW; ❑ Poor quality of the material; ❑ Unknown performance; ❑ High NA availability in most regions; ❑ Low-tech recycling plants; ❑ Lack of established market; ❑ Distance of collection/delivery *vz.* distance from NA mines.

Figure 2. Strengths and weaknesses related to CDW recycling in Brazil, based on [7][12][15][16][17][18][19].

4.3. Growth and economic representativeness of CDW in Brazil

There is no consolidated information available on the CDW market or its economic representativeness in Brazil. In 2014, construction consumed 811 million tons of cement and natural aggregates [1], thus considering the generation of the residues only in the construction phase, an important market can be exploited. In addition to these values, we must consider the waste generated in renovations or demolitions, the main CDW generators in Brazil [3][4][5][6][7].

According to Brazilian Association of Public Cleaning and Special Waste Companies - ABRELPE [20], the Brazilian municipalities collected about 45 million tons of CDW in 2017, an average of 123 thousand tons of CDW per day or 600 g.person-day. Although the RA market is not yet exploited, there are still some challenges to overcome. The latest sectoral research by the Brazilian Association for the Recycling of Civil Construction and Demolition Waste [17] shows an optimistic perspective based on the capacity of treatment plants in operation. Over 52% of plants have a nominal capacity to produce up to 3000m^3/month, and another 31% over 10,000m^3/month. Still, until 2015, only 11% of those operated with full production. At the time, 93 plants were producing around 431,500 m^3 of RA per month, while the total installed capacity was 958,000 m^3. Moreover, the research also showed that RA price is up to R$20.00 per m-3 (around US$ 5 per m-3).

Considering the total generation [17] and the maximum total production capacity of the mills [20], it is possible to infer that only 0.5% of the total CDW generated per year in Brazil is recycled, the other 99.5 % is mainly destined for landfill. Thus, the installed capacity of CDW recycling plants is underappreciated but still much below CDW availability.

In 2009, Miranda et al. [7] have already identified the basic structure available in the Brazilian recycling plants: loader or backhoe, vibrator feeder, conveyor belt, jaw crusher or impact, permanent magnetic separator or electromagnet, and vibrating screen. In this way, the material is comminuted and separated by size without any quest to improve its quality. Thus, the final product carries characteristics equal to the input material.

5. Proposal of Brazilian CDW product system and modeling approach

The results from the Literature review are summarized in the proposed product system for the Brazilian market (figure 3). The figure shows the potential input wastes according to Brazilian classification and the path to be followed by the waste until the output for the recycled products, using the waste concrete gravel as the desired RA output. The dotted line in the system represents by-products. The dashed line that separate flows represent the change on waste management responsibility (from construction managers to recycling plants' managers), also representing a monetary change between stakeholders (the waste disposal or recycling services). The authors suggest that to avoid misinterpretations on the allocation for recycling product, when the recycling processes depend upon a tertiary service, the recycling process should be treated separately from the construction and demolition process, and to the future use, and only further connected to them.

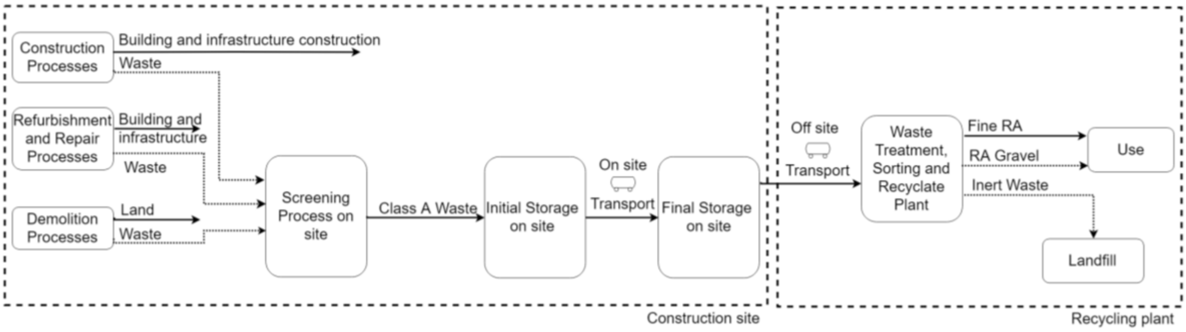

Figure 3. The potential input wastes according to Brazilian classification and the path to be followed by the waste until the output for the recycled products, using the waste concrete gravel as the desired RA output.

From there, the questions that arise are: how to allocate environmental impacts, from an LCA perspective, in this system? Should burdens from waste management be allocated to waste provider, or to the disposable and recycling services? And how to represent avoided burdens from recycling to the consumers of the recycled materials? These questions concerned the following discussion of approach and decision while modeling an LCA on CDW management. As well as the definition of the proposed product system for the Brazilian CDW recycling scenario, the definition of the system model and allocation should be considered since it is a multifunctional process.

5.1. The Ecoinvent® database and the CDW EoL

The Ecoinvent database provides data, generally generic and average data, that can serve as a background in defining or adapting datasets. The dataset regarding the recycling of CDW, for example, has its origin in Switzerland. According to the "Life Cycle Inventories of Waste Treatment Services" report from Ecoinvent® [31], there are three main disposals/recycling of CDW options in Swiss, direct recycling, partial recycling after sorting, and direct final disposal without recycling - represented in the Figure 4 as "A", "B" and "C", respectively.

The inventory distinguishes the construction materials according to the recyclability, for example, those destined for recycling and those destined for disposal in a landfill. No distinction is made between different building phases source of wastes (construction, refurbishment, and repair or demolition), and all datasets consider the same demolition energy within the system boundaries. Thus, CDW is only originated from the demolition stage, diverging from the Brazilian reality.

Following the methodology provided by Ecoinvent® [31], no bonus or burden compensation are given for recycling material, on the versions preview to v. 3. No partial allocation of burdens from recycling processes to the first product and recycled products were made. Instead, the system boundary for both "A" and "B" disposal options does not include the recycling process, but includes sorting plants and the disposal of non-recyclable material. In this sense, waste concrete gravel, for example, does not include the recycling plant burdens, once the data "cut-off attributes all further processes (transport, sorting, recycling, etc.) to the recycled product consumer and not to the first user of the (raw) material" allowing, in this way, to conclude that the data is directed towards the end of life of the building.

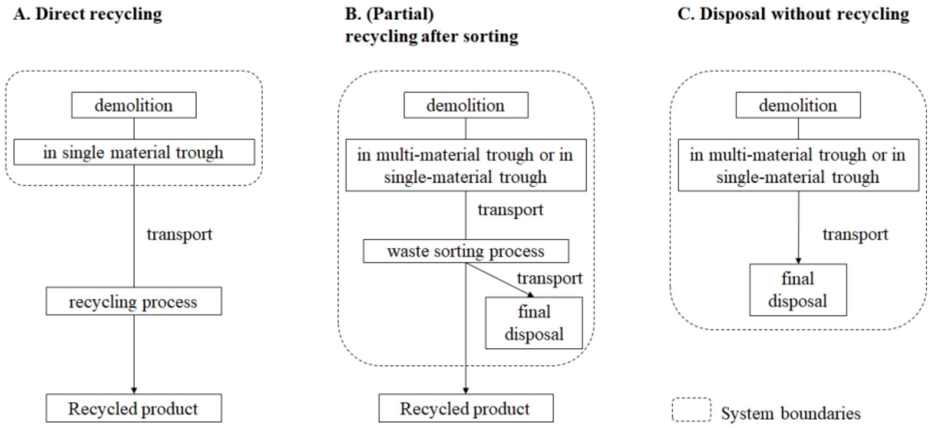

Figure 4. System boundaries of the three types of CDW disposal options according to Doka [31].

5.2. A new perspective in LCA of CDW management

According to Baumann and Tillman [32] the allocation problem happens in three basic cases: (I) when processes result in several products, meaning multi-outputs; (II) waste treatment processes that have different input sources, meaning multi-inputs; and (III) open loop recycling, meaning that a product is recycled into a different product, which implies that they share common activities, as the extraction of the virgin materials. The allocation can be avoided in the two first cases by detailing the model, but it is not true for the third case. Baumann and Tillman (2004) indicate the procedure to be adopted is either allocation through partitioning or system expansion. Partitioning would be applicable to traditional attributional LCAs, as the system expansions would work better to LCAs modeling effects of changes (consequential).

In the case presented on CDW recycling market in Brazil, the three allocation problems are observed, due to multi-inputs (construction, demolition, refurbishment, etc.), multi-outputs (different class of residues), and to the fact that the recycled products as concrete gravel have an open loop recycling process.

Also, the replacement of NA by RA is not expressive in the Brazilian market due to the lack of offer (low recycling content rates). Thus, the consequential approach based on Ecoinvents datasets wouldn't be appropriated in this case, once it would take a long time or an extreme change in CDW management policies so that the replacement affects NA market. In this last case, the consequential approach would feature the potential effects of RA use in the new constructions. Moreover, a system expansion would be needed, and the other materials recycled included as by-products in the same process, which is not integrated into the Ecoinvent consequential datasets.

That being agreed, the attributional approach would then be used with the need for an additional allocation procedure. Among the literature, Saade [33] presents a new approach to the decision-making process by the co-product user industry. Some factors contributed to the definition of this new approach, such as: the inadequacy associated with the use of the most common allocation criteria (mass and economic value), where the scarcity of virgin raw material is replaced by the co-product and benefit of the recycling of a co-product to the detriment of raw material consumption; the avoided impact approach, as typically adopted, fails to distribute the benefit fairly, since the environmental burdens that cease to exist with the replacement of virgin raw material by the co-product are reduced in their entirety from the multifunctional process which generated the co-product without considering, for example, the impacts associated with the processing of the co-product, avoided loads (eg end-of-life) and other results for co-product reuse. The author then proposes an alternative manner of calculating the avoided impact. This proposed approach consists of adding or subtracting from the avoided impact associated with the replaced product, all potential loads caused and/or avoided by the replacement. The net avoided impact is then the avoided impacts from the substituted product (value given by conventional allocation), minus the impacts associated with the processing of the by-product or waste, and other burdens from the recycled material life-cycle until its uses (such as transport), plus the impacts associated with the business as usual (BaU) final disposal of the waste [33]. Thus, it is possible to evaluate the environmental viability of the recycling process.

In the case of CDWs, the use of RA minimizes the potential impacts of NA extraction that is not extracted. Then, first the environmental load of the amount of NA that can be substituted by the RA in the assessment inventory should be considered as negative inputs. Secondly, there are impacts through the CDW beneficiation process, mainly related to transportation of waste and distribution of the recycled material, and electricity consumption for the comminution process. Those would be considered as positive inputs. Similarly, within the approach suggested by Saade [33], are considered the negative input the not disposing of the waste. In this case, BaU scenario would be the landfilling, and the recycling or reuse of the material would also represent avoided burdens.

6. Final remarks

According to the system resulted from the literature review, the background databases and literature reference may be used for analysis with some regards.

The first important issues to pay attention is the objective of the analysis and boundary of the system to be analysed. The review made in this study, as well as the guidelines for calculation method on assessment of the environmental performance of buildings in the BS EN 15978:2011, might suggest the differentiation of two types of analysis regarding the CDW: the EoL scenario for construction demolition, and CDW recycling and reuse analysis. Both are not mutually exclusive. One may carry an analysis of EoL scenario for one building and include the recycling and reuse avoided burdens (Module D, according to EN 15978). However, the analysis does not exemplify the market for recycled construction materials, once it would be representing only that demolition waste portion of the market. For analysis considering the recycled materials, the origin and composition are meaningful for the inventory of sorting and recycling process, and the intended use is critical regarding the rates of recycled content use.

Regarding Ecoinvent® datasets, some inputs need to be removed during inventory adaptation because they are not part of the analysis by the system model and product system suggested for the Brazilian scenario. Considering the recycling market, the construction waste burdens would be spared. As previously discussed, in developing countries these burdens could be significant, due especially to the transport of waste. Adjustments of the current data available are necessary in order to reflect the scenario of the CDW Brazilian recycling management and plants. Following the discussion made, these datasets are more advisable to be used when performing EoL scenarios only. RA, for example, is not a co-product of construction, however, the avoided burdens should be accounted when performing new constructions or materials LCA with recycled content. Local inventories should be used when analysing these avoided burdens.

The characteristics adopted by the systems models currently available in the Ecoinvent® database suggest that the adoption of the cut-off system is the most appropriate, and it is possible to combine this system model with the new approach proposed by Saade [33] in order to consider the potential impacts avoided serving as an incentive to the recycling process. With such integrated modelling, all life-cycle process of waste recycling is added to the environmental avoided impacts. The integrated modelling can then represent a better approach to the realistic benefits of recycling.

The identification and availability of information on the representation of CDW recycling in the Brazilian economic scenario may, together with the inventory of other information, corroborate with the elaboration of market data for Brazil.

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Consequential life cycle assessment of Brazilian cement industry technology projections for 2050

Gomes V[1], Cunha M P[2], Saade M R M[1,3], Guimarães G D[1], Zucarato L[1], Ribeiro C H[2], Gomes da Silva M[4]

[1]School of Civil engineering, Architecture and Urbanism and [2]Economy Institute of the University of Campinas, Brazil
[3]Université de Sherbrooke, Canada
[4] Federal University of Espirito Santo, Brazil

[1] vangomes@unicamp.br;

Abstract. In the upcoming decades, cement production growth is expected to exceed the increase in availability of clinker substitutes. Increased clinker replacement rates in cement and use of alternatives fuels were pointed out as the main alternatives for reducing emissions of the national cement industry, whilst increasing cement production in 2050. Consequential life cycle assessment (CLCA) offers a framework to capture environmental consequences from demand alterations. Modelling the cement production and markets involved is however challenging, given conceptual (only unconstrained markets are considered) and practical modelling limitations (e.g. model granularity compatible with CLCA interests). This paper refers to an ongoing work and adopts a two-stage approach to discuss the effects of the change on the average cement production process in Brazil. We first performed a CLCA without formal affected market identification to estimate the potential environmental impacts of the technology change proposed in the Brazilian Cement Technology Roadmap. Secondly, we used a Computable General Equilibrium (CGE) Model of the Brazilian economy to (more) realistically foresee short-term effects induced by such change. The CGE model comprises 102 economic activities, including cement production and its production chain. Our results indicate that (i) increasing the proportion of calcined clay and limestone filler as clinker partial substitutes and (ii) excluding charcoal from the fuel mix composition at the kiln would impact all economic sectors. Our preliminary findings suggest that the increased efficiency in cement production would create some rebound effect that would not invalidate the emission benefits from displacing energy and virgin materials. Additional impact categories and consequences in other economic sectors should be further investigated.

1. Introduction

The recovery of the Brazilian economy from its current recession, and subsequent GDP growth plus the infrastructure and housing deficit should drive up cement demand steadily from 2020 to 2040. According to the Cement Technology Roadmap for Brazil [1], the production is expected to reach its peak in 2045, should it follow a high- (170Mt) or a low-demand variant (127 Mt), considered more realistic. Such long-term growth poses a considerable challenge to the Brazilian cement sector in terms of energy demand and CO_2 emissions.

The cement manufacturing industry is one of the five most energy intensive sectors in the world. Typically, 30% to 40% of the direct CO_2 emissions result from burning a mix of fuels, whilst 60% to 70% are produced by the chemical reaction that converts limestone into calcium oxide (calcination) to form Portland clinker. Additional indirect 5% of CO_2 emissions result from electrical consumption by the industrial plant. Whilst the calcination contribution (63%) and the burning of fuels (36%) are within world average emission ranges, indirect emission from electricity consumption in Brazil is only about 1%, due to its distinguished, highly renewable (>70%), electricity matrix.

In 2014, the Brazilian cement industry utilized 1.5 million tons of waste (8%) and biomass (7%). At the current level of thermal substitution, the remaining 85% of the fuel mix is fossil-based, mostly petroleum coke (petcoke). These figures show potential for increased use of biomass and waste - including municipal solid waste - as fuel, given the favorable characteristics cement kilns offer to coprocessing - i.e. combined operation of manufacturing cement together with the burning of waste – favoring impact reduction from otherwise inadequate disposal of waste in nature [1].

Simulated contribution of non-renewable fossil fuels in cement production could diminish from 85% to 45%, due to increased share of waste and biomass in the fuel mix. Decrease in the projected thermal and electrical intensity would become more noticeable after replacement of obsolete equipment by 2030 and reach 3,2 GJ/t of clinker (92 kWh/t of cement) by 2050 [1].

The Brazilian raw material has higher magnesium carbonate content and, therefore, higher calcination factor than the world average. Still, the Brazilian cement industry has one of the lowest specific CO_2 emission levels in the world, due to mitigation actions implemented over recent decades, such as use of alternative fuels and clinker substitutes. Blast furnace slag (bfs) and fly ash have been used as additives to Portland cement for decades.

In 2014, more than 95% of granulated bfs produced in the country was consumed by the cement industry [1]. However, increased use of bfs by the cement industry is challenged, in the short and medium term, by the lower growth in supply in relation to the increase in cement production, due to the rising global competition faced by the national steel industry; and in the long term by the evolution of technological processes, with a lower production of slag per ton of pig iron produced. Fly ash shows a similar trend, due to lower investments in coal-burning thermoelectric plants, decarbonization of the Brazilian electric grid, and low utilization factor of thermoelectric plants, which was around 50% in 2013 [1].

Considering the constrained supply of the major clinker substitutes used today (bfs and fly ash) and the increased demand for cement in the long run, the Roadmap BR projected decreases in the clinker factor (proportion clinker/cement) based on increased proportions of limestone filler and calcined clay as clinker alternatives. Practical implementation of such measures still faces technical, economic and legislative limitations created by e.g. different applications of the final product, environmental regulations and technical standards, local availability of raw materials, logistics complexity and costs, contractual difficulties to ensure waste supply, and challenging performance (calorific power, high moisture and concentration of chlorine or other detrimental substances) [1]. Nevertheless, these assumptions formed the basis of our assessment.

Consequential LCA (CLCA) modelling aims at identifying the study boundaries to encompass likely consequences of an action or decision [3]. While attributional life cycle assessment focuses on describing the environmentally relevant impacts of the activities that contribute to a specific property of a product or process, consequential assessment describes how environmentally relevant impacts will, or could, change in response to the studied action or decision [5]. Attributional and consequential modelling are therefore intended to answer different questions [3]. Attributional LCI aims at answering "how are environmentally relevant things (pollutants, resources, and exchanges among processes) flowing within the chosen temporal window?" whereas Consequential LCI aims at answering "how will flows change in response to decisions"? [6].

Ultimately, the differences between attributional and consequential LCA are the result of the choices made in the Goal and Scope Definition phase of the general LCA process [5]. In order to incorporate possible consequences, CLCA models include additional economic data like marginal production costs, elasticity of supply and demand etc [4].

In CLCA, the system boundaries are defined to include the activities that change as a consequence of a small change in the demand for the studied products. To understand the potential consequences of a decision that involves the substitution of one product with another, the differences between the alternative product systems - that have the same output, fulfil the same performance requirements, i.e., have the same functional unit - are modelled [5]. Prox and Curran [5] explain the step-wise procedure originally proposed by Weidema et al. [7], which consists of: Step 1 – describing the product by its properties; Step 2 – identifying market boundaries; Step 3 – identifying product alternatives; Step 4 – defining the functional unit; and Step 5 – determining reference flows for alternatives.

The functional unit is the service delivered by the product system (i.e. it represents the meeting of the demand for an additional unit of the product under study), which provides a reference for inputs and outputs to be related. The choice of functional unit should reflect the quantity, properties, and duration of the product/service of interest. And ensure same functionality for the alternatives compared. Where it represents the meeting of the demand for an additional unit of the product under study, the functional unit does not displace any marginal product [2].

The system boundary definition determines which processes are to be included (or not) in the assessment. CLCA only considers ‘unconstrained markets’, that is, those represented by determining products. A determining product is defined as a product for which demand is directly linked to its production. Contrastingly, a co-product is said to be dependent when demand for it has no influence on its production. Such ‘constrained markets’ are excluded from the CLCA system boundary. Also, CLCA should only include the activities that change as a response to an additional demand for the functional unit, and the corresponding marginal effects, i.e. the effects that take place *in addition to* what would have happened without an increased demand for the functional unit (*ceteris paribus* principle), displacing e.g. marginal virgin materials and energy flows [2].

This paper aims at assessing the environmental consequences of the proposed change for the cement production technology in Brazil, by identifying the reference flows for alternative energy and virgin materials whilst offering wider consideration of reflections on other productive sectors. Our baseline was the production system in 2014, modified by incorporating fuel mix and cement composition projected by the Roadmap BR for 2050.

2. Method

We followed a two-stage approach to discuss the effects of the change on the average cement production process in Brazil. We first perform a CLCA without formal affected market identification to estimate the potential environmental impacts of the predicted change by solely using data published in the Roadmap BR [1]. Secondly, we used a general equilibrium model of the Brazilian economy (Section 2.5) to (more) realistically foresee which short-term effects are induced by this change.

Our CLCA was conducted following the ISO standards. First, the goal and scope of the study are outlined, to set the context for the study and ensure that the outcome is consistent with its objectives. The adopted functional unit provides a reference for inputs and outputs to be related. The corresponding system boundary is described separately below. SimaPro 8.5 supported the assessment. The inventory that reflects the studied system is composed by primary data for the clinker production (foreground), and secondary data from the Ecoinvent v3.4 database adapted to the Brazilian energy mix (background). Finally, the environmental implications were reviewed in the impact assessment step using CML-IA baseline v3.05, and the results were interpreted and iteratively revised.

The goal of our CLCA was to estimate the potential environmental impacts of the decision to implement two major technology changes in the Brazilian cement production process projected for 2050 described in the Roadmap BR [1]: change in cement composition (route 1) and change in the fuel mix used (technology route 2), relatively to cement production as per 2014 (baseline).

Key to defining the scope of CLCA is an endeavour to foresee what changes are induced by implementing the decision under assessment. The geographical scope of this assessment is Brazil, which defines the related legislative, political, and market contexts important to determine the marginal processes and technologies affected by the changes in demand analysed. The technological scope refers to cement production as per 2014 (baseline) and the same production capacity but after the technology changes considered. The temporal scope of the assessment is 2014-2050. Long term, investment-intensive route 3 (carbon capture and utilization or storage - CCUS) is not included in this study. Therefore, the time horizon refers to short term marginal effects (‘operational margin’). This means that existing capacity can absorb the shocks of changes in demand for the functional unit and only changes in the utilization of existing production capacity are considered.

Table 1 summarizes characteristics of clinker and cement production as per 2014 (baseline) and after technology changes projected for 2050.

Table 1 - Characteristics of cement production as per 2014 (baseline) and after technology changes projected for 2050 [1]. Determining and dependent products as indicated.

1 t of (average) cement 2014 (baseline) Inputs	**1 t of (average) cement 2050 Inputs**
3,5% gypsum 1% other	3,5 % gypsum 2% other (+1%)
14% ggbfs (dependent) 3% fly ash (dependent) **3% calcined clay (determining)** **8% limestone filler (determining)** **68% clinker (determining)**	11% ggbfs (-3%) (dependent) 2,3% fly ash (-0,7%) (dependent) **4% calcined clay (+1%) (determining)** **25% limestone filler (+17%) (determining)** **52% clinker (-16%) (determining)**
Fuel mix clinker (3,5 GJ) **6% charcoal (determining)** 85% petcoke (dependent) 0,7% agricultural waste (dependent) 4,6% scrap tires (dependent) 3,5% industrial blend waste (dependent)	**Fuel mix clinker (3,22 GJ)** **0 charcoal (-0,21 GJ) (determining)** 45% petcoke (-40%) (dependent) 3,7% agricultural waste (+3%) (dependent) 5,1% scrap tires (+0,5%) (dependent) 4% industrial blend waste (+0,5%) (dependent) 7,4% sewage sludge (+7,4%) (dependent) 17,4% non-hazardous waste (+17,4%) (dependent) 17,3% municipal solid waste (+17,3%) (dependent)
113 kWh average electricity demand	92 kWh average electricity demand (-21 kWh)

The defined functional unit for this study is 1 ton of (average) Roadmap BR cement technology projected for 2050. Figure 1 shows the CLCA System boundary used in this study. Only determining products from the fuel mix (charcoal) and from the clinker substitute palette (limestone and clay) were computed within the system boundary. Displaced virgin materials refer to flows suppressed by increased shares of calcined clay and limestone filler to reduce clinker content. Displaced energy and electricity refer to the removal of charcoal from the fuel mix and increased technology efficiency in cement manufacturing.

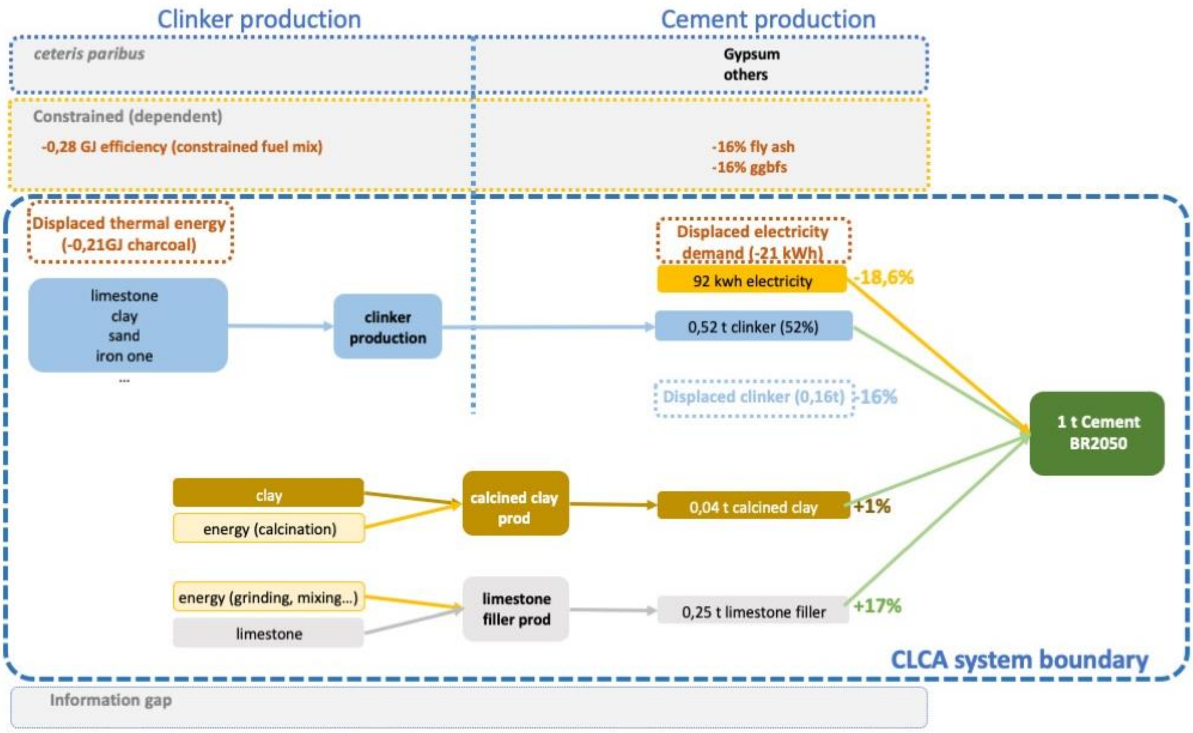

Figure 1 – CLCA System boundary used in this study showing displaced energy (thermal and electricity) and materials (clinker) and added inputs (calcined clay and limestone filler). All dependent products (constrained markets) are excluded.

2.1. Economic modelling

A Computable General Equilibrium (CGE) model enables to capture the consequences that a technological change from one single sector has on the output level of all other sectors of a given economy. For didactic purposes, Figure 2 illustrates a simplified (two-sector) economy according with the CGE model used in this paper.

In the domestic economy, the production level (XDj) of each sector (j) will combine an aggregate of inputs from the intermediate consumption (IC, e.g. X_{11} and X_{21} for sector 1, in Figure 2) with value added (VA) through a Leontief function, which requires inputs in constant proportions. The value added (VA) in each sector combines the capital (Kj) and labor (Lj) factors through a Constant Elasticity of Substitution (CES) function, which allows the substitution between the capital (Kj) and labor (Lj) factors whenever their relative prices change; whilst the intermediate consumption (IC) from a sector (j) refers to the use of inputs in a constant proportion (Leontief Function) and each of these inputs is in its turn a combination of domestic (XDDj) and imported (Mj) inputs..

The proportion of the production level (XDj) that stays in the domestic market (XDDj) or is exported (Ej) is defined by a 'constant elasticity of transformation' (CET) function, which considers the changes in the product's relative prices in the international and domestic markets. The domestic production of product j (XDDj) is then combined with that product imports (Mj) through an Armington function, which considers the product's relative prices in the domestic and international markets. The resulting sector supply of product j in the domestic economy (Xj) feeds the intermediate consumption (IC) and the final demand (FD), the latter composed of household consumption (C), government consumption (GC) and investments (I), essentially in civil construction and capital goods.

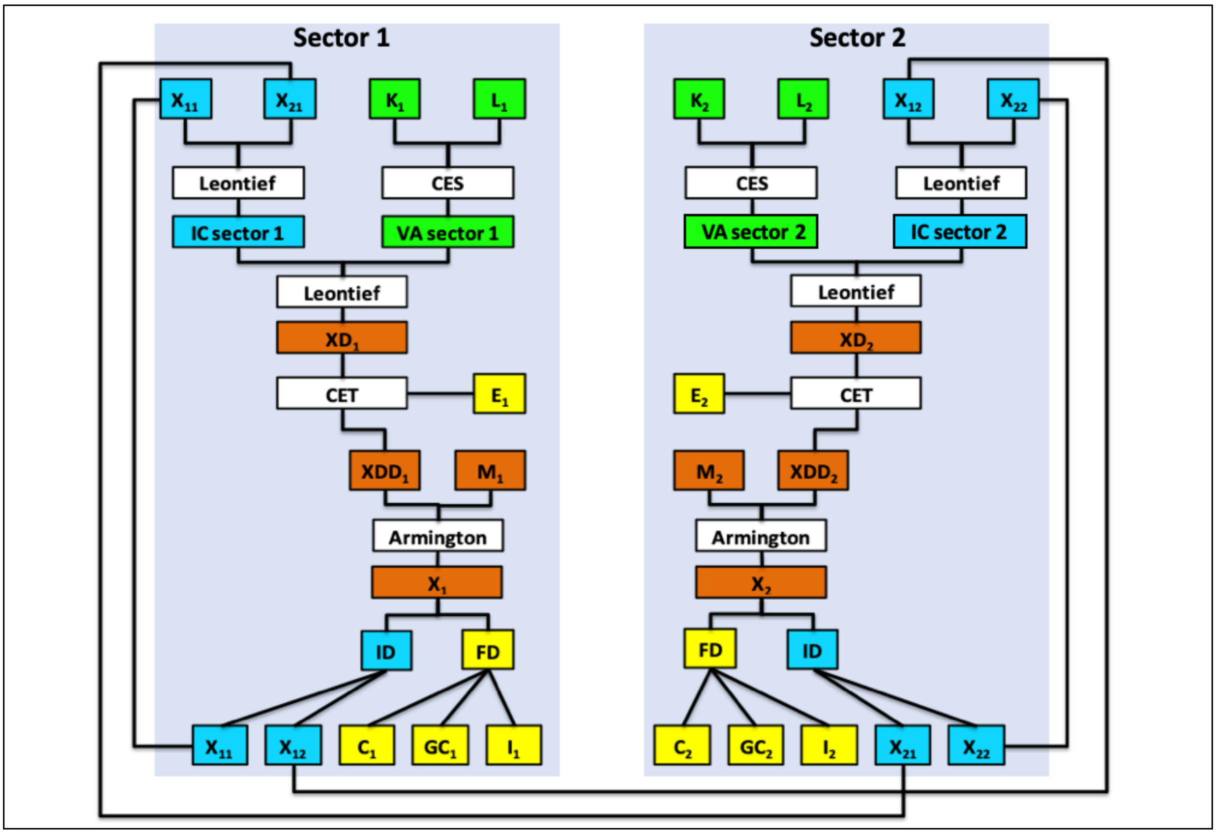

Figure 2 – CGE model used in this study illustrated for a two-sector economy. Blue boxes represent the products and services' intermediated consumed (IC). Green boxes show the primary production factors: labor (L_j), capital (K_j), the elements of VA, the value added. Production (CES, Leontief and Armington) and transformation (CET) functions are shown in the white boxes. The brown boxes stand for the sector supply of products: X_j is the supply in the domestic economy, composed of the product's domestic market, XDD_j (production level XD_j minus exports E_j), and its imported share, M_j. Finally, the yellow boxes consist on the final demand products of the economy: E_j is the exported proportion of the product; C_j and GC_j are respectively the household and the government consumption; and I_j represents the investments.

This CGE model is built upon some classical assumptions: (i) the supply of each good and each factor of production (capital and labor) is equal to its demand - clear markets; (ii) each activity operates at zero economic profit (each sector operates in a perfect competition market, such that one sector's revenues are equal to all of its costs, including remuneration over the capital factor); (iii) families maximize their utility in the consumption of goods, subject to the restriction of their income subtracted from their savings; (iv) firms seek to minimize their cost for a given level of production, subject to their technological constraints; (v) the government spends its revenue (taxes collection) on the provision of public services, social security expenditures and savings formation; (vi) it is assumed that all investment is financed by savings; (vii) savings are made up of external savings from government and households; (viii) external saving is given by the inverse of the trade balance, which is the difference between exports and imports.

The functions of demand for capital and labor in each sector of the domestic economy derive from the CES function that combines these two factors to result in value added. For each product, the demand function of household consumption results from the utility function LES (Linear Expenditure System). The investment demand function for each product is a Cobb-Douglas type, in which the share of expenses with each product is constant. Finally, the supply of public services results also from a Cobb-Douglas function: in this case, spending on each service is constant relative to government's collection.

The database used in the CGE model refers to the Brazilian National Accounts [9] for the baseline year (2014). An Input-Output Matrix was estimated from the National Accounts data using the method proposed by [8]. A 102-sector input matrix was then derived to determine the intermediate consumption. For this paper purposes, it was necessary to disaggregate the sectors of cement, clay and limestone production. Information for these activities were obtained from National Union of the Cement Industry – SNIC, and the Annual Industrial Production published by the Brazilian Institute of Geography and Statistics – IBGE [10].

3. Results and discussion

3.1. CLCA outcomes

To estimate the changes in material and energy flows resulting from the proposed technology changes in cement production, the environmental impacts were calculated relatively to the reference unit – 1 t of cement (modified technology), as shown in Table 2.

Table 2 - Material and energy flows considered and respective original Ecoinvent dataset/process. Dataset for clinker was modified based on primary data collected; dataset for calcined clay was developed based on primary data. Remaining (secondary) datasets were modified to account for the Brazilian conditions.

Ecoinvent Dataset/Process modified	Quantity	Unit
Clinker {RoW}| production | Conseq, U	-1,60E-01	t
Charcoal {GLO}| production | Conseq, U	-1,46E-03	t
Electricity, medium voltage {BR}| market for | Conseq, U	-2,10E+01	kWh
Limestone, crushed, for mill {RoW}| production | Conseq, U	+1,70E-01	t
Calcined clay	+1,00E-02	t

The amount of clinker substituted (i.e. avoided) and corresponding quantities of its substitutes - limestone filler and calcined clay - were defined by the cement production changes proposed by the Roadmap BR [1], as indicated in the CLCA system boundary (Figure 1). The modified manufacturing process is more energy-efficient, due to combined decrease in electricity demand (from 113 to 92 kWh/t cement) and in thermal needs. No prospective scenarios regarding alterations on the Brazilian electricity grid until 2050 were predicted. In view of CLCA methodology, charcoal was the only thermal energy source analysed. Of the total 0.28 GJ reduction, 0.21 GJ result from suppressing charcoal from the fuel mix. Its corresponding mass is presented based on a calorific value of 23 MJ/kg.

The datasets used were minimally modified for adherence to the Brazilian reality; hence, electricity and water inputs were altered to Brazilian data. Clinker and calcined clay production datasets were formulated using Brazilian average information, incorporated in novel datasets already delivered to Ecoinvent and to be published in version 3.6. The cement composition proportions used in the dataset (and actual displaced materials) refer to collected data in 2017 for Portland cement CP V – similar to European CEM I, whereas the Roadmap BR used weighted average of all produced cement types. This will be refined as this work progresses.

Results for the CLCA are presented in Figure 3 for different impact categories. The substitution of clinker reduces environmental burdens due to materials involved in its composition and energy required in process such as calcination, grinding and mixing. Incorporating limestone filler and calcined clay as substitutes indeed adds in impacts, but the net impact in each category is always reduced.

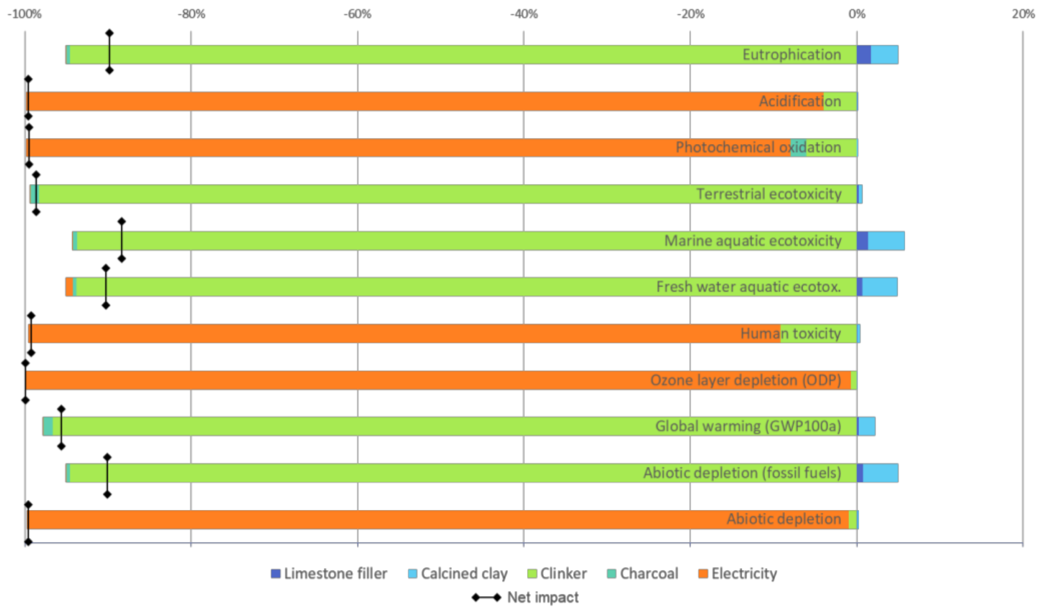

Figure 3 – CLCA results for altered energy and material flows relatively to the 2014 baseline (vertical line at 0%). Bars at the negative (left) side of the horizontal axis indicate impacts reduced.

3.2. Affected sectors and changes in production levels

From the equilibrium observed for the Brazilian economy of 2014, in the CGE model, exogenous changes were made in the participation of clay, limestone and charcoal in the cement production, consistently with

Table 1. These changes lead to a new economic equilibrium captured by the model. The industry-proposed changes modelled for cement production technology would enhance its economic efficiency and reduce cement's production cost, which would in turn reduce the product's price, and ultimately increase its demand and production. The technological change in the cement sector trigger changes in prices and ultimately in the production levels of all 102 sectors of the economy. For simplicity, Table 3 list is truncated to show only the sectors with the highest increments or reductions in production level.

Table 3 - Sectors with the highest production level increments or reductions after applying the cement technology change

Sector	**Change in production level**
Cement	+0.0714%
Pulp and Mechanical Pulp Manufacturing	+0.0268%
Construction	+0,.0233%
Other non-metallic mineral products	+0.0227%
Paints, varnishes, enamels and lacquers	+0.0119%
Manufacture of petrochemical Diesel	-0.0046%
Clay	-0.0310%
Pesticides	-0.0445%
Fertilizers	-0.0457%
Forestry	-1.1324%

The economic model assumes that inputs are used in constant proportions. Therefore, the additional demand for cement propagates activity increments across 81 economic sectors, whilst the remaining 20 sectors would reduce activity. The cement sector obviously shows the highest increase in production for being directly affected by its cost reduction, but it also directly stimulates e.g. production in the pulp

manufacturing (paper bags) and the construction sectors, besides the general increase in the whole economic activity. The highest reduction in the forestry sector production level stems from the suppression of charcoal as a thermal energy source in the revised cement production technology. Fertilizers and pesticides demand decrease accordingly. Reduction in clay production level consistently reflects the decreased flow of clay and slightly increased activity in the limestone sector (+ 0.00141%) in the revised cement composition.
Due to the cement cost matrix, the reduction of clay (overall input mass balance ~ -15%) and increase of limestone (overall input mass balance ~ +1%) reduced input costs by about 1.91%. The cost reduction reduces the cement price, which allows for the reported increase in demand and consequently in production. As the share of limestone in the cost of cement is much higher than that of clay, reduced expenditure on inputs affected proportionally little the final cement price. The emission balance would be positive but, from the economic perspective, the 0.07% increase in cement sector activity depicts a rebound effect, that is an increase in production level (and corresponding emissions and impacts) resulting from a technology change envisioned to decrease specific emissions (per t). This aspect shall be further investigated and characterized.

4. Final remarks

This simplified consequential LCA performed were based on the predictions brought forth by the Cement Production Roadmap Brazil, and showed that the two possible routes for impact minimization do not backfire: not only is the carbon intensity within the sector significantly reduced, all other assessed impact categories presented net reductions of at least 80%. The global equilibrium model, on its turn, showed that all 102 economic sectors are quantitatively affected by the predicted changes, with marginal increased or decreased production levels. We are currently working on the integration of the equilibrium model output with LCA tools to quantify the mentioned difference.

As with any LCAs in countries lacking a national inventory, our study was sometimes hindered by the absence of representative data. We attempted to limit this issue with dataset adaptation to best represent the national production scenario. Moreover, no prospective modelling of the electricity grid in 2050 was assessed. With the current worldwide trend to decarbonize electricity mixes, one could argue that the avoided impact in the next decades would be lower. Still, for GWP, the major benefit comes from clinker reduction, so conclusions would not have been deeply altered from a GHG emissions perspective.

Consequential LCAs are usually coupled with the step-wise procedure approach to identify the markets affected by a predicted change in demand, as briefly discussed in section 1. Our modelling relied on predictions already developed by the cited technology roadmap, assuming composition changes (and their quantities) according to specific sectorial information. These approaches involve subjective assumptions but facilitate the exploration of CLCA’s more sophisticated concept without increasing data collection complexity. The ease of application is however hindered by a biased perception of the economic sector’s response. Our paper, albeit only exploring the output of an equilibrium model without its full connection to LCA modelling, already shows how the demand change unfolds into the whole Brazilian economy. This is an ongoing work and additional impact categories and consequences in other economic sectors will be further investigated.

Acknowledgments
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Enhancing consistency in consequential life cycle inventory through material flow analysis

Cordier S[1,2], Robichaud F[3], Blanchet P[2], Amor B[1]

[1] Interdisciplinary Research Laboratory on Sustainable Engineering and Ecodesign (LIRIDE), Department of Civil and Building Engineering, Université de Sherbrooke, Sherbrooke, QC J1K 2R1, Canada
[2] NSERC Industrial Chair on Eco-Responsible Wood Construction (CIRCERB), Department of Wood and Forest Sciences, Université Laval, Québec, QC G1V 0A6, Canada
[3] Forest Economic Advisors, LLC, 298 Great Road, Littleton, MA 01460, USA

sylvain.cordier@usherbrooke.ca

Abstract. Wood products are gaining interest in the building sector, due to their potential in sequestering greenhouse gas emissions. However, increasing wood materials use in the built market can have unforeseen changes in the material supply chains. Consequential Life Cycle Assessment (CLCA) allows the assessment of changes in material supply chain. To quantify and link those consequences, the affected physical flows need to be estimated. Material Flow Analysis (MFA) can bring to CLCA modelling more representative and quantitative information than the commonly used hypothesis in consequential modelling. Indeed, MFA considers physical constraints (technology performances and material availability), in addition to account for mass balance. The main objective of this presentation is to illustrate how such consistency is added to CLCA through an MFA of wood products in non-residential (NR) buildings in the province of Québec (Canada). Wood flows are tracked to identify their end-use markets and trends in consumption. To overcome the lack of data and bring insights on the sector's dynamics, such as stock variations and potential discarded flows that supply recycling markets, residence time model and also extrapolation and correlation between physical and economic parameters are used. Results show how flows can increase in the market before reaching their physical constraints, such as the available wood stock in the forest. These insights will significantly enhance the data collection for CLCA. In conclusion, the MFA brings support to CLCA by proposing a framework to model changes in the construction market.

1. Introduction

The consequential approach aims at modelling environmental impacts of the changes in the market due to a decision. Several methods exist to identify these changes [1]–[3], which all require an understanding of the market and flows. Indeed, the affected flows in the market depend on their expected sensitivity to the changes. But this requires different hypotheses on the state of the market before and during the changes. However, such characterization of the market is still a challenge for the development of consequential methodology in LCA. Indeed, for long-term assessments, assuming constant technological data is not sufficient, and data projection is required to build consistent prospective scenarios [2].

Recently, the consequential LCA approach started to be combined with the Material Flow Analysis (MFA) method, in order to build a system-wide inventory of flows associated to a given economic sector. Indeed, using MFA allows to track physical flows in the economy throughout their life cycle, including the end of life and exports [4]–[11]. Several studies showed MFA inflows and outflows (such as raw materials, finished products, old scraps, residues, and recycled materials) can provide information about both the dependence of a regional economy to some resource and its resource recovery potential [12]. Moreover, this tool brings insight into the dynamic flows of a sector. It helps to assess how important the market under study is regarding all the market and its physical constraints.

The MFA is a transparent tool that brings insight into the sector's dynamics. The Québec province is a good example because a political initiative projects to increase the use of wood in the NR buildings and no consistent and homogeneous accounts for engineering wood products (EWP) life cycle exist. The aim of this paper is to evaluate the state of the wood structural market for Non-Residential (NR) buildings by performing a material flow analysis of the EWP in the non-residential wood building sector. We then project scenarios to evaluate the potential consequences related to the growing EWP use. Dynamic MFA is expected to help in identifying and generating consistent flow and to capture trends in the market.

2. Method

The Quebec region is the geographical boundary of the NR building sector. The temporal boundary of the sawnwood demand, for the structure of new NR buildings, includes the 2010-2050 period. The system contains the stages of domestic harvesting, transforming (1st and 2nd), manufacturing of structural products, and using those products. These stages consider the softwood structural products which can represent cross-laminated timber, glued-laminated timber, or roof frame. The material losses from the first transformation are included.

The methodology to quantify the wood in the NR building structures is a top-down approach. Firstly, it defines the building sector at an aggregated level, with in our case, the value of the building permits. Secondly, to disaggregate this sector and get an amount of wood, we combined several parameters such as the share of the structure in the building cost, the price of a wood structure and the share of the building containing a wood structure. To match numerous inconsistent databases, the data reconciliation method in the MFA tool is performed with STAN software [13].

2.1. Quantifying the wood

The estimation of wood in the NR construction market (equation 1) implies several parameters extracted and adapted from Geskin Conseil [14]. The following equation presents the used parameters:

$$\frac{BP\ (\$) * \mathrm{SCs}\ (\%) * \mathrm{WBs}\ (\%)}{WSp\ (\frac{\$}{\mathrm{m}^3})} \quad (1)$$

The first parameter ***BP*** is the value of building permits. It can represent the spending and the size of the NR construction market at an aggregated level. Indeed, building permit data are used as a leading indicator for the construction industry since getting a building permit is one of the first steps in the construction process and is a major input of expenditures by companies and governments to build buildings [[15]–[17]]. However, the values ($) of the building permits are disaggregated to consider the value of the new building constructions among all the types of work such as improvements, conversion, addition. The scenarios only consider the building permits for new buildings with two scenarios (a maximum and a minimum).

Among the value of a building, the share (%) of the structural cost ***SCs*** (material and installation) in the total building cost (associated with the building permit) is necessary to consider the structure. We determined this share with several case studies from public [18] and confidential review (on behalf of the Ministry of Forests, Wildlife and Parks) [19] on the NR buildings whose structure is made of wood. The case studies of the confidential report are selected from a collection of hundred wooden buildings to meet the needs of ensuring the representativeness of the Québec public building context and to guarantee a coherence of the whole despite the many uses of wood for construction. The criteria consider the year of construction, the 100% wood structure, the building classification (recreation, sport, culture, education, health, offices and warehouses), the diversity of building vocations and the potential reproducibility of the project [19].

In order to convert the dollar values into the amount of wood, we introduced ***WSp*** the price of installed wood structure ($/$m^3$) in the estimation. This is important to consider this price instead of the one of softwood lumber because the wood products are gaining value throughout the transformation chain from the sawmill to the building, which increases the price per cubic meter. Therefore, we avoided overestimation of the wood cubic meter installed in the NR buildings.

Finally, some buildings have a wood structure, not all. Therefore, we applied the coefficient ***WBs*** to consider the share of buildings using wood. It is this share which drives the modelling of wood consumption in NR buildings. Currently, around 28% of new NR buildings (4 stories and less) are using wood structure according to a survey (on behalf of cecobois) conducted with engineers and architects [20].

2.2. Projecting the quantification of the wood

We estimated a minimum and a maximum scenario of potential wood use in NR structure until 2050, according to the minimal and maximal parameters' values. The 2050 as a long-term horizon is set because of the estimated growing population after 2050 [21], suggesting there will be still a need for construction. Moreover, depending on the current market volume, a short-term analysis would not reflect consistent and significant effect because of the inertia of the market and the barriers. For future work, the buildings have a long lifetime (more than 50) and the future discarded flows of buildings would start to appear after these 50 years. This will involve a future secondary wood resource supply. The respective estimations of parameters are described below. The projection is made for each year in order to track changes between the starting calculation date (i.e. the time of the starting decision or change) and the final state. The idea is to follow the flows to understand if there might be intermediaries' consequences during the change modelling.

2.2.1. Demand of wood in the NR buildings

The expected competitive trends are helpful to identify the most sensitive suppliers to a change [22], [23]. In that sense, future trends in the market are required and each parameter must be predicted to simulate the increasing use of EWP in non-residential construction. Predictions of the concerned parameters are not available with enough information. So, it is essential to remind that a prediction remains highly uncertain. Such uncertainty will be part of our future work. Following, we present assumptions of the parameter's predictions concerning the building permits, the softwood lumber price and the share of NR building with wood structure. We assumed a constant evolution of the share of structural cost in the total building cost. This assumption implies that structural cost and building cost are linearly dependent.

To project the building permit, we assumed it to follow the existing population projection [21]. The observed strong correlation (R^2>0.8) between the total building permits and the population of Québec (figure 1) was the reason for this assumption.

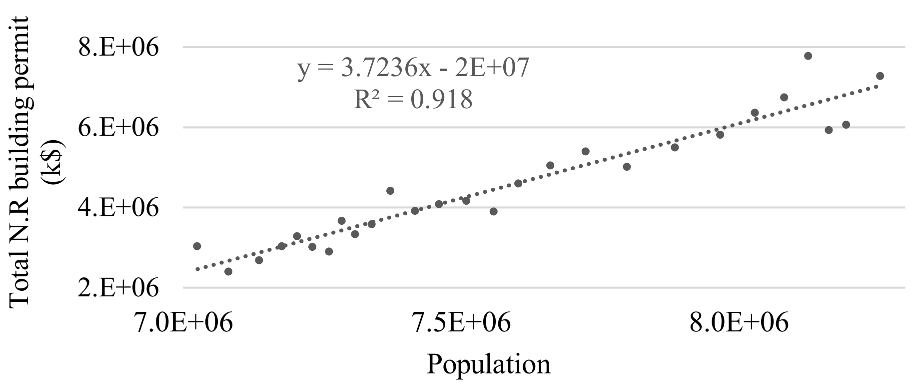

Figure 1. Correlation between building permits [17] and population [24] in Québec (1991-2017).

The following figures present the projections we made for the share of new NR buildings with wood structure (***WBs*** - figure 2) and the cubic meter price of the softwood lumber (linked to the ***WSp*** - figure 3). In the NR building structures, wood usage is an emerging market and no historical data are existing in the context of Québec. Therefore, we considered a prospective approach to model the increase of wood in the NR buildings. The projection of the potential share of building with wood structure is assumed to follow an S-shaped curve because the developments of EWP for building structure are not obvious linear process [25]. Indeed, when the first projects are successfully achieved and when the concerned public approves its technological breakthroughs, its development may follow a typical logistic S-growth [26].

Concerning the price projection, it follows the past trend of the average of the softwood lumber's prices (adapted from FEA - Forest Economic Advisors [27]). The minimum and maximum projection considered the historical minimum and maximum values which are projected following the trend of the average. This does not provide with precise figures but shows the price variability. As mentioned in subsection *2.1.,* the cubic meter price of the installed wood structure is considered in the modelling instead of the lumber cubic price. To do this, we applied a coefficient to represent the added value of the engineered wood product compared to lumber.

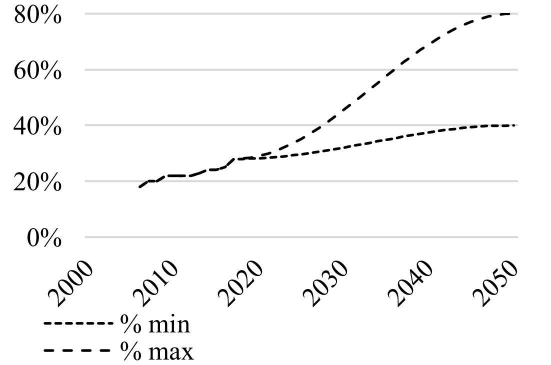

Figure 2. Projection of the potential share of the buildings with wood structure - WBs.

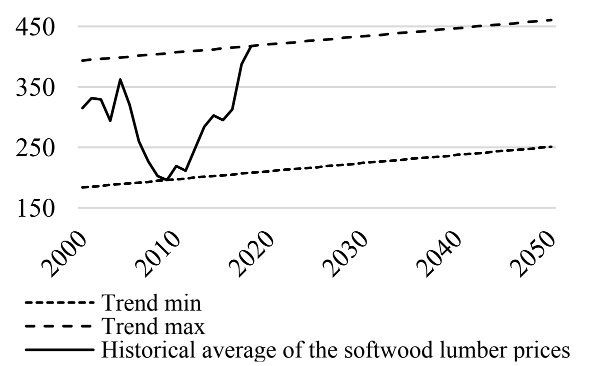

Figure 3. Projection of the softwood lumbers prices ($\$/m^3$).

2.2.2. The wood supply chain

The modelling of the increasing wood demand drives the wood product flows throughout the supply chain (from the buildings to the forest). Therefore, to estimate the amount of wood resource, we investigated the wood supply chain. It is at the sawmill, when roundwood is processed into standard lumbers, that there is the higher loss of matter. Historical statistics gave the improvement trend of each sawmill yield for each output such as the lumbers, the wood barks, the chips and the sawdust per cubic meter of roundwood.

Projecting this improvement trend with a retrospective approach allows representing the sawmills' efforts to reduce co-products production (wood barks, chips, and sawdust) and increase efficiency. Indeed, those efforts include the use of thinner saws that reduce the cutting thickness, the use of optimized multi-saw slitting machines - straight sawing and curve sawing - and the recovery of parts during trimming to transform them into smaller parts [28]. We assumed the current trend will continue because changes are gradually as long as sawmills are improving their equipment. But this implies sawmills can invest thanks to the growing market. However, this reduction cannot be infinite. To do so, we constrained the reduction with an asymptotic limit of each yield according to the minimum values available in the statistics databases [29], except for the barks we supposed constant. Therefore, we projected the yields until their respective limit. But it is also important to notice that the number of lumbers and by-products must verify the material balance with roundwood as long as the yields are decreasing. So, if the yield of lumbers per roundwood reaches its limit before one of the co-products, the sum of the three co-products yields per roundwood cannot decrease anymore even if their respective assumed limits are not reached.

In order to evaluate the wood demand effect for NR building sector related to other sectors, we introduced the wood consumption of the other final uses in accordance with the material balance between the lumber imports, exports, and sawmill productions.

3. Results

The results relate to the estimated amount of wood products for the new NR building structures and the amount of roundwood which is required for this sector as well the others.

3.1. Wood in new NR structures

The following figure displays the two scenarios of the wood quantity for new NR building structures. We built these scenarios regarding the different uncertainties of the main parameters presented above.

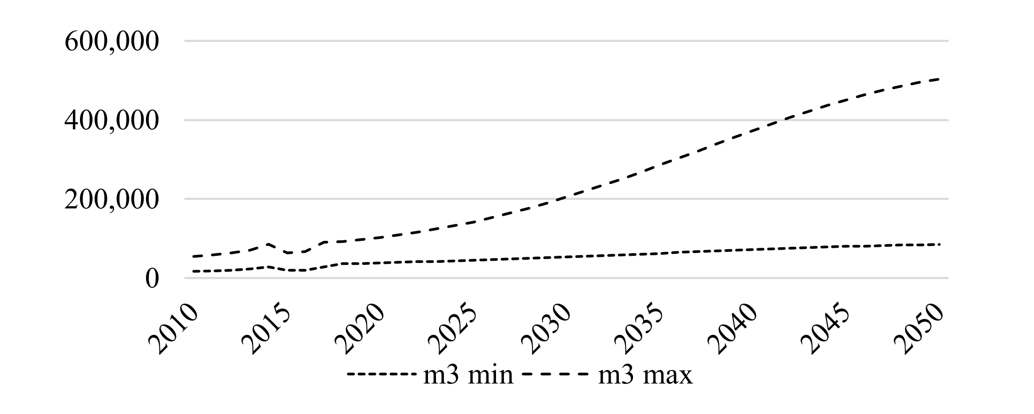

Figure 4. Estimation of wood products (m^3) in the structure of new NR buildings in Québec.

The minimum scenario follows an S-shaped curve, but the target of the ***WBs*** is so small that it seems to follow the trend. This scenario shows a negligible quantity because it also considers the maximum cubic meter price of installed wood in the structure. There is consistency in the sense that the more wood is expensive, the less it may be used. However, the price is not related to other endogenous parameters such as the availability of the resource.

3.2. Softwood roundwood harvesting

The importance of the additional softwood roundwood demand regarding the other domestic markets is illustrated in this section. The obtained results depict the additional demand for wood for NR building structures may be unconstrained by the resource availability if harvesting for other end-uses is constant. We also notice if the additional demand remains negligible and other end-use markets are constant, then the consequences of the decision may only occur in the investigated sector. This will imply to consider competition between structural material. Figure 5 shows the historical harvesting of softwood and resource availability in public and private forest in Québec [30] and the projections made. As shown in figure 5, even if the additional demand is negligible, considering the trend of other sectors will result in a constrained resource before reaching the expected time horizon.

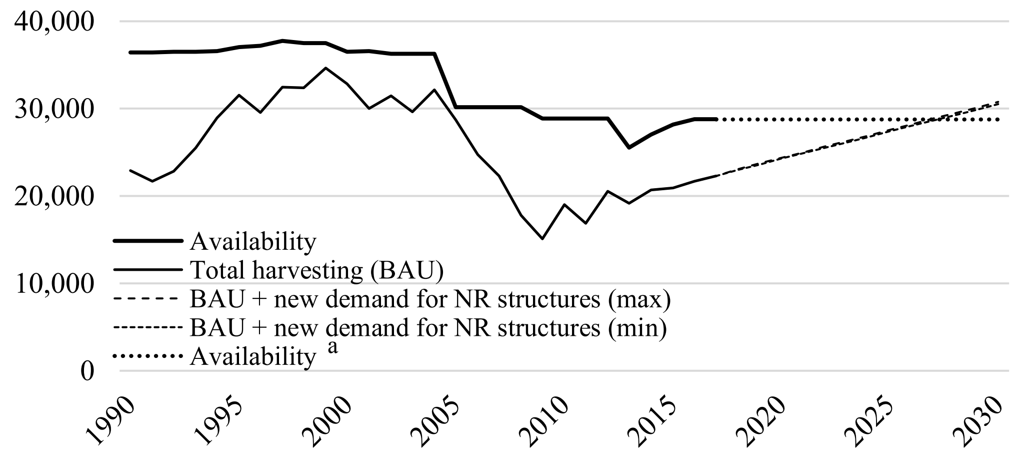

Figure 5. Total domestic softwood harvesting for NR building and others projected end-uses (‘000m^3). [a] Considering constant availability

The MFA allowed indicating the softwood lumber exportations [31] accounted for around 50% of the total harvesting in the 10 past years. This mainly drives the past harvesting trend implying that exportations may constrain the development of the NR wood products in term of resources availability. With the MFA in the wood supply chain, it is also possible to investigate the effects of additional sawmill by-products by assessing their potential demand for end-use markets (e.g. pulp, paper, cardboard, veneers, plywood, and panels, or Cogeneration and Energy Products).

4. Discussion

We presented a method to account for material in the emerging market of NR wood structure. Secondly, we investigated the dynamic wood flows in the supply chain to understand the effect of additional demand.

Regarding the account of material in the emerging market of NR wood structure, the parameter of the added value is specific to the wood buildings sector. Indeed, it allows considering the value which is added to wood during the EWP processing between the sawmill and the construction of the buildings. However, the lumber price is a dynamic and endogenous parameter and the added value is linearly dependent on it. By the end, the equation (1) respects the fact that, if the wood price is skyrocketing then it can deter timber harvesting. It results in an amount tending to zero. But there is a limitation here. The wood harvesting modelling does not consider the relationship between the resources price and its availability in the regional forest. In addition to that, the new buildings may not only include the structure but also the envelope which can possibly use wood. This additional demand for NR buildings is missing in this flow accounting. The quantity estimation is important to model representative additional harvesting regarding the potential of the emerging market to grow.

The results show how and when the limit in the resource availability can be reached depending on the assumption of all markets using the same resource. According to the assumptions, it does not appear relevant to look for consequences that will occur in the current supply chain because the wood quantity for NR building seems to remain negligible compared to others. One of the main sources of uncertainty in such studies concerns the evolution of the NR market related to others which use the same resources. It is an issue because both will contribute to reaching the limit.

Our research shows how MFA helps to identify EWP flows in the Québec non-residential buildings. This MFA provides a snapshot of the EWP use across years and considers trends. The estimation of wood quantity is related to the price, the population growth and the spending of the sector. It is important to underline that dynamic material flow analysis mainly consider the material intensity per square meter and statistical data on the total floor area put in place or the material intensity per capita and the population of the country to estimate the material demand. Therefore, the presented methodology to estimate the quantity of wood should be compared to other methods using these parameters. Also, in the following work, system boundaries should be expended to understand the effects of EWP demand on the other structural materials as well as the effects of the stock accumulation on future discarded material.

To make the MFA less uncertain, we would need the share of the materials in the building archetypes and the distribution of those archetypes. But for an emerging market, dealing with a lack of data is obvious (non-existent or confidential). Also, as an emerging market, the price of the structure per cubic meter (WSp - $/m3) and the share of the structural cost among the building permit value (SCs - %) may be overestimated compared to a well-established future market. Concerning the wood products, we only considered the softwood sawnwoods, which are the raw products for structure products such as cross-laminated timber, glued-laminated timber or roof frame. As a consequence, the roundwood harvesting is overestimated because the sawnwood processing implies around 40% of material losses as barks, chips, and sawdust. If we considered a share for structural panels, such as oriented strand boards and laminated veneer lumbers, the processing yield would be less because all the roundwood (excepted the barks) is either destroyed as strands or laminated as laminated veneers. To overcome this bias, the share between the sawnwood products and other structural panels would help to disaggregate the cubic meter of the installed wood structure. This would imply one yield for the softwood sawnwoods and another one for the panels made of softwood and hardwood. As a consequence, the total and softwood harvesting would be less.

By tracking material flows of a sector, MFA supplies the CLCA modelling with a framework for several purposes. It identifies physical flows directly affected by a decision and models their trend. The dynamic MFA is a tool that brings insight into the evolution of a given economic sector thanks to a parameterized system-wide inventory of its flows. It supports the CLCA inventory modelling (i.e. the state of the market before and during the changes) and shows how the changes can be significant or constrained.

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Consequential LCA of demountable and reusable internal wall assemblies: a case study in a Belgian context

Buyle M[1,2], Galle W[3,4], Debacker W[4,5], Audenaert A[1]

[1] Energy and Materials in Infrastructure and Buildings (EMIB), University of Antwerp, Groenenborgerlaan 171 – 2020 Antwerp, Belgium;
[2] Sustainable Materials Management, Flemish Institute for Technical Research (VITO), Boeretang 200 – 2400 Mol, Belgium;
[3] VUB Architectural Engineering, Vrije Universiteit Brussel, Pleinlaan 2 – 1050 Brussels, Belgium; E-Mail: waldo.galle@vub.be
[4] VITO Transition Platform, Flemish Institute for Technical Research (VITO), Boeretang 200 – 2400 Mol, Belgium;
[5] Smart Energy and Built Environment, Flemish Institute for Technical Research (VITO), Boeretang 200 – 2400 Mol, Belgium;

matthias.buyle@uantwerpen.be

Abstract. The transition from a linear to a circular economy is essential to reduce the environmental burden of our society. A key issue is to prevent a shift of the environmental burdens and take the consequences of a decision into account, for example based on a consequential life cycle assessment (LCA). However, limited practical guidance is available on how to implement consequential LCA in the context of the construction sector. Therefore, the aim of this study is twofold. First, to quantify the potential environmental and burdens of introducing circular design alternatives for internal wall assemblies to the Belgian market. Second, to review the methodological implications on the results of a consequential LCA with a particular focus on consistently identifying marginal suppliers and substitution routes, acknowledging the time dependence and closed-loop nature of the design alternatives.
In total seven wall assemblies are assessed over a period of 60 years, with a refurbishment every 15 year.
The results show that a low life cycle impact can be achieved for assemblies that are designed to be used again and have a higher initial impact, such as a plywood boarding connected reversibly to a demountable metal frame substructure, as well as for assemblies with no possibilities for direct reuse that have a low initial impact, such as a drywall system with a wooden substructure. Further, regarding the methodological scenarios on marginal supplier identification, the range of possible outcomes is however much larger for the demountable wall assemblies than for the conventional ones.

1. Introduction

The transition from a linear to a circular economy is essential to reduce the environmental burden of our society by overcoming the divergent interests of economic and environmental prosperity [1]. Despite the efforts in building related research and development, the implementation of circular economy thinking in the construction sector is still in its infancy. It is mainly limited to minimising waste and maximising recycling [2–4]. Nevertheless, more radical experiments appear in the academic and innovation debate. They optimise the valorisation of materials at the end of their first functional service life, e.g. by considering existing buildings as material banks [5], or by designing demountable and reusable building elements such as internal walls [6–8].

However, increasing circularity does not automatically lead to more sustainable products and buildings, which emphasises the need for a quantitative assessment. Established methods such as life cycle assessment (LCA) proved their value for making well-informed environmentally sound design and construction choices [9]. Yet, there is not just one single way of performing an LCA despite the the general framework of ISO 14040/44 [10,11]. Still many methodological choices must be made throughout a study. Against the background of assessing the transition towards the circular economy, the market-based and change-oriented nature of the consequential modelling approach is of great interest, as it allows to make environmentally responsible policy and design choices. To date, there is a lack of consequential LCAs evaluating and illustrating their relevance for the construction sector [12].

In this context, the goal of the present study is to assess the potential environmental benefits and burdens of introducing circular design alternatives for internal wall assemblies to the Belgian market. This assessment is realised by performing a consequential LCA, acknowledging the time dependence and closed-loop nature of the design alternatives. The corresponding objectives of this case study are to (1) collect alternative internal wall assemblies, (2) introduce various consequential modelling approaches to understand the relevance and improve the robustness of the results and to explicitly account for the corresponding modelling uncertainty and (3) include multiple end-of-life scenarios to address the uncertainty regarding future life cycle interventions and technical evolutions.

For this case study, seven internal wall assemblies are assessed. To provide a sound basis for comparison, these assemblies include both conventional and demountable alternatives. The first are designed for a typical linear service life with a waste-generating refurbishment and end-of-life scenario, the latter are designed with a high reclaim and reuse potential at the end of their functional service life.

2. Methods

2.1. Case study

The present case study includes seven wall assemblies that have divergent compositions, but meet the same technical requirements (see Fig. 1). The first four alternatives (i.e. Wall 1 to 4) resemble the most commonly applied wall assemblies in the Belgian construction sector [13], namely masonry walls and drywall systems. They do not follow any design guideline related to the circular economy, but they will serve as a reference. The alternatives (i.e. Wall 5 to 7) feature a wood-based boarding, each time supported by a different demountable substructure. They are proposed by the authors following earlier prototyping by Paduart et al. [7,8]. The fifth alternative consists of prefabricated wooden boxes, while the sixth and seventh alternative rely on a single-profile and an assembled metal frame substructure. These alternative assemblies follow the design guidelines for the circular economy [6]: the substructures are demountable, the boarding is connected in a reversible way and all components resist the wear and tear of repeated disassembly and reuse. More detailed information can be found in Buyle et al. [14].

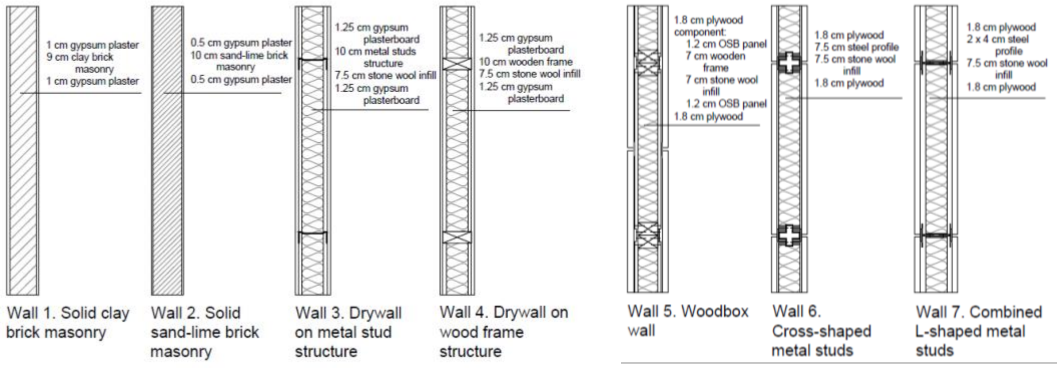


Fig. 1 Conceptual representation of the analysed wall assemblies

2.2. Life cycle assessment

2.2.1. Goal and scope. In the present case study the theoretical framework for consequential LCA of Weidema et al. was followed [15]. This implies that only small and medium scale changes in demand and long-term effects were considered, assuming perfectly elastic markets and no interaction between markets. Within this methodological system delimitation, all wall assemblies and their alternatives are equivalent and compared with respect to the following functional unit: *a 1m² space dividing wall (non-load bearing) that meets Belgian requirements for energetic and acoustic performance of residential, school and office buildings, during a period of 60 years,*

2.2.2. Life cycle inventory. In consequential modelling two of the most important aspects are (1) the identification of marginal suppliers (i.e. the activities affected by a change in demand) and (2) the substitution of non-determining by-products on the market. Additionally, the seven wall assemblies have a different end-of-life potential, varying from direct reuse to demolition with limited recycling potential. However, the actual practice at the end-of-life is highly context and user dependent. Given this uncertainty, multiple scenarios are included: four methodological scenarios regarding the identification of marginal suppliers and five end-of-life scenarios. The substituted activities and the avoided products are always the marginal ones [15]. Consequently, the methodological scenarios affect all life cycle stages including the end-of-life stage.

2.2.2.1 Methodological scenarios: marginal supplier identification The two most important steps in the procedure of Weidema et al. [15] are the delimitation of geographical market boundaries and a systematic identification of market volume trends to identify the suppliers the most sensitive to a change in demand. In this context, a market should be interpreted as all countries in the world from which materials are imported to Belgium, directly or indirectly. Two approaches to identify geographical market boundaries are included, proposed by Buyle et al. [16] and Pizzol and Scotti et al. [17]. The first approach is a bottom-up approach based on an iterative procedure (referred to as scenario [IT]) is starting from the specific location of the change in demand, using trade and production data. The central concept is to define market boundaries by comparing the traded volume of a product to the total production volume of a market. The second approach is a top-down approach based on a network analysis (referred to as scenario [NA]) applied to global trade data where the clusters represent geographical markets.

Next, the suppliers the most sensitive to a change in demand are identified. Within a stable or growing market, suppliers are evaluated based on their potential for expanding production capacity, which is a proxy of their competitiveness. In this case study the trend in production volume was chosen as a criterion, under the assumption that the suppliers yielding the largest increment in production volume are the most competitive ones. The trend in production volume was calculated by applying a linear regression analysis to the time series of yearly production data. Based on this calculation principle, the marginal suppliers were tracked down using two types of data. The retrospective approach (referred to as RETRO) is based on historical data available from statistical agencies, reflecting current trends. The prospective approach (referred to as PRO) relies on forecasted data obtained from other models, reflecting expected trends. The retrospective approach is characterised by a high availability of data with a low level of uncertainty. However, a key assumption in this case is that historical trends are representative for future situations. Indeed, the prospective approach can provide a more nuanced image of expected future developments, yet future predictions are per definition uncertain.

A pairwise combination of the previous approaches results in four methodological scenarios: RETRO[IT], RETRO[NA], PRO[IT] and PRO[NA]. Marginal suppliers are identified at country level, so country specific life cycle inventories (LCIs) were built for all identified marginal suppliers. The ecoinvent database v3.3 was used to model background processes.

2.2.2.2 End-of-life scenarios For the modelling of end-of-life scenarios, the Belgian reference study for LCA in the construction sector, namely Environmental Profile of Building elements (EPBE) [13], was followed as guideline. The five scenarios are briefly described below. Not all scenarios apply to every wall alternative. For the conventional walls, only the three most conservative scenarios can be included ({Bau}, {En}, and {Rec 1}). Direct reuse of the components is technically not possible in those cases as they cannot be disassembled, so both the most advanced recycling scenario {Rec2} and the {Reuse} scenario are excluded.

- Business-as-usual {Bau}: This represents the current practice in Belgium according to EPBE.
- Maximised energy recovery {En}: All combustible waste is sent to waste incineration plants featuring energy recovery. For non-combustible waste the {Bau} scenario is applied.
- Improved recycling {Rec 1}: An improved recycling practice is assumed, based on higher recycling rates compared to the {Bau} scenario, anticipating future technological developments.
- Optimised recycling {Rec 2}: This is a further improved recycling practice, including higher recycling rates and off-site reuse, enabled by Design for Change.
- Maximised reuse {Reuse}: Components are used again directly in the same building without any additional treatment or transport; a 5% material loss assumed for every refurbishment.

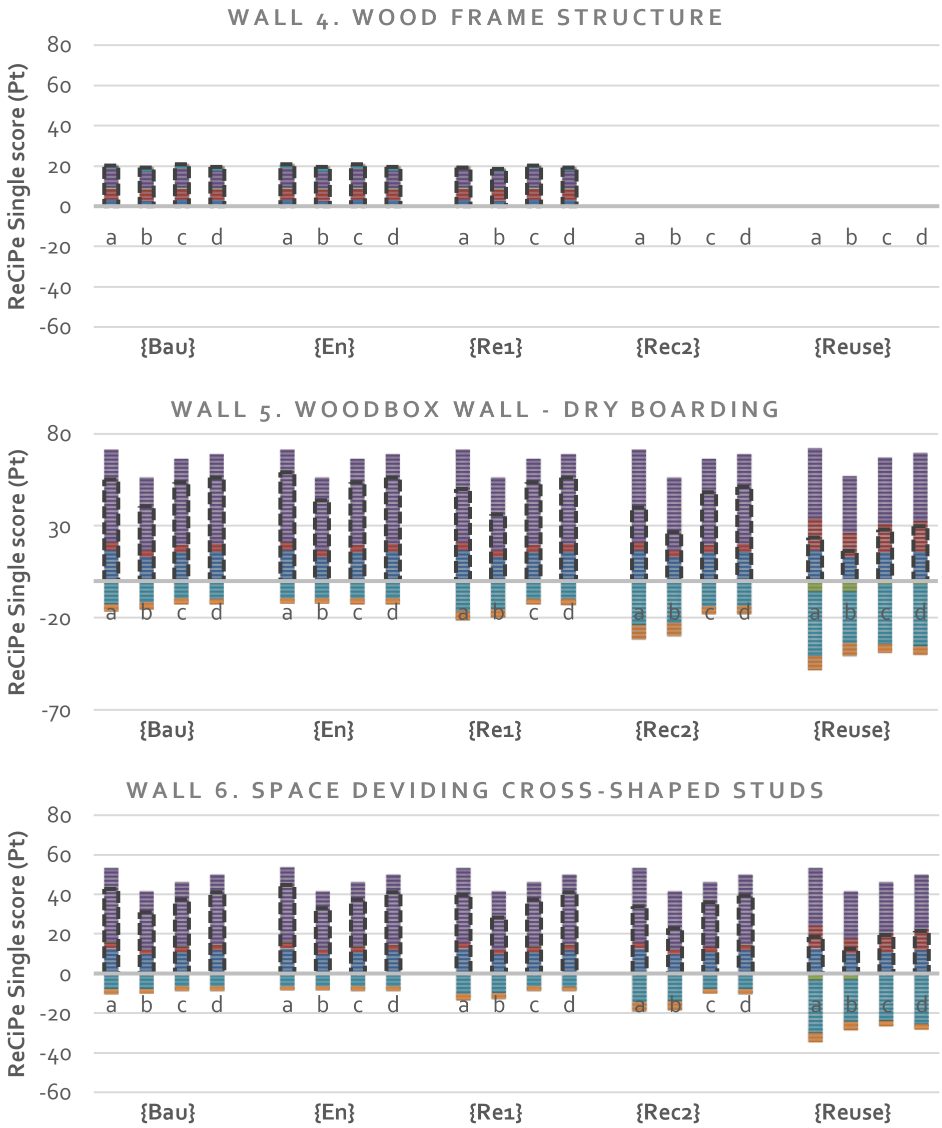
2.2.3. Life cycle impact assessment. The method used for the impact assessment is ReCiPe v1.13, applying a hierarchist perspective. To facilitate the interpretation of the effect of methodological choices in the LCI modelling, a single score indicator is applied. However, in addition to the single scores, results of all midpoint impact categories are included as well and available online (see *Appendices* and [14]).

3. Results

This section presents the results of the consequential LCA, considering the total service life of the wall assemblies. The studied period is 60 years, which corresponds to the estimates in other Belgian research, though individual components can have a shorter service life. An average periodicity of 15 years is assumed for refurbishments as discussed by Galle [18]. The results will be presented based on the classification of different life cycle stages as described in EN 15804 and EN 15978 [19,20]. These guidance documents describe an attributional framework that does not fit the goal and scope of the present case study. Nevertheless, its classification is instructive and will be maintained, even though this is a full consequential LCA.

The life cycle impact of the three demountable and reusable wall assemblies (Walls 5-7) is compared with the conventional assembly with the lowest impact, namely the drywall on wood frame structure (Wall 4), see **Error! Reference source not found.**. For full details, see Appendices and [14]. Three assemblies show the best environmental performance when the entire service life and the different end-of-life scenarios are considered: the conventional drywall with a wooden substructure (Wall 4) and the two assemblies with a demountable metal frame structure but only for the maximised reuse end-of-life scenario (Wall 6 and 7). Apparently, the lowest life cycle impact can be achieved for assemblies designed to be used again but with a higher initial impact, as for assemblies with no possibilities for direct reuse but with a low initial impact. The reason for the high life-cycle impact of the demountable assemblies is that some materials of the demountable walls have a short estimated service life compared to the total studied period. Plywood for example has an estimated service life of 35 years. In other words, even though these walls are designed to be fully reusable, after 35 years they need to be replaced by new ones during the second refurbishment. Wall 5 has a much larger initial impact compared to Wall 6 (27 to 44% higher) and to Wall 7 (24 to 41% higher). So, given a refurbishment rate of 15 years, this wall assembly is not competitive with Wall 6 and 7, nor with the reference Wall 4 from an environmental point of view. Wall 6 and 7 show almost identical results, with a slight preference for Wall 6 with an impact that is 1.5 to 3 % lower than Wall 7.

In Fig. 2**Error! Reference source not found.** the results for the methodological scenarios are presented as well. In the case of the conventional wall assemblies, there is only a small divergence in results of around 10% between the scenarios, while for the demountable ones this deviation can range up to 25%. Many of the typical construction products such as aggregates, clay, bricks, cement and gypsum products are traded on relatively small markets. Therefore, the identified marginal suppliers do not vary that much amongst the scenarios, nor does the impact per supplier.



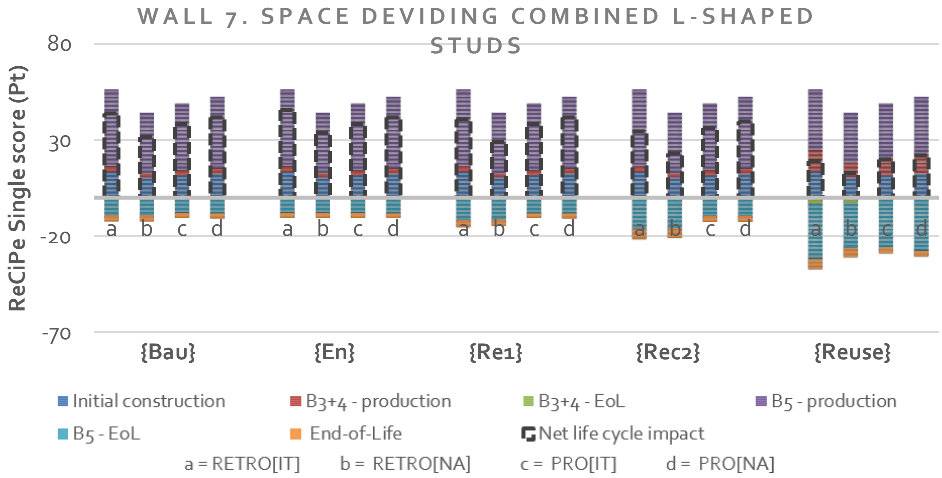


Fig. 2 Life cycle impact for wall assemblies 4-7

The situation for wood-based products is completely different than for all other materials, which apparently leads to larger differences in the outcomes for the demountable walls. First, these products are traded more intensively and over larger distances. This results in bigger deviations between the iterative procedure [IT] and the network analysis [NA] when the geographical market boundaries are defined. Second, climate, forestry practice and dominant tree species can all have a major effect on the final environmental impact, in particular for the midpoint impact category 'land use'. In case of plywood for example, having sawlogs as the most important raw material, the network analysis [NA] results in a market dominated by European countries, as they have intensive trade relationships. The iterative procedure [IT] adds China as an important partner country too, given its direct trade connection with Belgium. Obviously, the inclusion of China leads to increased transport distances, yielding higher impacts for the [IT] scenarios. Additionally, in the retrospective approach, the Chinese market for sawnwood is mainly covered by imports, among others from Russia having less favourable climate conditions, poorer forestry practices and larger transport distances. In the prospective approach the domestic Chinese sawnwood production, which has a lower impact compared to Russia's production, has a much larger share. A similar reasoning applies to the [NA] results, with a shift from Western to Eastern European countries in the retro- and prospective scenarios. However, in this modelling option, the impact increased in the prospective scenario due to higher transport distances and less favourable climate conditions between others.

4. Discussion and conclusion

The present case study contributes to the methodological theory of consequential LCA by making the implications of different modelling choices explicit. Therefore, it takes a multi-model approach, evaluating seven alternative internal wall assemblies and subjecting each of them to four methodological scenarios. Additionally, five possible end-of-life scenarios were considered. The results show that the demountable and reusable wall alternatives have a similar or better environmental profile compared to the conventional ones, if regular refurbishments or transformations are realised by reusing existing components. However, the large range in possible outcomes illustrates the importance of a quantitative environmental in the search for well-informed design choices.

The theoretical framework of Weidema et al. [15] is the most widely used framework which focuses on long term changes in perfectly elastic markets. However, in most studies the suppliers affected by a change in demand and the consequences of a decision are identified based on observations of historical or current trends [16]. In this study clear differences in results were observed when applying both a retrospective and a prospective approach, indicating the limited relevance of retrospective trends when trying to estimate long-term consequences. In reality however development is typically not a linear process, but it follows rather a S-shaped curve [21]. Such non-linear trends can be captured by forecasting models which output forms the basis for the prospective approach. So even though such data are per definition more uncertain, they can provide a more nuanced image of expected future developments. They are particularly relevant when a structural reformation of a segment of the economy can be expected. The latter can be market driven, e.g. a decreasing demand for pulpwood in the paper industry combined with a sharp increasing demand for wood fuel [21], or due to legislation, e.g. the prevalence of renewable electricity production in expected newly installed generation capacity [22].

The methods used in this work consists of two distinct and independent steps. First markets are identified applying an iterative procedure ([IT]) or a network analysis ([NA]), which results in a list of countries. Afterwards the most sensitive suppliers are identified based on their increment in production volumes. In these procedures some criteria were introduced, e.g. to decide when a trade flow is relevant to consider to define geographical market boundaries or the minimum increment in production required for a supplier to be considered as being competitive. Such an approach has some pros and cons. There is no scientific ground for selecting a threshold value, making it an arbitrary choice by default. However, this does not mean that attributing a value to a criterion is a priori a meaningless and random decision. Taking the values attributed to the criteria that affect the size of the identified market as an example. The choice of a low value can be interpreted as a study of all potential suppliers, assuming that the existence of a trade link is a sufficient precondition to react to a change of demand. Choosing a higher value prioritizes the most important trade partners, which indirectly upgrades the magnitude of a trade connection to a criterion for competitiveness as well. So, the inclusion of well-chosen threshold values can obviously be an advantage, as the modelling assumptions can easily be tailored to the goal and scope definitions. In this study the goal was to identify the potential marginal suppliers, so a low value was applied. For statistical support of this interpretation, see Buyle [12]. An alternative approach is proposed by Sacchi [23] and Prosman & Sacchi [24], namely a trade-based criterion for supplier selection focusing on circular supply chains. The effect of a change in demand was followed directly down the supply chain until the end-markets with sufficient unconstrained production capacity are reached. An important advantage here is that indirect trade can be accounted for, which appeared to be relevant in both linear and circular supply chains.

A limitation of this study is that the method was only applied on products without specific function-based requirements supplied to a general market. For such products more data is available and at the same time no additional customer segmentation is needed. Such an additional customer segmentation might result in much smaller market niches or even in a direct link between suppliers. In this case, even if data is available, it might be more efficient to take a shortcut and identify the marginal suppliers qualitatively. More research on this topic in needed.

In this work the main focus was on consequential LCA by following the theoretical framework of Weidema et al. [15]. This framework entails some strong assumptions such as suppliers being fully constrained or perfectly elastic. By relaxing these assumptions, a model could yield a better reflection of reality. There are some other models that can provide relevant results as well. An interesting approach is to integrate equilibrium models in consequential LCA. Such models form a counterpart to the framework of Weidema et al. as typically a short time horizon is considered and the consequences of a change in demand are modelled based on elasticity of supply and demand. Both models are complementary. Weidema's heuristic approach focuses on long term changes in perfectly elastic markets, while equilibrium models assess short term effects. So, a symbiosis of both models could help achieving the long-term goals without inducing short-term negative consequences.

To conclude, this case study points out the potential benefits of introducing demountable and reusable walls. Further research will need to focus on optimising and refining the mentioned wall assemblies and expanding the number of methodological scenarios. In addition, an assessment and multi-objective optimisation at the building level is an opportunity for further research, taking into account the building- and user-specific context.

Appendices

Supplementary information can be found at:

https://www.dropbox.com/sh/j6tgmphfaoz6u0s/AAAgoWA0eTbxFzost-XJRiq1a?dl=0

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Probabilistic LCA and LCC to identify robust and reliable renovation strategies

Galimshina A[1], Hollberg A[1], Moustapha M[2], Sudret B[2], Favre D[3], Padey P[3], Lasvaux S[3], Habert G[1]

[1] ETH Zürich, Institute of Construction and Infrastructure Management (IBI), Chair of Sustainable Construction, Stefano-Franscini-Platz 5, 8093 Zürich, Switzerland
[2] ETH Zurich, Institute of Structural Engineering (IBK), Chair of Risk, Safety and Uncertainty Quantification, Stefano-Franscini-Platz 5, 8093 Zurich, Switzerland
[3] University of Applied Sciences of Western Switzerland (HES-SO), School of Business and Management Vaud (HEIG-VD), Laboratory of Solar Energetics and Building Physics (IGT-LESBAT), Avenue des Sports 20, Yverdon-les-Bains 1401, Switzerland

galimshina@ibi.baug.ethz.ch

Abstract. Buildings are one of the largest energy consumers and greenhouse gas emitters in the world. As the largest part of the energy consumed by the existing non-insulated buildings occurs during the operation stage, retrofitting the building stock is crucial to reduce the environmental impact. To guarantee that the retrofit measures provide economic and environmental benefits, the whole life cycle should be assessed. However, the identification of environmental and at the same time cost-effective solutions is difficult due to the complexity and the uncertainty involved. Currently, simplified approaches based on limited assumptions are used that can lead to inaccurate results. This paper proposes a method for identifying robust renovation scenarios for residential buildings in Switzerland. The method and the developed tool use 47 uncertain parameters and Sobol' indices to identify the most influential parameters. As such, robust renovation strategies can be identified in the early design stage.

1. Introduction

Buildings are the largest energy consumers in the world [1]. The largest part of the energy consumption of existing buildings occurs during the operation stage. Therefore, retrofitting buildings is crucial to reduce environmental impacts and meet the United Nations (UN) climate action goals. In order to assess the environmental impacts holistically, it is vital to assess the whole life cycle. *Life Cycle Costing* (LCC) and *Life Cycle Assessment* (LCA) are two well-known approaches for assessing the economic and environmental impacts of buildings. However, the conventional LCA and LCC approaches apply deterministic assumptions for many parameters. These assumptions are taken for the input model parameters (e.g. material properties, selected material costs and environmental impacts) as well as exogenous parameters, which cannot be affected by the designer but directly impact the model response (e.g. room temperature, external climate, discount rates, price growth rates). These assumptions are highly uncertain and the consequent inaccuracy might lead to the big performance gap between the computed model and real result. Therefore, the question of uncertainty and data reliability has to be addressed to apply LCA and LCC as a practical and robust tool to assist policy decisions. Data quality and sensitivity of the results to the input data and the taken assumptions have been discussed in the field of LCA [2], [3]. Recent studies have shown that there is a balance point when the renovation can still be cost-effective and environmentally-friendly [4]. However, studies also highlighted the fact that the resulting uncertainties of LCC and LCA might be higher than the difference between two solutions [5]. Therefore, to achieve the robust renovation scenario in terms of LCC and LCA, the uncertainty sources need to be identified and quantified through rigorous statistical treatment. The current paper proposes a method to define the renovation scenario depending on the level of knowledge of the building. It is based on preliminary investigations in the field of historic building renovation [6]. The aim is to identify a robust renovation scenario by combining advanced statistical methods with the LCA and LCC methodologies. The proposed method is applied to an existing residential building located in Switzerland. The results show how to prioritize renovation strategies and at the same time determining the key parameters influencing the renovation using Sobol' indices [7].

2. Methodology

The methodology of the paper is shown in the Figure 1. First, the model for LCA and LCC calculations is created. After that, all possible renovation measures are selected and uncertain parameters for each measure are identified. Each uncertain parameter is described by a possible variability range and a distribution, which are selected according to literature sources or expert interviews. Then, the sensitivity analysis for all the measures is performed to understand the priorities for the renovation strategy. Finally, the uncertainty quantification on the selected strategy is applied to see the influence on the total LCC and LCA results. These steps are explained in further detail in the following.

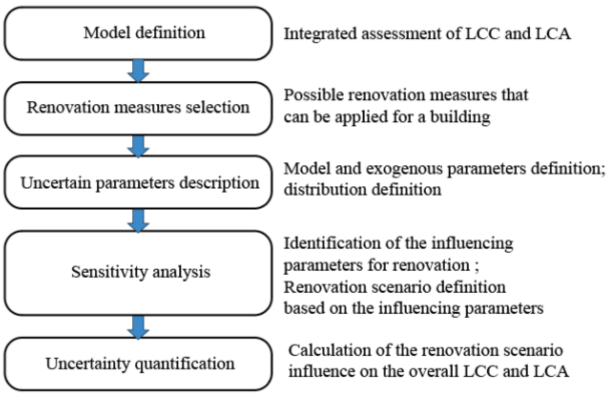


Figure 1. Methodology steps.

2.1. Integrated calculation for LCA and LCC.

The model includes three steps – heating demand calculation, LCC and LCA. The overall objective is to create an integrated workflow for LCC and LCA. The metrics of interest for the integrated assessment are the total costs and environmental impacts. For both, LCA and LCC, the functional unit refers to the use of the building over its lifetime. A period of 60 years is used as a reference study period of the building at the year of renovation according to the Swiss standard SIA 2032 [8]. The whole calculation process is conducted using python programming language.

Heating demand. The first step of the process includes the operational energy demand calculation which is performed according to the Swiss standard SIA 380/1 [9]. The calculation is performed using a quasi-steady state approach based on monthly values in order to achieve low computational costs.
Life cycle cost. The heating demand results are used for the LCC analysis. The stages for LCC include initial costs, operation, replacement and demolition. The net present value approach is selected for this study as a well-recognized and broadly used approach [10]. The cost data is taken from the Swiss Federal Office of Statistics [11].
Life cycle assessment. In parallel with LCC, an LCA is applied. The conventional life cycle stages according to SN EN 15978 with the modules A1-A3 (production), B4 (replacement), B6 (operational energy use) and C1-C4 (end of life) are used as system boundaries for this study. KBOB "Ökobilanzdaten im Baubereich", a Swiss database is used for the life cycle impact assessment of the building materials and technical systems [12]. The greenhouse gas emissions (GHGe) are used as an

indicator for climate change, (unit expressed in kg CO_2-eq) and calculated based on the IPCC Global Warming Potential (GWP) characterizations factors [13].
After the initial model is set, the validation of the heating demand results is performed using the Lesosai software which also complies with SIA 380/1 standard [14]. After the model is set, the possible renovation measures are applied in the model.

2.2. Renovation measures selection
Renovation strategies can be characterized differently depending on the design stage as well as different stakeholders. For instance, the priorities in renovation strategies for the whole Swiss building stock is likely to be different from the renovation priorities for one specific construction period or for an individual building as the level of details and knowledge about the initial model might vary highly. In case of different stakeholders, portfolio managers might have different perspective on renovation strategies and therefore, different goals compared to real estate managers or building owners. Therefore, a strategy that is able to cover all possible renovation scenarios is needed.

The model is able to cover different levels of details. This allows modelling the input parameters and seeing their influence on the total LCA and LCC results. The method allows to assess different renovation strategies and understanding the most influential parameters using Sobol indices.

The range of design parameters is selected to include all possible solutions, i.e. from the current state of the building to renovation solutions that comply or even outperform the requirements according to Swiss standards (e.g., the SIA 380/1 for the heating demand). Initially, the sensitivity analysis is performed to understand the influential parameters for the renovation in terms of LCA and LCC. Afterwards, the uncertainty quantification using polynomial chaos expansion (PCE) is used to see the influence of the input parameters' range on the results.

2.3. Uncertainty quantification
Uncertainty quantification (UQ) aims at identifying all sources of uncertainty in the parameters of a model and assessing how they affect the model response. Sensitivity analysis is an important tool in UQ and allows to identify which input parameters, and combination thereof, influence the model output the most. The analysis is often carried out by propagating the uncertainty throughout the model, *e.g.* using Monte Carlo simulation. However, the resulting computational cost is prohibitive, as it would require thousands to millions of calls to the computational model. In this work, the computational model described above is approximated by a surrogate model, *i.e.* an easy-to-evaluate proxy. More specifically, *polynomial chaos expansions* (PCE) are used as a surrogate model as they allow efficient representation of the model response and can further be used for sensitivity analysis.
Polynomial chaos expansion. A finite variance computational model is considered $Y = \mathcal{M}(\boldsymbol{X})$ that allows to compute some quantity of interest (herein, heating demand, LCA or LCC) and which takes as input an M-dimensional random vector $\boldsymbol{X} \sim f_{\boldsymbol{X}}(\boldsymbol{x})$ whose marginals are assumed to be independent. PCE allows for a spectral decomposition of the random variable Y onto a set of orthonormal polynomials [15]:

$$Y = \sum_{\boldsymbol{\alpha} \in \mathbb{N}^M} y_{\boldsymbol{\alpha}} \psi_{\boldsymbol{\alpha}}(\boldsymbol{X}) \quad (1)$$

where $\psi_{\boldsymbol{\alpha}}(\boldsymbol{X}) = \prod_{i=1}^{M} \psi_{\alpha i}(X_i)$ are a set of multivariate orthonormal polynomials obtained by the tensor product of univariate polynomials. These polynomials are selected according to the marginal distribution of the random variables X, α alpha are a set of indices and y_α are coefficients to be computed.
In practice, this infinite series is truncated into a finite set of polynomials, thus leading to an approximation. The surrogate model is obtained by calibrating the coefficients y_α for a given set of polynomials. This can be achieved using different methods, among which are least-squares techniques. This requires first generating an *experimental design* (ED) $\{ \mathcal{X}, \mathcal{Y} \}$, where $\mathcal{X} = \{\boldsymbol{x}^{(i)}, i = 1, \dots, N\}$ correspond to uniformly sampled input points and $\mathcal{Y}$ are the corresponding model evaluations, i.e. $\mathcal{Y} = \{\mathcal{M}(\boldsymbol{x}^{(1)}), \dots, \mathcal{M}(\boldsymbol{x}^{(N)})\}$. N is the ED size and typically ranges from tens to a few hundreds. Given the

ED, the coefficients are computed using least-squares minimization or other advanced techniques. Details on practical computation of PCE can be found in Gratiet *et.al*[16].

Global sensitivity analysis. Global sensitivity analysis [7] aims at quantifying the importance of each random input in the variability of a model output. Many methods found in the literature are based on the decomposition of the output variance [17]. Sobol' indices are a popular technique that belong to this category of methods [7]. Assuming that the input $\boldsymbol{X}$ are independent, the Sobol' decomposition of the model $\mathcal{M}$ reads [18]:

$$\mathcal{M}(\boldsymbol{x}) = \mathcal{M}_0 + \sum_{i=0}^{M} \mathcal{M}_i\,(x_i) + \sum_{1\le i\le j\le M}^{M} \mathcal{M}_{ij}\,(x_i, x_j) + \cdots + \mathcal{M}_{1,2,\ldots M}(x_1, \ldots x_M), \tag{2}$$

where M_0 is a constant and the other summands satisfy the following orthogonality condition:

$$\int_{Dx} \mathcal{M}_{i1,\ldots,is}(x_{i1,\ldots}x_{is}) f_{X_{i1}}(x_{i1}) \ldots f_{x_{is}}(X_{is}) \quad d_{xi1\ldots}\, d_{xis} \;\; = 0, \quad 1 \le i_1 \;\le \cdots \le\; i_s \le M, \tag{3}$$

It can then be shown that the output variance can be decomposed as follows [7]:

$$D = Var[\mathcal{M}(\boldsymbol{X})] = \sum_{i=1}^{M} D_i + \sum_{1\le i\le j\le M}^{M} D_{ij} + \cdots + D_{12\ldots M} \tag{4}$$

where

$$D_{i1,\ldots,is} = \int_{Dx} \mathcal{M}_{i1,\ldots,is}(x_{i1,\ldots}x_{is}) \quad f_{X_{i1}}(x_{i1}) \ldots f_{x_{is}}(X_{is}) dx_{i1} \ldots dx_{is} \tag{5}$$

The Sobol' indices are eventually obtained by normalizing the partial variances and read:

$$S_{i1,\ldots,is} = \frac{D_{i1,\ldots,is}}{D} \tag{6}$$

The first-order Sobol' indices relate to the univariate term and express the additive effect of each input taken separately. Higher-order Sobol' indices (combination of two or more variables) represent the interaction effects. Finally, the total order index for a given variable represents its own effect together with any interaction. A small value typically means that the parameter has very little effect on the output variability. As a consequence, setting the corresponding variable to a constant value would not affect the distribution of the quantity of interest. On the contrary, a large value means that the analyst should focus on reducing the corresponding parameter uncertainty.

Sobol' indices in the general case are computed using Monte Carlo simulation. However in this paper, we consider PCE-based Sobol' indices as developed by B.Sudret [19]. Sobol' indices can be obtained at no additional cost by simply post-processing the PCE coefficients. Further details on the computational aspects of sensitivity analysis can be found in the corresponding UQLab users manuals[20].

3. Case study

The chosen case study is located near Lausanne, Switzerland. The building was constructed in 1972 and has a total energy reference area of 1440 m^2. The ground floor is partly occupied by the commercial space of 50 m^2. The initial properties of the building can be seen in the Table 1.

Table 1. Initial building properties before renovation

Element	Existing state of the building
Ext.wall (Residential)	4cm mineral wool, U = 0.56 W/(m²K)
Ext.wall (Shop)	4cm mineral wool, U = 0.71 W/(m²K)
Ground floor	2cm cork in the shop, U = 1.4 et 3.2 W/(m²K)
Ceiling against attic	6cm mineral wool, U = 0.5 W/(m²K)

Windows	Double glazing (low-E layer, PVC frame, U=1.91 W/(m²K), gp = 0.55

The current case study was selected from the eRen building models, because they cover different construction periods and were already characterised for their initial states i.e. before any renovation [21]. The construction period for this building was selected to be 1970s as it represents the majority of the Swiss building stock (32.5% of the entire building stock, [22]). Different goal and scope and settings for the model parameters can be chosen for the renovation measures of this building. They are presented in Table 2 for the three scopes of the assessment which are described below in separate sub-sections.

Table 2. Parameters' setting for the renovation of the building envelope in the three assessments

	1st assessment	2nd assessment		3rd assessment	
Goal of the study	*Screening assessment of all possible measures*	*Comparative LCA & LCC of two heating system replacement with a distribution of the U-values for the renovation of the envelope*		*Comparative LCA & LCC of two heating system replacement with specific U-value and materials for the renovation of the envelope*	
Element		**Solution 1**	**Solution 2**	**Solution 1**	**Solution 2**
Heating source and system	Random heating systems (oil, gas, coal, wood pellets boilers) floor and radiators heating	Wood pellets boiler, floor heating	Gas boiler, floor heating	Wood pellets boiler, floor heating	Gas boiler, floor heating
Roof insulation thickness	Random values between the existing state and an improved U-value of 0.15 W/m^2*K			0.2 m	0.1 m
Windows	Random values between the existing state and an improved U-value of 0.6 W/m^2*K			Triple glazed, wooden frame, U-value –1.2 W/m^2*K	Double glazed, PVC, U-value –1.4 W/m^2*K
External walls	Random values between the existing state and an improved U-value of 0.2 W/m^2*K			No insulation	No insulation
Floor insulation thickness	Random values between the existing state and an improved U-value of 0.2 W/m^2*K			0.15 m	0.1 m

3.1 Variability of all possible measures (screening assessment)

In the first screening assessment, we assume the user of the tool does not know which scenarios to apply for the replacement of heating systems and for the renovation of the envelope. The idea is first to describe all possible renovation measures with different U-value requirements for the elements from no renovation up to very low U-values and different heating system types. For example, each building element can be kept either in its current state (uninsulated) or renovated according to different U-values (e.g., 0.25, 0.20, 0.10 [W/m^2*K], etc.). The U-values after renovation were varied using continuous variables for the thicknesses and thermal conductivities values to ease the probabilistic assessment.

Similarly, we also take into account the expected variations of the exogenous parameters, which can be seen in the Table 3. These parameters cannot be influenced by the designer and therefore, this uncertainty cannot be reduced during the design stages. The values were fixed based on variations around the conventional values defined in the SIA 380/1 standard and in the CRB (for costs' parameters).

Table 3. Exogenous parameters in the screening assessment and in the two comparative LCA & LCC

Parameter	Distribution	Range, moments
Room temperature	Uniform	19 - 23 °C
Discount rate	Uniform	1 - 3 %
Price growth for heating	Uniform	3.5 - 5.5%

Thermal bridge	Gaussian	Mean – 10%, Std – 5%
Airflow	Uniform	0.7-0.9 $m^3/(m^2*h)$

After the ranges of model and exogenous parameters are defined, the sensitivity analysis is conducted to identify the most sensitive parameters for this level of knowledge (screening assessment). To understand how the selected levels of performance for the envelope and technical systems influence the total LCA and LCC results, the uncertainty quantification using PCE method is applied in UQlab [23].

3.2 Comparison of two renovation scenarios

Following the screening assessment, in a second step, comparative LCA and LCC are conducted. Two solutions of replacement of the heating system are chosen and compared (cf. Table 2). We assume the replacement of the old oil boiler by a new gas boiler (baseline case) and the replacement of a new wood pellet boiler ("environmental friendly" alternative). Each scenario is coupled with different renovation measures for the envelope (roof, external walls, windows and floor). For each scenario, the renovation measures of the building elements take random values for the insulation thickness, the thermal conductivity, the associated environmental impacts, and the investment costs between the existing state and an improved energy-efficient renovation as already introduced in section 3.1.

In the third assessment (i.e., in the second comparative LCA & LCC analysis), a specific renovation scenario is applied for the building envelope (with a given U-value for each element after renovation. Assumptions for this scenario are presented in Table 2. This scenario represents the one defined in the eRen project. The same range for exogenous parameters as the ones presented in Table 3 were considered in these two comparative assessments.

4. Results

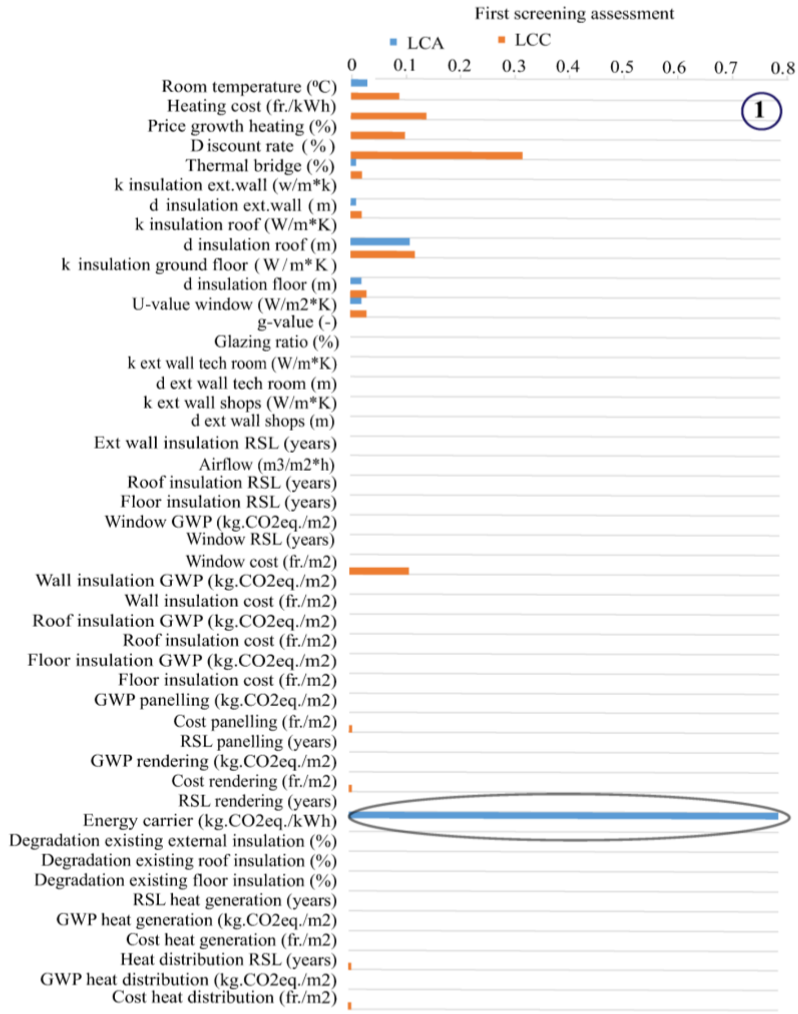
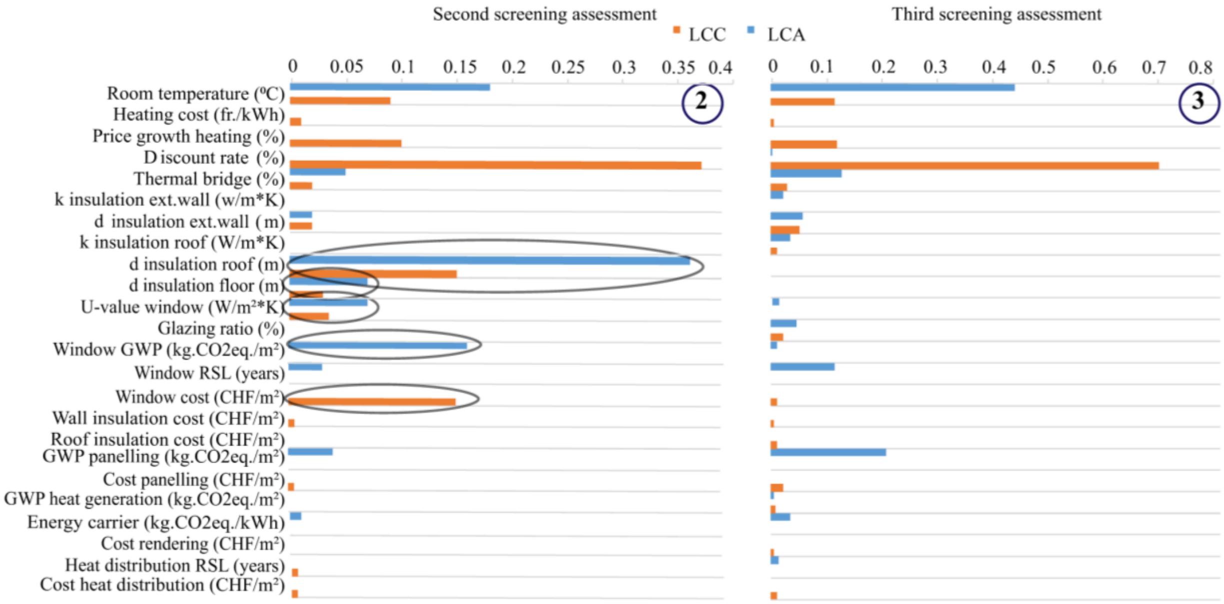


Figure 2 (1). Sensitivity analysis using Sobol indices for the screening assessment when the variability of all the measures was applied.

As it was mentioned in section 3, 47 model and exogenous parameters used for the building heating demand, LCA and LCC calculations are considered. The first screening assessment includes a range for all of them. The second and third assessments only include a range for the parameters that have an influence on the total LCA and LCC results.

As it can be seen in Figure 2(1), when the variability of all measures is applied (using assumptions from section 3.1), we notice that from the 47 parameters defined with a range, only about 8 of them present a sensitivity index of more than 0.05. Looking at the LCA, the variance of the output GHG emissions is only driven by the uncertainty on the choice of the energy carrier. In terms of life cycle costs, more parameters are sensitive: model parameters (the heating costs, windows costs, the density of the insulation for the roof) and exogenous ones (room temperature, price growth heating, discount heating). Interestingly, the heating cost is comparatively less sensitive to the output result than the heating environmental costs (energy carrier GHG emissions). This can be explained by the higher variance of the energy carriers GHG emissions directly influencing the output results (GHG emissions of the building, see Figure 3).

In the second and third comparative LCA & LCC, when the energy carrier is selected for each scenario using assumptions from Table 2, there is no more variability on the energy carrier GHG emissions. So the Sobol index becomes zero for this “known” parameter. In this case (Figure 2(2)), other model parameters become sensitive in each scenario of heating system replacement (according to Sobol) e.g., the roof insulation and windows. In terms of exogenous parameters, for LCA, modelling parameters are prevailing in the first and second screening assessment, and once the roof insulation, windows and heating system are renovated, the exogenous parameters become of highest importance. In terms of LCC, it can be seen that the exogenous parameters appear to have high importance already in the first screening assessment (e.g. discount rate and price growth rate for heating).



Figures 2(2) and 2(3). Sensitivity analysis for the second and third assessment (for specific heating systems' choice)

After the sensitivity analysis is conducted, uncertainty quantification for the selected renovation scenario is performed. As is was mentioned earlier, sensitivity analysis is helpful to identify the most sensitive parameters of the renovation measures. It goes along with the uncertainty quantification of different renovation scenarios but it cannot provide the optimal solution for the renovation. Therefore, at the current stage, two options were selected as possible renovation strategies.

Figure 3 presents the probabilistic LCA and LCC results when all renovation measures are considered. The results show an important variability of both GHG emissions and total costs in CHF.

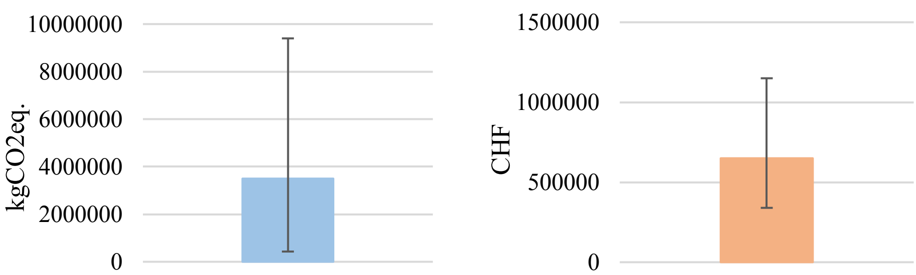


Figure 3. LCA and LCC results for the uncertainty quantification on the screening assessment of the building (variability of all possible measures).

The results for the probabilistic LCA and LCC for the second and third assessment are presented in Figures 4-5.

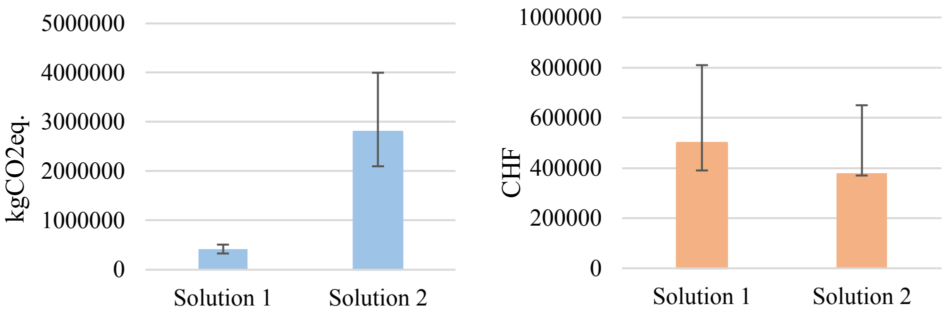


Figure 4. Comparative LCA and LCC results for solutions 1 and 2 using the applied measures of the second assessment.

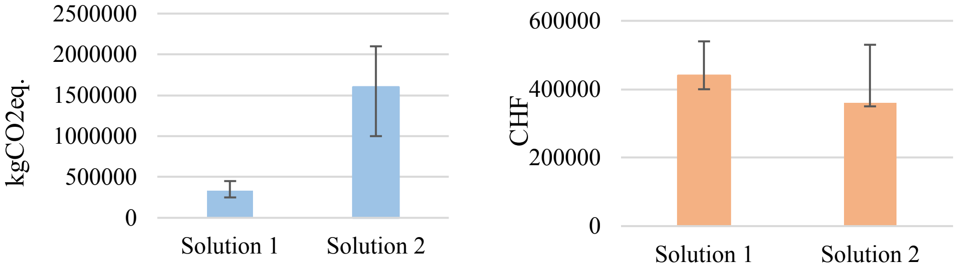


Figure 5. Comparative LCA and LCC results for solutions 1 and 2 using the applied measures of the third assessment

While the first sensitive parameter in the screening assessment is fixed (in the second and third assessment) using low-GHG emissions heating systems' solutions (wood pellets and heat pump), an important decrease in the mean value as well as uncertainty for both LCC and LCA can be observed. It can also be seen from two solutions that the decrease of the mean value for LCC does not occur with the same proportion as for LCA, which means that low GWP renovation measures do not necessarily yield low NPV. Therefore, an optimal solution that is both cost-effective and environmentally friendly still needs to be found. This can be potentially achieved by using multi-objective robust optimization under uncertainties.

Interestingly, Figure 4 shows that solution 1 is a robust solution for lowering the GHG emissions compared to the solution 2 (as the error bars do not merge between the two). In contrast, we cannot distinguish the two solutions in terms of life cycle costs. This shows the usefulness of such combined statistical approach with usual LCA and LCC methodologies.

5. Discussion

The current study shows how to identify the influential parameters for the renovation using a sensitivity analysis. This approach allows understanding the focus of the renovation at the early design stage. At the current stage, the method is able to handle stochastic calculations of LCA and LCC of building renovation scenarios. The renovation scenarios definition can be more or less detailed (see section 4 with a first screening assessment to a very specific third assessment). However, proper optimization process is needed to identify the best renovation strategy.

So further development will include the optimization under uncertainty, which allows understanding the renovation priorities as well as finding the optimal solutions in terms of LCA and LCC.

In this paper, the approach was applied for one residential building in Switzerland. In the future, the aim is to analyse the applicability of this method for the Swiss building stock. In order to find an optimal robust solution for the renovation of the building stock, building archetypes for different construction periods will be analysed.

The current method also shows that there is a non-negligible influence of the exogenous parameters on LCC and LCA, which means that even with identification of a precise renovation scenario with powerful statistical treatment, there are still many uncertainties in the building's life cycle. Therefore, it is crucial to consider parameters like occupants' behaviour, possible degradation rates for the building materials and economical parameters like price growth rates and inflation. The associated exogenous parameters shall also be considered with their uncertainty (including climate change trends) for a more realistic analysis. In the current study, climate data from SIA was used and the modelling of the relevant climate data for this type of analysis is currently in progress.

6. Conclusion

A statistical method combined with existing LCA and LCC methodologies was applied to the renovation scenarios of one residential building in Switzerland. The proposed framework is able to compute probabilistic LCA and LCC to compare different renovation strategies for different levels of knowledge of the existing building. It also identifies the most influential parameters for each type of assessment (screening or detailed). First results show the range of impacts and costs for all possible renovation measures when the energy carrier and heating system are not chosen or known. Once the heating system is fixed, the level of uncertainty on LCA and LCC is much reduced allowing to focus on the renovation of the building envelope. A first comparative LCA and LCC on two renovation scenarios shows that the choice of the best scenario is robust for the LCA while it is not possible to conclude on the LCC part. It can also be observed from the results of uncertainty quantification that the minimum value is always closer to the mean than the maximum value, which means that without uncertainty consideration the values at risk for both LCC and LCA are high. This highlights the necessity of uncertainty propagation when LCA and LCC are used during the decision-making process.

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Scenario uncertainties assessment within whole building LCA

Guimarães G D[1], Saade M R M[1 2], Zara O O C[1], Silva V G[1]

[1]School of Civil Engineering, Architecture and Urban Design, Department of Architecture and Construction, University of Campinas, Brazil
[2]Université de Sherbrooke, Canada

gabrieladiasguima@gmail.com

Abstract. Uncertainties evaluation is increasingly gaining traction within life cycle assessment (LCA), due to its key role as environmental decision support tool. When applied at whole-building scale, the large variety of materials, subjective choices and long lifespans introduce parameter, scenario and model uncertainties throughout the life cycle. Since normative choices are unavoidable within whole-building LCA (wbLCA), in this article we carried out a so-called 'scenario' uncertainty assessment for one illustrative case study. First, three uncertainty sources were selected, to include the two drivers most frequently cited in literature (reference service life and end of life management alternatives) and material wastage, a relevant issue to factor in variable construction optimization levels in contexts like Brazil. Cumulative energy demand (CED) and CML 2001 v.2.05 methods were used for calculating deterministic values of non-renewable embodied energy and global warming potential in SimaPro 7.3 The uncertainty assessment combined scenario analysis, stochastic modelling (Monte Carlo simulation of triangular probability distributions for the uncertainty drivers investigated) and global sensitivity analysis (GSA). The GSA confirmed the dominant contribution of the operational phase - strongly influenced by components replacement rate - to of life cycle non-renewable embodied energy and global warming potential result variance, whilst construction and end of life stages showed no correlation with life cycle results. Findings from this research also highlight the strategic importance of gathering service life information adherent to the assessed context. Building components replacement rates induced by the Brazilian standard are overestimated relatively to international figures used in LCAs worldwide.

1. Introduction

The environmental assessment of whole-buildings inevitably includes uncertainties, since they are complex assemblies with a high number of materials, unpredictable lifespans, and hard to predict future uses [1]. Scenario uncertainties can be defined as those resulting from normative choices made throughout the building's life cycle, which create multiple possibilities of conducting the assessment and therefore a range of values for its results [2].

Although the need to assess the influence on normative choices in wbLCA is acknowledged, no consensus was reached on the most appropriate methodology to do it [3]. Scenario analysis practice is recurrent to aggregate uncertainty information to LCA results [3–6]. Despite strategically highlighting materials and life cycle stages that most influence results, it assumes linearity and ignores correlations between parameters [3,7]. A higher number of choices and materials, for example, impose challenges to accurate evaluation through deterministic values, which means that its interpretation is limited.

On their turn, statistical evaluations aims at adding information to how assertive the result value is [8]. Selecting representative distributions is essential to uncertainty analysis, especially when it comes to high influence inputs. Each scenario developed has particular chances of occurring. Uniform distributions can be used when little more is known beyond its minimum and maximum values. Indeed, the scarce studies using MC in the wbLCA literature normally assume uniform probability distributions, which assigns equal probabilities of occurrence to all possible alternatives (scenarios) [2,9]. Though the use of uniform distribution is a step forward relatively to simply performing scenario analysis, it is unlikely to properly describe real life events. Triangular distributions are still imperfect and based on very limited information but can be useful for deriving approximate probability distributions through estimation of three points (minimum, maximum, most frequent) pertaining to that distribution, thus improving assignment of different probabilities to all alternatives considered.

Given the lack of a consensus procedure for assessing how ‘scenario uncertainties’ affect wbLCA results, in this paper we tested three alternative techniques for a selected case study, to identify the most promising approach(es).

2. Method

The LCA was developed in accordance with ISO 14040 [10] and the European Standard BS EN 15978:2011 [11]. The functional unit was the whole-building, and the scope of the study was Cradle-to-grave with options, restricted to modules A1-A3, A4-A5, B1-B6, C1-C2. Using a single inventory database is recommended for consistency sake but was unfeasible at the time of study. We used primary data on cement, mineral admixtures and concrete products. Most secondary data were collected from the Ecoinvent database v3.2, with some inputs from literature. Non-renewable Embodied Energy (EE NREN) and Global Warming Potential (GWP) were selected to illustrate our study, through the use of CML 2001 and Cumulative Energy Demand (CED) impact assessment methods.

The selected case study was a steel frame building designed as a “minimum lifecycle embodied energy and emissions’ (minLCee) Living lab [12], as shown in Figure 1. Its integrated design process optimized resource use, and included storm water management, low-energy space conditioning installations, green roof and wall, PV array, online resource use and internal monitoring, among other recommended practices.

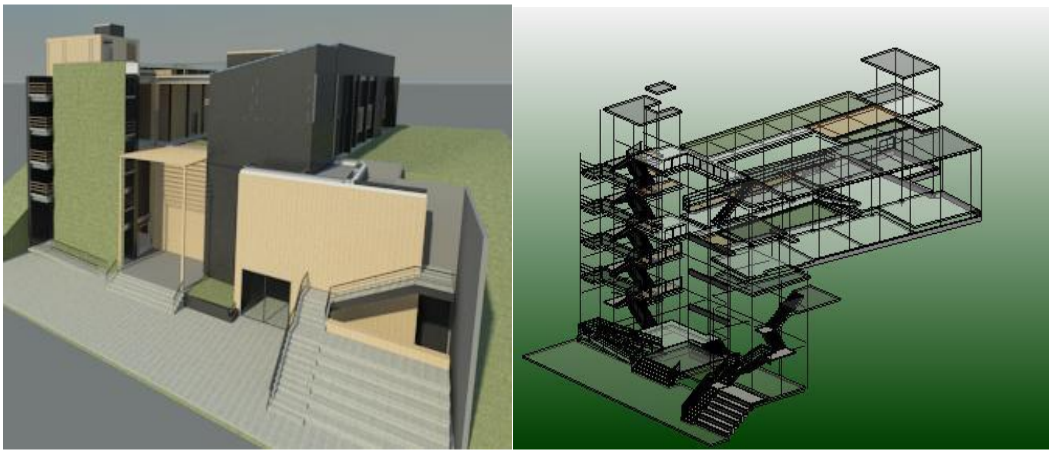

Figure 1 - Renderings from the minLCee living lab's building information model

Insights provided by three different approaches for scenario uncertainty assessment were analysed: multi-scenario analysis, stochastic modelling with uniform distribution, and stochastic modelling with triangular distribution.

2.1. Multi-scenario analysis

We began the uncertainty assessment by using multi-scenario analysis to run the LCAs and consider variations induced by each choice investigated. Scenario analysis is a type of sensitivity analysis frequently applied to evaluate LCA results, which consists of estimating and comparing effects that normative choices introduce in the results, by formulating different corresponding scenarios. Three alternatives plausible in the present or short-term Brazilian context were suggested for each uncertainty source studied [13], and an overall analysis considered the range of possible outcomes. A total of 27 scenarios was developed (Figure 2).

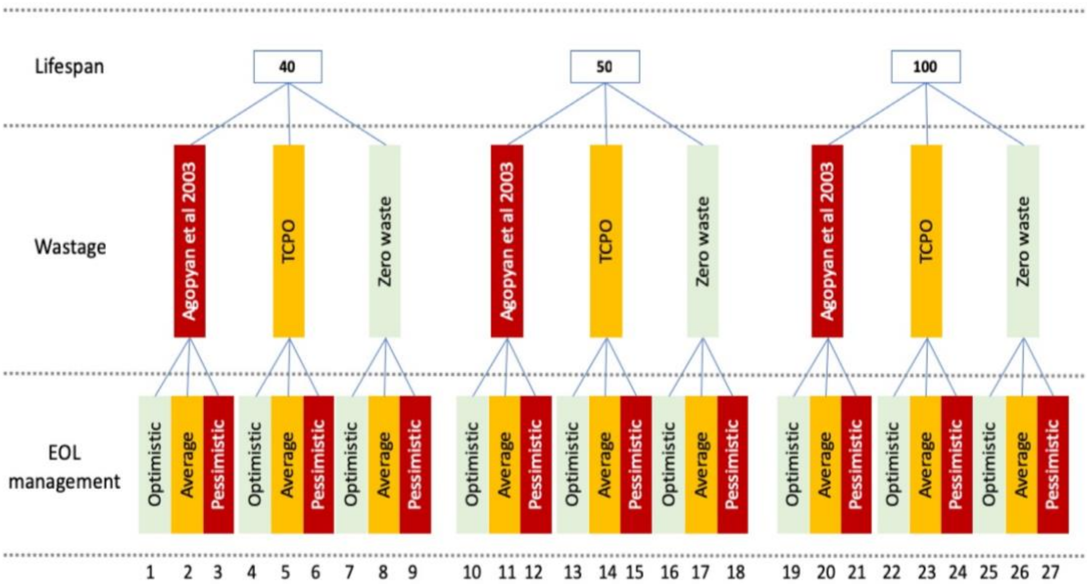

Figure 2 - Range of scenarios analyzed

Our systematic literature review indicated that the most frequently studied wbLCA choices are the building's reference service life information and waste disposal flows. The chosen lifespan scenarios were based on the Brazilian performance standard [14] minimum compliance level (50 years), and inspired by the lowest (40 years) and highest (100 years) values found in the literature review, to respectively take into account the international trend of producing buildings with elongated service life to make better environmental use of resources, as well as developing countries reality characterized by waste and maintenance intensive technologies [15].

To meet the stipulated reference service lives scenarios, the steel frame was protected against corrosion. Since the case study is situated in a C3 corrosivity category environment [16], the protection system was a 200mm-thick alkyd resin surface coating that creates a barrier between the environment and the structure, with a durability of 15 years.

Regarding waste disposal flows, different scenarios were developed to represent realistic alternatives for demolition/deconstruction and material transport to suitable management sites. Scenario A outlines an extremely inadequate disposal, in which 100% of the produced CDW is sent to the city landfill. Scenario B acknowledges the Brazilian construction reality, in which a 21% of CDW is recycled [17]. Finally, scenario C follows the European waste policy new directive for 2020, in which waste is seen as a valuable resource and 70% of CDW is recycled [18].

Finally, a third uncertainty source was included to consider material wastage during construction and maintenance activities. Since wbLCA are typically carried out before actual construction takes place, wastage is estimated and the choice for value source might influence the overall environmental performance. Although wastage is not explicitly addressed in the wbLCA literature reviewed, and the latter scenario seems to be assumed as default, such procedure would significantly underestimate impacts in the Brazilian reality. For this article, we considered a zero waste scenario and two additional variants, using the wastage values extracted from the Brazilian Table of Price Composition (TCPO) [19] and from Agopyan et al [20], whose collection of bottom-up representative field data from all over the country exposed the significant deviations that some construction services and activities could show relatively to the national average, although data were representative for construction practiced 15 years ago and such deviations can be outdated. TCPO presents typical average values and is an information source largely used by the national construction community and offers an updated - though less inclusive - outlook to ground contextualized assessments.

2.2. Stochastic modelling and global sensitivity analysis

Stochastic modelling was performed by running Monte Carlo sampling simulations (MC) with the @ Risk Excel add-in to quantitatively estimate the uncertainties arising from modeling choices made over the wbLCA. The analysis used 10,000 iterations for each impact category, as recommended in the literature.

Production stage modules A1-A3 and construction module A4 (transport) were calculated as deterministic points since they are not influenced by the normative choices considered (material wastage, service life, EOL management strategy). The output computed in the MC simulations were the sum of values in each life cycle stage.

The input data for MC depends on the probabilistic distribution chosen to best represent the model. Triangular probabilistic distributions assumed for each of the uncertainty sources analyzed in the construction, use and end of life stages. Three point's estimates were derived from occurrence frequency of each normative choice extracted from the reviewed literature for each scenario.

From the MC-simulated results, we ran global sensitivity analysis to identify the most influential inputs in the output's uncertainty measurement (contribution to variance) and in obtaining additional parameters iteration information [7].

3. Results and Discussion

3.1. Multi scenario analysis

Figure 3 and Figure 4 show life cycle results for the multiple scenarios developed. For both impact categories selected (non-renewable embodied energy and global warming potential), the influence of reference service life on wbLCA results is very clear: the columns are basically proportional to the reference service life, with slight contributions from the other (construction wastage and EOL) aspects factored in.

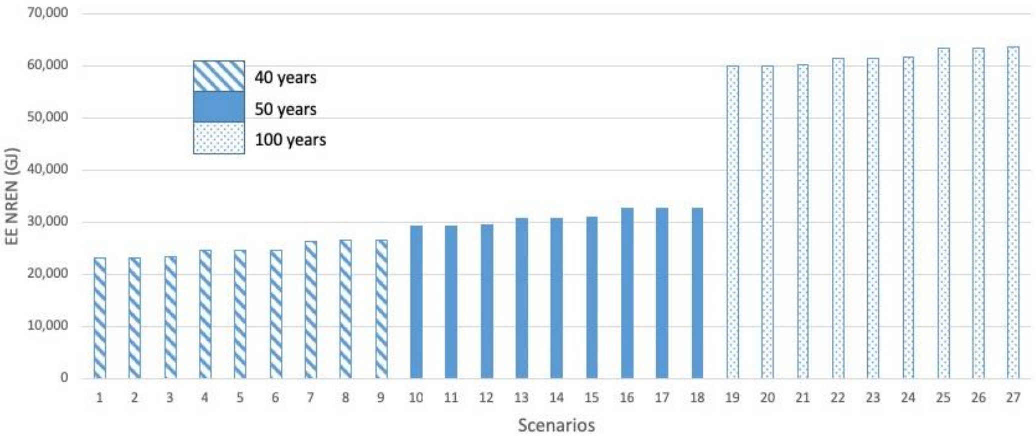

Figure 3 - Multi-scenario results for embodied energy, non-renewable

The variation resulting from waste disposal alternatives after the building's service life was negligible, and alterations between scenarios do not exceed 2%. As to material wastage during construction activities, discrepancies between wastage values extracted from [19] and [20] were not expressive, but figures in both sources are considerably higher than zero waste assumption.

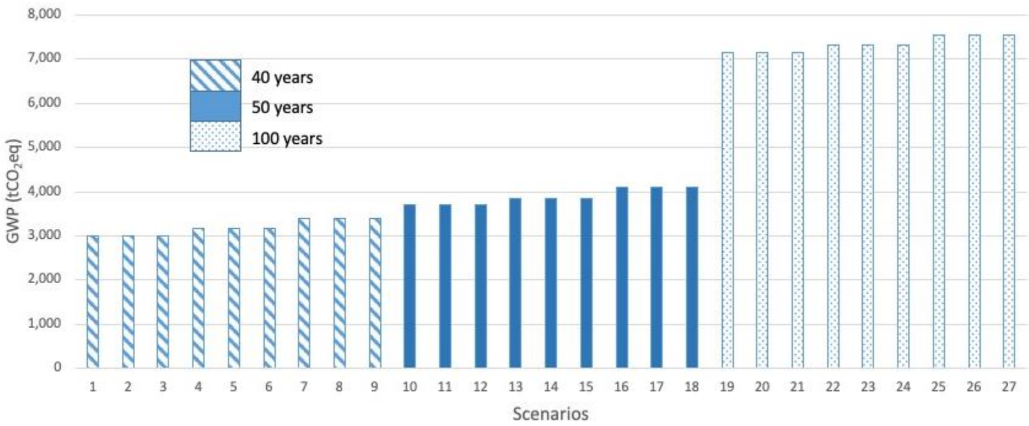

Figure 4 - Multi-scenario results for embodied GWP

3.2. Stochastic modelling

Table 1 details the inputs used in the uncertainty analysis. Even though the calculation model is simplistic in terms of its inputs and chosen distribution, it represents current whole-building LCA practice, in which accurate probability distributions are typically unknown and input parameters to generate even simple distributions unavailable.

In order to show how triangular distributions improve a given input's description relatively to less-informed uniform distributions, Figure 5 superposes uncertainty histograms displaying the range of possible final results for non-renewable embodied energy and respective occurrence probability . The uniform distribution flattens the curve and dislocate the (lower value, most probable) upper portion mostly towards higher (but least probable) values instead.

Table 1 - Input parameters for the Monte Carlo simulation

Input parameter detailing					
Variable	**wbLCA stage**	**Impact category**	**Values**		
			Min	**Average**	**Max**
Wastage	Construction (A5)	EE NREN (GJ)	382	1,768	3,708
Lifespan	Use (B1-B5)		8,902	15,066	45,886
EOL management	End-of-life (C1-C2)		164	225	349
Wastage	Construction (A5)	GWP (tCO_{2eq})	537	697	931
Lifespan	Use (B1-B5)		878	1,570	5,031
EOL management	End-of-life (C1-C2)		7	7	8

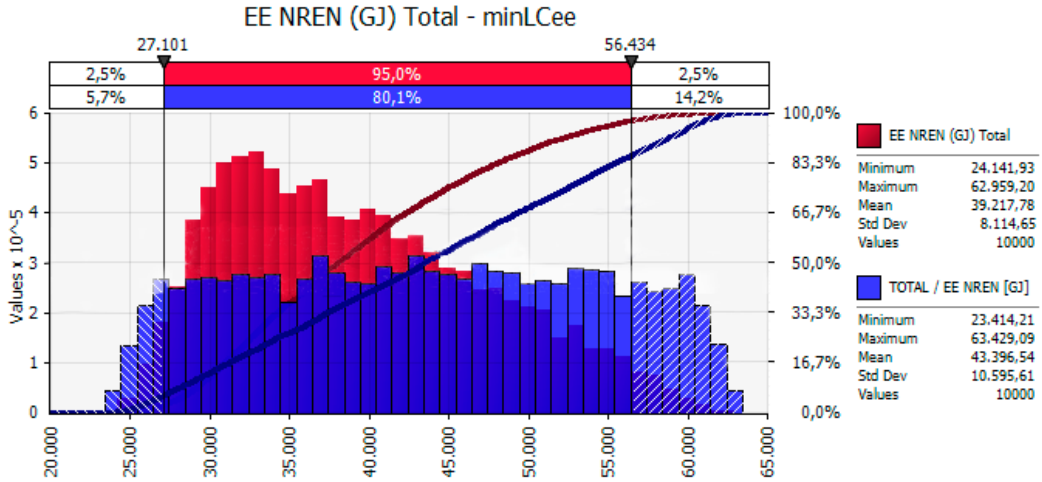

Figure 5 - Uncertainty statistical evaluation histograms, with the range of probable occurrence frequencies (axis Y) for the possible case study results for non-renewable embodied energy when uniform (blue) and triangular (red) probability distributions are assumed

Figure 6 features scatter plots showing the lack of correlation (homogeneous clouds, with Pearson coefficients near zero) between values of non-renewable embodied energy at construction (red dots) and end of life (green dots) stages and the life cycle total.

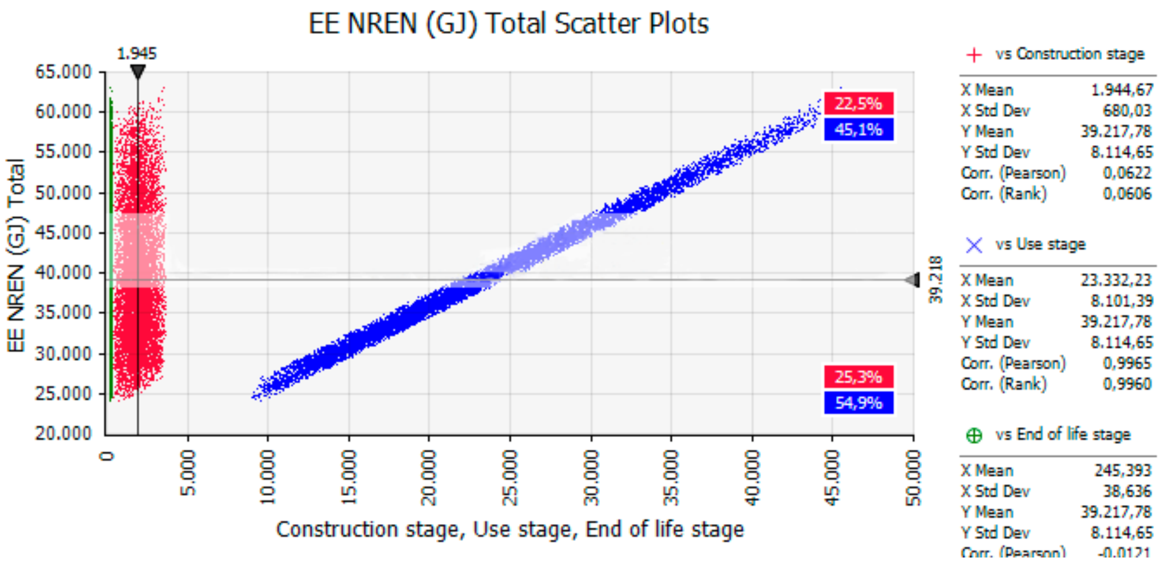

Figure 6 - Scatter plots for embodied energy non-renewable at construction, use and end of life stages

The data points resulting from the operational stage iterations (blue dots), which is strongly influenced by components replacement rates to achieve the established service life, assume a linear layout that indicates a solid correlation with the wbLCA results (Pearson coefficient near 1). Global warming potential results follow exactly the same pattern.

The global sensitivity analysis also confirmed the dominance (99,2%) of the operational phase's contribution to final wbLCA result variance. The uncertainty modelled in the construction stage contributed with the remaining 0,79%, whilst EOL effect was negligible, as shown in the radar graph (Figure 7). Such analysis is particularly useful in LCAs with a high number of choices to consider, for enabling evaluation of each input contribution separately.

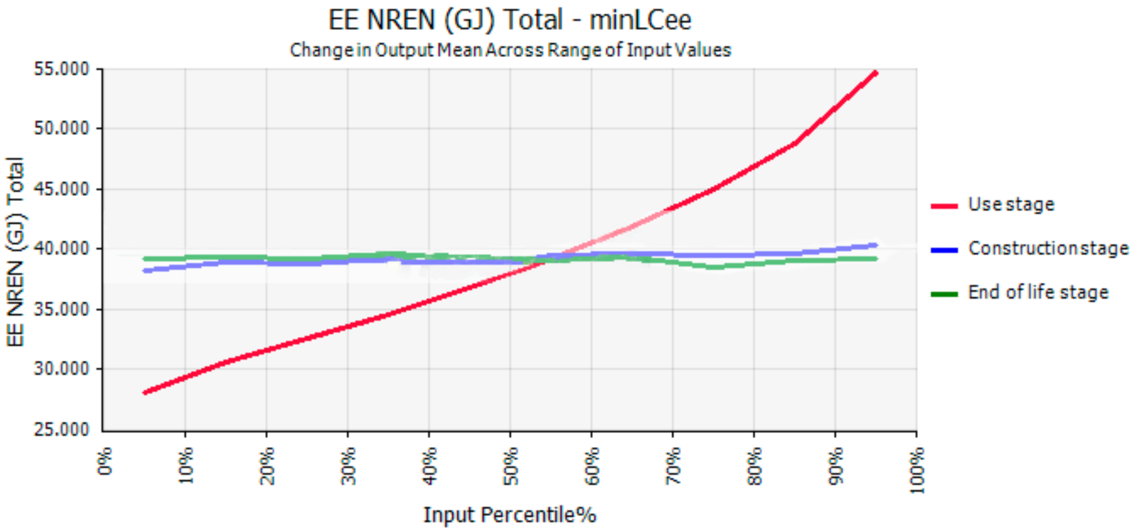

Figure 7 - Radar graph for EE NREN showing how the average output (life cycle EE NREN) changed through every input (values for use, construction and EOL stages) value interval. The sharper the slope of the line, the greater the influence.

4. Conclusions

To assess how scenario uncertainties affects wbLCA results, and to identify proper approaches to carry out such assessment, we performed uncertainty analysis through different, but incremental techniques: scenario analysis followed by stochastic modelling with probability distribution.

The sensitivity analysis presented a range of possible outcomes, with the use of deterministic values. It is a simplistic way of finding outcome variations attached to a diverse set of alternatives, and usually takes an expert eye to extract detailed and relevant insights. Nevertheless, it is important to point out macro trends and hotspots, like the use phase, in the case study analyzed.

After that, stochastic analyses were conducted to provide refined descriptions by adding occurrence probability in distribution curves. It became clear that uniform distributions typically represent the ignorance or data limitation regarding the input to be modelled rather than provide a good description of real-life phenomena. In this sense, triangular distributions offer a better approach to refine data entry and support further propagation of uncertainties regarding the realistic preferences of analysts in relation to the normative choices involved. Ideally, more accurate probability distributions should be pursued to describe the normative decisions involved in LCAs, but this seems still distant from quotidian decision-making processes in the construction sector. Also, this is a simple calculation model with few (only three) input parameters, devised for preliminarily testing a potentially improved methodological procedure. As such, the influence of triangular distributions and rectangular distributions on the result are still very clear. Increasing the number of iterations to 100,000 does not change the histograms shape. However, if several calculation steps are performed with multiple inputs, the results would possibly have to take a different form due to the central limit theorem. This should be further investigated.

Regardless of the classification, scenario analysis does not detract from the use of uncertainty assessment methods, since they have different purposes. At the current status of wbLCA inventory in countries like Brazil, despite failing to account for realistic variability, uniform distributions might be still useful to support MC simulations in cases of extreme lack of information.

The global sensitivity analysis showed the contribution of variation for each input data to the total uncertainty, and the correlation between the simulated data points for the inputs relatively to both impact categories outputs considered. For this study, the use stage contribution to the result variance was roughly 100%. Such findings highlight the strategic importance of gathering service life information adherent to the assessed context. Our model used building components replacement rates induced by the Brazilian standard, which are clearly overestimated relatively to international figures used in LCAs worldwide. It does not mean that international figures are better grounded, since recommended figures for carrying out LCA in some countries were basically transferred from elsewhere and some tools and e.g. certification approaches admit usage of the same values worldwide.

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Diagnosis of uncertainty treatment in neighbourhood life cycle assessments

Zara O O C, Guimarães G D, Gomes V

School of Civil Engineering, Architecture and Urban Design, Department of Architecture and Construction, University of Campinas, Brazil

oliviaorquiza2@gmail.com

Abstract. Urban areas are complex, multifunctional, long-lasting dynamic systems responsible for impressive resource consumption and environmental impacts. Assessments at the neighbourhood scale offers an important complexity compromise. This paper scrutinizes approaches for handling uncertainty analysis (UA) and sensitivity analysis (SA) in LCAs at the neighbourhood scale, aiming at identifying inconsistencies, limitations and challenges, and supporting the development of assessment guidelines. A systematic literature review was performed. Results from the final 35-paper sample show that only one-third of the papers actually performed some calculation. Two of the most recent ones used Monte Carlo (MC) simulations, whilst SA was mainly carried out through scenarios. Despite no clear trend is shown, this may indicate attempts to also apply MC at the neighbourhood scale. The basic quest in UA and SA, particularly global sensitivity analysis, is to balance quality and completeness of output information and computational force needed. Automating calculations, using lighter sampling methods and fast calculators should be further investigated. Finally, future studies could also focus on defining a minimum group of parameters to investigate and on which strategy to follow in specific data availability circumstances. Fuzzy sets seem better for environmental assessments with high degree of uncertainties and probabilistic distributions give results that are more precise. Dynamic models, future scenario uncertainty and spatial uncertainties propagation should also be further explored once the basic challenges for uncertainty assessment are overcome.

1. Introduction

A true sustainable future can only be achieved if urban settlements are diagnosed and treated at the core of the problem as they converge most economic, social and environmentally damaging activities. On the environmental front, traditional urban planning and city management seems to be struggling to deal with the multifunctionality, longevity and dynamism of urban systems, longing for powerful conceptual methodologies that can comprehensively handle its complexity, such as Urban Metabolism and Life Cycle Assessment (LCA).

Neighbourhoods, on the other hand, represent a city's primary cell and characterize the minimal scale for addressing urban spaces socio-economic aspects and the typical scale for urban development projects. Assessments at this scale, consequently, offer an important complexity compromise. Nevertheless, the intricacy inherent to the scale still culminates in an enormous amount of data management and, seeing as LCAs involve numerous calculations, its use to support decision-making can be hampered by the various uncertainties embedded in them [1]. Therefore, addressing uncertainty issues [2–7] is fundamental for improving data quality and the reliability and credibility of LCA studies.

This paper scrutinizes approaches for handling uncertainty analysis (UA) and sensitivity analysis (SA) in LCAs at the neighbourhood scale, aiming at identifying inconsistencies, limitations and challenges, and supporting the development of assessment guidelines. To do so, a systematic literature review was carried out aspiring to answer the following research question: '*How are neighbourhood LCA researcher/practitioner dealing with uncertainty issues?*'.

2. Method

A previous systematic mapping analysis (SMA) [8] was updated. From its 101-paper final sample, 41 articles specifically dealt with neighbourhood LCA, and were scrutinized to understand how uncertainty issues are being dealt with in LCA at that scale. Through an adaptation of systematic literature review (SLR) guidelines [9] and systematic mapping process [10,11], the research was developed following eight main steps:

i. Definition of main research questions driving the research;
ii. Search process;
iii. Relevance screening using exclusion criteria;
iv. Paper classification through a keywording process;
v. Data extraction and mapping;
vi. Comprehensiveness ranking regarding uncertainty issues;
vii. Synthesis of findings in descriptive or statistical manner;
viii. Discussion and analysis of the information extracted from the most relevant papers.

3. Results and Discussion

3.1. Definition of main research questions

Besides the main research question propelling this study, for each paper reviewed, additional sub-questions were also outlined to drive the research process: (a) *Was an uncertainty and/or a sensitivity analysis conducted?* (b) *Which types of uncertainties were analysed?* (c) *Were the uncertainty sources explained?* (d) *Were different types of uncertainties analysed simultaneously?* (e) *Were quantitative or qualitative uncertainty importance analysis performed on parameters?* (f) *Was the correlation between parameters acknowledged, discussed or explicitly accounted for?* (g) *Was the uncertainty methodological framework explained?* (h) *Were temporal and spatial variabilities considered?* (i) *How was the uncertainty distribution expressed and why?* (j) *Which mathematical calculation method was used?* (k) *Was mass and energy conservation discussed?*

The first research sub-question (a) aimed at determining if UA and SA are being tackled in the studied scale and with which frequency. The second, third and fourth sub-questions (b, c and d) intended to find if researchers at this scale investigate different types and sources of uncertainties in their studies and if/how they handle simultaneity effects. The fifth and sixth sub-question (e and f) envisioned to explore if researchers consider correlations and interactions between parameters and their individual contribution to total result uncertainty. The seventh sub-question (g) targeted at verifying if the UA presented by each work followed a determined framework and if that was transparently described. The eighth sub-question (h) aimed at finding if/how geographical and temporal variability were considered. Lastly, the final three sub-questions (i, j, and k) sought to understand the mathematically approach regarding UA and SA.

3.2. Search conduction

The search for primary papers to be analysed in this SLR begun by selecting only the researches classified as 'neighbourhood LCA' or 'neighbourhood hybrid LCA' at the second level keywording process of the previous SMA [8]. Subsequently, the following search terms and string formulation were applied to the 41 resulting papers: 'uncertaint*' OR 'sensitivit*' OR 'variabilit*' OR 'distribution' OR 'scenario'.

3.3. *Screening of relevant papers*

Seeing as these 41 articles had already been screened in regards to database provenance, peer reviewing, English language and being field or scale related, the main criterion that guided the inclusion of a paper on the final sample was that it should acknowledge at least once one of the search terms mentioned above: uncertainty, sensitivity, variability, scenario or distribution. After this process, 35 (85%) papers formed the final SLR sample.

3.4. *Keywording*

Each paper was then assigned to a keyword that best described its approach regarding uncertainty, sensitivity or scenario assessment (Figure 1). Nine papers (26%) regarded only scenario evaluation; 10 papers (29%) dealt superficially with uncertainty and sensitivity issues, usually by simply acknowledging its importance but not performing calculations; 4 articles (11%) regarded the three aspects simultaneously but only for reviewing purposes, not performing calculations. Twelve papers (34%) actually developed some calculation regarding either uncertainty (7 paper / 20%) and/or sensitivity analysis (5 papers / 14%), but in different detail levels.

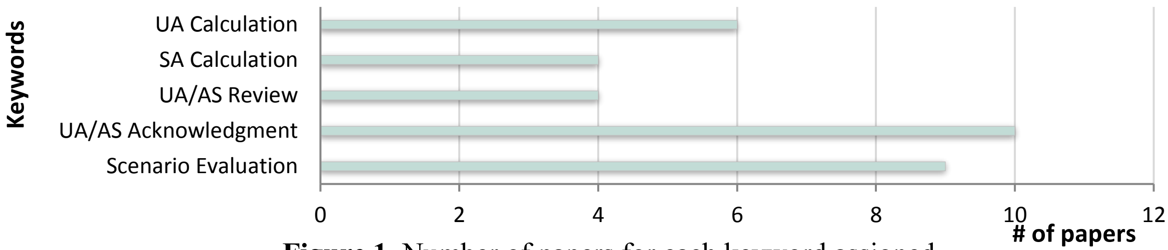

Figure 1. Number of papers for each keyword assigned

3.5. *Data extraction and mapping*

Besides the 14 categories presented in the previous SMA [8], the information collected from the 35-paper SLR sample was further categorized concerning: (i) uncertainty analysis performance; (ii) sensitivity analysis performance; (iii) scenario evaluation performance; (iv) uncertainty location; (v) uncertainty nature; (vi) uncertainty level; (vii) simultaneity; (viii) uncertainty importance analysis; (ix) correlation between parameters; (x) uncertainty framework; (xi) temporal variability; (xii) spatial variability; (xiii) uncertainty distribution form; (xiv) calculation method; (xv) conservation of mass and energy; (xvi) keyword; (xvii) ranking; (xviii) main findings.

3.6. *Ranking assessment*

The sample was categorized from A to E to describe how uncertainty, sensitivity or scenario issues were dealt with. Papers that actually performed some sort of UA calculation were rated as ‘A’; those that performed SA calculation, as ‘B’; review papers, as ‘C’; articles that only acknowledged UA or SA, as ‘D’; and papers that only performed scenario evaluation were rated as ‘E’. Finally, the papers were also assigned marks - (+++), (++) and (+) - according with the number of aspects (UA, SA or scenario) undertook simultaneously, until configuring a 10-class relevance ranking shown in Figure 2.

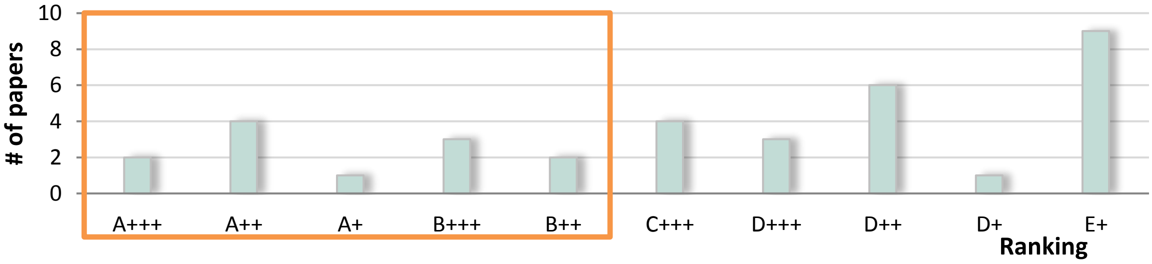

Figure 2. Paper relevance ranking categories

3.7. Synthesis of findings and Discussion

3.7.1. Uncertainty and sensitivity analysis performance. From the overall SLR sampled papers, 22 papers (63%) referenced uncertainty or sensitivity issues in some way. As mentioned above, 10 of the papers (29%) simply acknowledged the existence [12,13] and importance [14,15] of UA and/or SA, but did not calculate them. For instance, Fan et al. [16] highlighted the existence of uncertainty and subjective information as one of their study's limitations. Peuportier and Roux [17] recognized that their neighbourhood LCA results would be more robust if a sensitivity analysis was performed in buildings life span and occupants' behaviour. Huang et al. [18] stated that further research should be done to validate their new integrated life-cycle model for carbon footprint evaluation of districts results, and that a sensitivity analysis should be applied when using different data method and sources.

The empirical nature of the LCA performed by Norman et al. [19] removed some of the inherent uncertainty about the real world environmental effects of urban form and confirmed the validity to adopt widely acknowledged strategies such as automobile transportation reduction, public transit use increase, land use focused on higher density development near employment area, use of renewable energy and alternative fuels. Authors also recognized that their relative results' sensitivity to the choice of functional unit demanded a meticulous consideration given the repercussion that functional unit assumptions may have on urban land use policy.

While still not showing any uncertainty or sensitivity calculation, Heinonen et al. [20] acknowledged them in different aspects of their study. First, those authors opted to use a 25-year lifespan in their residential development LCA indicating that a longer perspective would only considerably increase the use phase assessment uncertainties and would not help to explain the major findings. Subsequently, they approached future uncertainties, stating that, although they accounted for emissions temporal allocation, they did not consider fluctuation on their intensities and consumption volumes over time, which would be very difficult to predict. Finally, while those authors recognized that a number of uncertainties present in their assessments could decrease results accuracy, they affirmed that those uncertainties were detailed in previous studies and should not compromise the general findings, as long as the average residents' aggregate level is maintained in the analyses. Lastly, while exploring perspectives to build a contextualized urban typo-morphologies library to facilitate LCA scaling up from building to territory scale, Sibiude et al. [21], proposed the characterization of representative city cells (qualitatively and quantitatively) that could be aggregated to create higher scale data. Authors, however, acknowledged the need for sensitivity studies to determine cell dimension and system's components data granularity issues, and the need for the evaluation of results uncertainty due to interactions between cells.

In another front and with more analytical depth, the four review papers (11%) also tackled UA and SA on neighbourhood LCA. Through a systematic mapping, Skaar et al. [22] investigated how algorithms and parametric LCA have been used to contribute to decision making for material, buildings and neighbourhoods. Among the 16,209 papers mapped, authors found that, the methods most used were simulation (14.7%), sensitivity analysis (9.4%), multicriteria (7.6%) and propagation (7.1%). Uncertainty analysis was performed in only 3.7% of the papers and statistical procedures such as Monte Carlo (2.1%) and Fuzzy sets (4.5%) had similar lower frequency.

Lotteau et al. [23], on the other hand, reviewed the UA performed by Stephan et al. [24] and the SA performed by Nichols and Kockelman [25], and highlighted the fact that the evaluation of scenarios performed by the other seven case studies on their sample could also be considered as sensitivity analysis. Additionally, authors emphasized that, considering that neighbourhoods are long-lasting complex objects, systematically including UA related to long-term temporal evolution of key parameters is an important challenge to be conquered.

Castaldo and Pisello [26], while reviewing different building dynamic approaches and tools for simulation of realistic dense urban environments, identified grey models as a good 'bottom up' method to be used when a system is lacking information or when a huge input data uncertainty is detected. Those authors also recognized UA and SA as important procedural extensions analytical tools to calibrate dynamic simulation methods, and that key parameters selection, model uncertainty ranges determination, improper model assumptions, simulation code errors and the lack of robust numerical algorithms must all be accounted for.

Mastrucci et al. [27] tackled UA and SA in different fronts in a review of bottom-up building stocks LCA studies analysed according to aggregation model (archetypes or building-by-building), energy analysis (statistical or engineering-based) and LCA performance. Authors highlighted the high uncertainty level of background inventory data adaptation for defining future energy mix scenarios; the higher uncertainty of end-point LCIA methods (relatively to mid-point) due to less consensual physical and social aspects, which introduce subjective value choices; and that while normalization and weighting steps should be addressed more often to enable comparability across studies, they represent an additional uncertainty source. Similarly to Lotteau et al. [23], Mastrucci et al. [27] concluded that few studies quantitatively evaluated input data uncertainty and variability and their propagation throughout the LCA, and that SA was mainly carried out through scenarios describing the evaluation of the stock, policy effects and refurbishment strategies.

The 12 studies (34%) that actually performed some sort of UA and/or SA calculations (highlighted in Figure 2) will be discussed in section 3.7.6.

3.7.2. Uncertainty types, sources and simultaneity. The type and source (location, nature and level [1,5]) of uncertainty was almost never specified in detail by authors. In the few cases it was, authors referred to parameter uncertainty [2], such as lack of representative inventory data or lack of knowledge of uncertainty distribution and, to a lesser extent, model uncertainty, such as temporal and spatial characteristics lost by aggregation, and the need for performing dynamic modelling.

For that matter, Mastrucci et al. [27] emphasized that uncertainty of model inputs, model parameters and modes structure is currently a major issue in LCAs of large building stocks due to the amount of missing information and assumptions to be made, suggesting that input parameter uncertainty characterization and modelling should be carefully addressed in this scale. Moreover, simultaneous analysis of different uncertainty types was seldom performed and, as Skaar et al. [22] have highlighted in their review, despite some advances regarding global sensitivity analysis application, simultaneous accounting for varying parameters and involved uncertainties is yet another under-researched method.

3.7.3. Uncertainty importance analysis and correlations. The lack of emphasis of the sampled papers on the contribution that individual parameter uncertainties might have on the total result uncertainty shows that uncertainty importance analysis [3] is under-researched in neighbourhood LCA studies. Correlation between parameters, although more expressive, are also rarely characterized and quantified. Resch and Andresen [28], while developing a relational database tool focused on systematizing and storing result data and study design for building LCAs, were among the few authors who acknowledged the importance of investigating the relationship between variables.

3.7.4. Uncertainty methodological framework. Due to the variety of types and sources of LCA uncertainty, UA should be guided by a framework [3], however, reviewed papers in general did not reference or present a precise uncertainty framework to be followed, making comparability between studies even harder. Uncertainty characterization phase [1] was almost never discussed in depth by authors and each followed their own process and calculation method. These facts are corroborated by Mastrucci et al. [27], who recommended the development of an uncertainty propagation framework supported by global sensitivity analysis and fast calculators, such as surrogate models, to overcome the limitations of lack of uncertainty propagation and stochastic sensitivity analysis in engineering-based models commonly applied to assess energy demand of buildings stock LCAs.

Although it did not constitute an uncertainty framework per se, Skaar et al. [22] suggested that, to account for LCA uncertainty, first a sensitivity analysis should be carried out to recognize the dominant parameters of the overall considered system, enabling a simplified LCA model while permitting a sharper overview of the multiperformance criteria and multiobjective optimisation decisions variance. Those researchers also recommended expanding the system of interest in terms of scales (from component to neighbourhood) and LCA stages (from A1 to C4 [29]) whenever possible and to use algorithms to manage the complexity and nonlinearity enhanced in the scale transition process. Such algorithms would help to reduce the risk of designing buildings that are suboptimal in the neighbourhood context; to address the key challenges of time and resource use; and to explore consequences, among others.

3.7.5. Temporal and spatial variability. Accounting for spatial characteristics and temporal evolution is very important to ensure that urban assessments effectively support decision-making. For more robust results, temporal evolution, dynamic models, future scenario uncertainty, spatial uncertainties propagation and scaling errors should be properly tackled [27]. Although static approaches are still majority, these aspects were fairly acknowledged by the studies reviewed. Stephan et al. [24], for instance, recognized the great uncertainty embedded in potential technological breakthroughs and the increased renewable energy's market share, and investigated the changes in key parameters over time, testing the effect of the parameter evolution on all scenarios studied. The first step of the methodology proposed by Walker et al. [30] is the recognition of area-specific measures, who also acknowledged the importance of having hourly energy consumption to identify accurate energy performance. Finally, the study presented by Sibiude et al. [21], as mentioned in section 3.7.1, focused on enhancement perspectives to simplify scaling up from building to territory.

3.7.6. Uncertainty distribution and statistical calculation method. Most of the twelve papers (34%) that actually performed some sort of UA and/or SA calculations did not detail the calculation process and methods used, but rather highlighted main assumptions made. From those, five papers (14%) focused on SA and, while some were more superficial [31,32], others went deeper into the subject. For instance, Lausselet et al. [33] proposed a LCA model for neighbourhood and performed a sensitivity analysis based on Sensitivity Ratio to investigate critical parameters, finding that the travel distance per inhabitant and the building' energy load were the two most influential parameters on the total emissions.

Nichols and Kockelman [25] developed a system of statistical models, energy equations, and estimates to account for a life cycle energy assessment (LCEA) of four different neighbourhoods in Austin, Texas. Those authors used Elasticities to estimate the relative sensitivity of neighbourhood energy consumption in response to changes in the built environment or user behaviour, concluding that, from the several urban design variables used in calculations, changes in population density and residential unit size could trigger the greatest per capita energy savings. Nichols and Kockelman [25] also suggested caution with their initial estimates due to the amount of uncertainty involved, and recommended the expansion of the built environment variables and household behaviours for future research.

Last but not least, while comparing LCEA and life cycle cost (LCC) of two social housing neighbourhoods in Mexico city – one compact design near the centre area and one sprawled layout located in the city outskirts – Ochoa-Sosa et al. [34] performed three sensitivity analysis to understand how commuting data influenced overall results. The first two SA consisted in modifying, respectively, the total commuting time and transportation spending ranges, and the data source for average speed for all trips and for public transportation. These aspects affected the overall results but did not change the relative results between neighbourhood cells (NC). Finally, 100,000-iteration Monte Carlo simulations (assuming normality in all data sources and unknown standard deviations as 5% of mean values) were carried out using R language and environment to iteratively change all data inputs and register the differences in CED and LCC. Those authors then concluded that the compact NC would have an overall better performance for CED (64%) and LCC (69%).

Analogously, some of the seven studies (20%) that performed UA calculations were more superficial regarding calculation processes and methods used [28,35–37] and others were more thorough. Stephan et al. [24] acknowledged the considerable amount of uncertainty that infringed their low-density neighbourhood LCA study in Melbourne, Australia, and used an interval analysis to account for data uncertainty and variability by determining suitable literature based ranges around the nominal values of embodied energy and operational and transport requirements. Those authors assumed symmetrical uncertainty boundaries to simplify the assessment, and stated that parameter uncertainty was very likely overestimated (due to the many parameters having a normal rather than a flat distribution), but that it should not affect findings, since the parameter deviation would occur similarly in both scenarios compared. Stephan et al. [24] also alleged that a probabilistic uncertainty model was not produced due to insufficient information for all the parameters assumed in the study.

Using an Urban Building Energy Model (UBEM) tool called the “Urban Modelling Interface”, De Wolf et al. [38] performed energy and carbon simulations on a residential neighbourhood block in Al-Qadisiyyah, Kuwait, to determine the embodied and operational carbon life cycle impact of current and 3 future scenarios situations (Upgraded envelope performance; Low carbon materials; and PV + Low Carbon). Simulation input parameter uncertainty was tackled by defining archetype descriptions as probability distribution and subsequently updating these to posterior joint multivariate distribution by Bayesian calibration using measured energy data points. De Wolf et al. [38] also acknowledged that a sensitivity analysis of the different building geometries could be performed due to the diversity of results.

Finally, Walker et al. [30] proposed a new decision support assessment methodology based on life cycle performance design (LCPD) and key performance indicators (KPIs) focused on the transition towards energy neutral neighbourhoods. The method followed four main steps and included a probabilistic sensitivity analysis at the end. First, the neighbourhood boundaries defined by stakeholder’s inputs are combined with local knowledge and area-specific resources and measures, to identify the realizable scenarios intrinsic to the geographical area. Subsequently, the annual energy performance of each scenario is estimated through simulation models based on the current energy consumption and the building’s demand profile. The authors emphasized the importance of having smaller resolution data at this point, such as hourly energy consumption, to identify the accurate energy performance. Then, a performance assessment of the energy consumption, CO_2 emissions and associated costs of energy infrastructural components is done considering all life cycle stages and using LCPD-based KPIs. In this step, a knowledge-based deterministic approach is used to predict the operational stage energy demand variation of the buildings until 2050 and results are represented in a performance matrix. Lastly, the performance matrix is converted into an opportunity-loss matrix using the minimax regret method, and decision makers decide on the best development scenario. Afterwards, this chosen scenario is further inspected through a 10,000-iteration Monte Carlo simulation of the KPIs parameters uncertainties to find the deviation of the results and the most influential uncertainty parameter. Finally, a multi-criteria decision-making matrix is used to assess the threats, risks and barriers to realize the chosen scenario via a weighting process.

4. Conclusions and final remarks

The SLR made very clear that uncertainty and sensitivity analysis are not being sufficiently performed nor detailed. None of the neighbourhood LCA studies reviewed presented a UA and/or SA comprehensive enough to satisfy all of the uncertainty facets proposed in the data extraction and mapping phase of this SLR. Few studies quantitatively evaluated input data uncertainty and variability and their propagation throughout the LCA, and SA was mainly carried out through scenarios describing the evaluation of the stock, policy effects and refurbishment strategies. These scarce quantitative results say little about the magnitude of uncertainties involved, beyond the general acknowledgement that they are certainly high. Indeed, neighbourhood LCAs are embedded with high uncertainty level due to urban settlements multifunctional characteristics. The large scale and complexity facilitates measurement imprecisions, lack of representative inventory data due to the high number of parameters, potential correlations and lack of knowledge about probability distribution. The dynamism and intricacy of its systems enhance temporal variability and non-linearity issues (Table 1).

Table 1. Neighbourhood LCA Uncertainty Examples

	Type/Source	Goal and Scope	LCI	LCIA
Location	**Parameter Uncertainty**		Data aggregation / extrapolation Building stock embodied energy Lack of knowledge of uncertainty distribution	Foreground unit process data representativeness and variability
	Model Uncertainty		Extrapolation from similar processes Variability in process relationships Static/linear modelling	Modelling structure representativeness
	Scenario Uncertainty	Functional unit Neighbourhood boundaries Modelling framework	Building stock lifespan Allocation methods Waste handling	Impact categories selection Time horizon of impacts Spatial horizon of impacts
Nature	**Epistemic Uncertainty**	Geographical representativeness Temporal representativeness Technological representativeness	Energy consumption (annual/hourly) Commuting distance/time Foreground and background data representativeness	Indicators representativeness Indoor vs outdoor emissions Regional environmental sensitivity
	Ontic Uncertainty	Variability of performance characteristics	Occupants' behaviour variability Societal and institutional variability Technological breakthroughs	Indicators' relationships variability CF variability

The type and source of uncertainties was almost never specified in detail by authors. Also, simultaneous analysis of different uncertainty types was seldom performed, despite some advances regarding global sensitivity analysis application. That is possibly related to the computational requirements, which are added to the high amount of missing information and assumptions to be made when assessing large building stocks. In this regard, uncertainty propagation frameworks, supported by e.g. global sensitivity analysis and fast calculators, such as surrogate models, may help to overcome the limitations of lack of uncertainty propagation and stochastic sensitivity analysis.

Authors generally do not detail their uncertainty assessment framework, do not state or detail the uncertainty characterization phase (location, nature and level of uncertainty) and follow their own process and calculation methods. Furthermore, important aspects regarding UA and SA are not being significantly considered, such as uncertainty importance analysis, correlations between parameter, temporal and spatial variability and conservation of mass and energy. A protocol for declaring the methodological framework and uncertainty assessment steps would be very helpful for comparing studies and advancing the body of knowledge in the field.

Two – but among the most recent - papers used Monte Carlo simulations, but with great disparity in the number of iterations used. The basic quest in UA and SA, particularly global sensitivity analysis, is to balance quality and completeness (i.e. number of parameters simultaneously analyzed) of output information and computational force needed. In terms of computational capacity, shifting from 10,000 to 100,000 makes a big difference. In other scales it seems to have some consensus on using 10,000 iterations and it is not clear if 100,000 would be really needed to reach convergence.

In UA carried out in other scales, MC support seems dominant. Although the reviewed literature does not indicate a similar clear trend, this may be an indication of attempts to apply sampling techniques also at the neighborhood scale. For buildings, for example, a robust assessment procedure can be to define, for each uncertainty source investigated, data points to describe at least a triangular probability distribution as input for MC simulations, which in turn supports global sensitivity analysis. An undisputable limitation is the high number or scenarios needed (at least three per uncertainty source). This number grows progressively as the number of parameters considered increases, meaning that several LCAs must be carried out to feed the simulations, which will also increase computational demand. If this part can be somehow automated, its application might become more frequent in the near future. Also, sampling methods with less computational requirements, like the Latin hypercube sampling, or the already mentioned use of fast calculators and surrogate models.

Finally, future studies could also focus on defining a minimum group of parameters to investigate in LCAs at this scale, and on which strategy to follow in specific data availability circumstances. Fuzzy sets seem better for environmental assessments with high degree of uncertainties and probabilistic distributions give results that are more precise. Static approaches are still majority in the specific literature, but dynamic models, future scenario uncertainty and spatial uncertainties propagation should be further explored once the basic challenges for uncertainty assessment are overcome.

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The regenerative building*: A concept of total sustainability*

Gambato C[1], Zerbi S[2]

[1] Researcher, Department for Environment Construction and Design, Institute for Applied Sustainability to the Built Environment, University of Applied Sciences and Arts of Southern Switzerland, Canobbio, 6952, CH

[2] Professor, Department for Environment Construction and Design, Institute for Applied Sustainability to the Built Environment, University of Applied Sciences and Arts of Southern Switzerland, Canobbio, 6952, CH

carlo.gambato@supsi.ch

Abstract. The concept of building's sustainability is progressively evolving, from the mere issues of limiting the energy needs of the building, extends to include new areas. The long-term sustainability visions (in Switzerland the "2000 W Society" by year 2100) imply not only technological changes but above all radical changes in the human behaviour. A multidisciplinary study, carried out by SUPSI and specialists, proposes a method for determining the parameters for the design of a building by year 2100. It also shows that in order to achieve long-term sustainability goals (primary energy reduction and CO_2 emissions per capita, 2000 W and max 1 ton CO_2), alimentation can be considered as a building need. The high potential in reducing primary energy needs in this area makes possible to compensate others energy consumptions and CO_2 emissions of the building inhabitants and of the building itself. The sustainable building of the future shall therefore: - present a zero or compensated operating energy need; - present minimal energy need for construction; - allow food production (Urban Farming, Building Integrated Agriculture) through natural and regenerative agriculture (self-production); - promote and act as a shelter for local flora and fauna (regenerative); - respect the soil stratigraphy (reversible).

1. Introduction

The concept of building's sustainability is progressively evolving, from the mere issues of limiting the energy needs of the building, it extends to include new areas. The long-term sustainability visions (in Switzerland the "2000 W Society" by year 2100 [1]) imply not only technological changes but above all radical changes in human behaviour. This vision is in line with the objectives of the Swiss Federal Council's Energy Strategy 2050 [2] and is a recognized instrument of the Swiss energy policy. In addition, land consumption and biodiversity loss are increasingly becoming important issues in Switzerland.

The present study proposes measurable values and target design parameters concerning energy and CO_2 emissions for the construction, operating energy and mobility of buildings by the year 2100. Moreover, it integrates themes such as biodiversity, reversibility and the innovative concept to consider alimentation as a building need in order to achieve long-term sustainability goals (primary energy reduction and CO_2 emissions per capita, 2000 W and max 1 ton CO_2). A concept of total sustainability is proposed.

2. Methodology

2.1. Society 2000W (Swiss long-term sustainability vision)

The 2000 W Society vision refers to a maximum per capita energy need equivalent to the consumption of 2000 W for 8’760 hours/year. Per capita consumption includes the areas of living, mobility, food, general consumption and infrastructure.

In the field of buildings’ construction, the 2000 W Society vision is translated in the technical norm SIA 2040 [3], which imposes limits on energy and CO_2 emissions for construction (grey energy), operating energy and mobility related to buildings. These limits have to be respected and operated by the end of the year 2050 (intermediate target of 3500 W per capita). Buildings, sustainable neighbourhoods and the 2000 W Areas built in Switzerland today are in line with the SIA 2040, i.e. the vision of the Society at 2000 W at 2050. The objective of the study is to provide measurable values and design parameters that are concretely applicable in the daily practice but extending the limits (kWh / m^2) and ($kgCO_2$ / m^2) from 2050 to 2100.

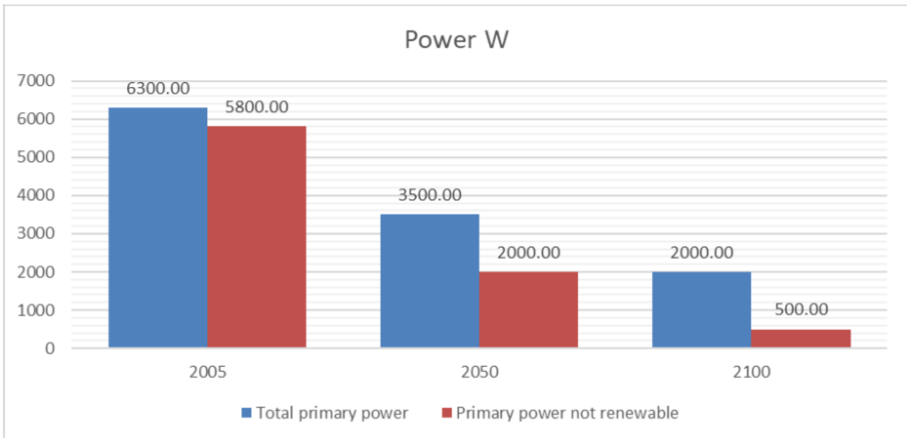

Figure 1: Per capita energy power (total and not renewable) today (2005), targets for 2050 and 2100

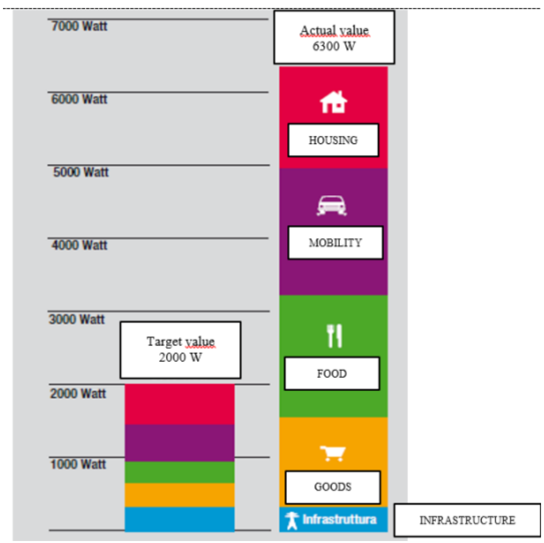

Figure 2: Sectors considered in the 2000 W Society concept. The objective for the year 2100 is to reduce by two thirds the maximum per capita total energy need to the consumption of 2000 W for 8,760 hours per year, which is currently around 6000 W.

The technical norm SIA 2040 imposes limits on energy and CO_2 emissions for construction (grey energy), operating energy and mobility related to buildings so that the energy performance of the construction sector can achieve the objectives by the year 2050 (3500W per capita). The study extends the design limits at year 2100, using the same methodology as the actual norm and the 2000W Society (for housing). The value of non-renewable primary energy extended at 2100 for buildings results actually too low to be achieved in relation to what is feasible today (refer to Figure 3) [4].

An innovative approach is proposed to solve this problem. Is introduced the concept that another need is to be considered related to the building and its occupants: food. This topic is important in the way to get the goals of the achievement of the Society 2000 W. The total energy primary power today in the field of food is deduced from the global average per capita Switzerland balance according to the 2005 statistics and amounts to 1’300 W and 2.08 tons of greenhouse gases [5]. Relating these quantities to buildings and applying the reduction factors on total primary energy at 2100, the target design values were obtained at the year 2050 and 2100 (refer to colums “2100 Theoretical target” and “2100 Reachable” of Figure 3).

Housing	SIA 2040		SUPSI Study			
	2050		2100 Theoretical target		2100 Reachable	
	Primary energy not renewable [Mj/m^2]	greenhouse gas [kg/m^2]	Primary energy not renewable [Mj/m^2]	greenhouse gas [kg/m^2]	Primary energy not renewable [Mj/m^2]	greenhouse gas [kg/m^2]
	new buildings		new buildings		new buildings	
Construction	110	8.50	*27.5*	4.25	110	8.5
Operating energy	200	2.50	*50*	1.25	13	0.7
Mobility	130	5.5	*32.5*	2.75	104	4.9
	440.00	16.50	**110.00**	8.25	**227.00**	14.10
Alimentation (food)	*683.00*	*17.33*	217.00	4	98	5.67
Total			**327.00**	12.25	**325.00**	19.77

Figure 3: Targeted values at 2100 in the different areas and reachable values (housing).

As can be deduced from Figure 3, the theoretical limit value of non-renewable primary energy calculated at 2100 (110 MJ / m^2), is difficult to reach (evaluation according to the the SIA D0236 norm[4]) despite by providing efficient, well-insulated, low grey energy constructions, which exploit renewable energy sources (e.g. wood) in areas well served by public transport in the peri-urban area. However, considering a personal completely vegetable diet, it is possible to obtain a value of non-renewable primary energy that is half of the limit value (98 MJ/m^2 vs 217 MJ/m^2). Therefore, this energy and emissions savings can compensate the other needs for construction, operating energy and mobility. With this innovative approach it is possible to reach the total target value at 2100 of 327 MJ / m^2 (limit 327 MJ / m^2, obtainable 325 MJ / m^2) (Figure 3 and Figure 4).

The theory introduces the innovative concept that it is possible to establish and respect the values targeted at 2100 in the areas of construction, operating energy and mobility, acting also in the context of the alimentation related to the building. Food can be considered as an energy need (with consequent emissions of greenhouse gases) related to living and the building itself similarly to the sector of mobility. In this way, considering the sector of food, it is possible to raise the target value on the building in a feasibility field but respecting the global limits at 2100. The target values for non-renewable primary energy for the Society 2000 W at 2100 are shown in the column “reachable” in Figure 3 and Table 1.

It should be noted that the values established at 2100 regarding operating energy, construction and mobility, although they are possible to be achieved, remain very low. The design of the building must therefore use materials and systems characterized by very low grey energy content (e.g. low or no tech solutions), characterized by a complete use of renewable energy sources. The respect for these target values remains a design challenge today that needs to be investigated.

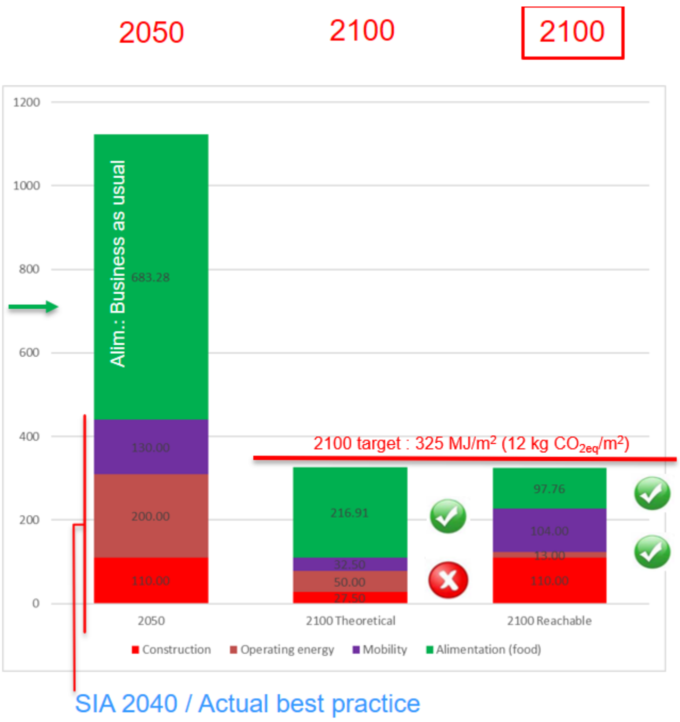

Figure 4: Achievement of the new values targeted at 2100 (2100 feasible column) considering the compensation of the energy needs of the building thanks to the energy saving due to diet. Without compensation, the objectives on the building are not reachable (2100 theoretical column)

Table 1: Proposal of project target values in terms of not renewable primary energy for the building by the year 2100 within the framework of the Swiss Sustainability Vision (2000W Society).

	2100 Design values	
Areas of analysis	Primary energy[a] (MJ/m²)	CO2 emissions (kg/m²)
Construction (gray energy)	110	8.5
Energy needs	13	0.7
Mobility[b]	104	4.9
Nutrition	98	5.67
Total energy	325	19.77
Total power [W]	*618* [c,a]	

[a] Not renewable primary energy
[b] Daily mobility
[c] Considering a swiss average of 60 m² / inhabitant (Society 2000W)

2.2. Alimentation

The alimentary theme can be no longer ignored and is to be tackled on a global [6][7][8][9], territorial [10][11][12], and local level, also by constructions [13], and by living [14] more generally. In 2011, study "Environmental Impacts of Swiss Consumption and Production" [11] edited by the Federal Office for the Environment showed that among the consumption categories, nutrition is the most important and causes 30-40% of the total environmental impacts. Moreover was confirmed in 2018 by the "Swiss Environment Report" [15] that the sector of consumption and production with the greatest environmental impact is food (28%), followed by housing (24%) and mobility (12%). Furthermore, a study [12] regarding the Society 2000 W, identified 107 people who would already respect today the concept of a 2000 W Society in terms of energy but do not respect the vision in terms of greenhouse gases because their meat consumption is responsible of approx. 0.9 ton / year alone, thus making impossible to respect the total limit for all areas (1 ton). Finally, it has already been determined in studies carried out analysing the energy impacts of in-place 2000 W Society buildings in Zurich (technical requirements for the year 2050), that the food sector (meat consumption) is very critical for the achievement of the per capita energy balance and emissions target [14].

From the point of view of buildings' construction and architecture, this topic is translated through the integration of food productions in the cities or directly in buildings (Urban Farming and BIA - Building integrated agriculture [13]). The winning pavilion designed by the Swiss Solar Decathlon team could represent a valuable example [16]. The diet is strongly characterized by the behavioural aspect. In the present study, in order to allow energy or CO_2 compensation through food, a regime without animal derivatives is considered as it is characterized by the lower impact in terms of energy and CO_2 [5].

2.3. Biodiversity

Considering that in Switzerland about half of the natural habitats is threatened [17], nearly half of the native species are threatened [17], that 60% of urbanized areas are watertight [17] and urbanized areas may be richer in species than agricultural areas [17], the urban space can be considered a refuge for species that have lost their natural habitat.

In a view of total sustainability, biodiversity must be integrated into all aspects related to the building and the external area. It is possible to design the building in order to act as a refuge for flora and fauna (on facades, roofs and nearby area), so that the building can help regenerate an impoverished soil with its presence.

2.4. Reversibility

The expansion of urbanized areas and infrastructure causes fragmentation of habitats for animals and plants [17]. In Switzerland between 1985 and 2009, the urbanized area increased by 23% [17]. The soil is therefore to be considered as a non-renewable resource.

The sustainable building should avoid soil sealing and compaction. Typically, the building is suspended, i.e. with punctual pile structures. By the end of the computed building life-time the soil should be returned to the environment without damage and enriched in biodiversity (regeneration). Loss of soil and fertility must be avoided.

3. Case Study

After the execution of the study, the intention is to build an experimental building in Ticino in collaboration with a private partner. The experimental pilot building will have to enable the inhabitants to respect the per capita parameters of the Society 2000W at year 2100 as well as to be regenerative and reversible (construction technology should increase local biodiversity). In this phase, preliminary evaluations were carried out on the construction characteristics that a single-family building (2 people) should have in order to respect the construction limits described in Table 1.

Three different housing plans (Figure 5) and 3 different system configurations have been evaluated (heat pump and photovoltaic, wood heating, wood heating with certified electricity purchase) for each scenario (total of 9 scenarios). The limits concerning non-renewable primary energy have been verified. With regard to mobility, the average standard conditions in Ticino were considered, while for food it was considered a completely plant-based regime without animal derivatives [5]. The preliminary characteristics of the building (construction / plant) were determined in order to respect the limits, in terms of W per capita.

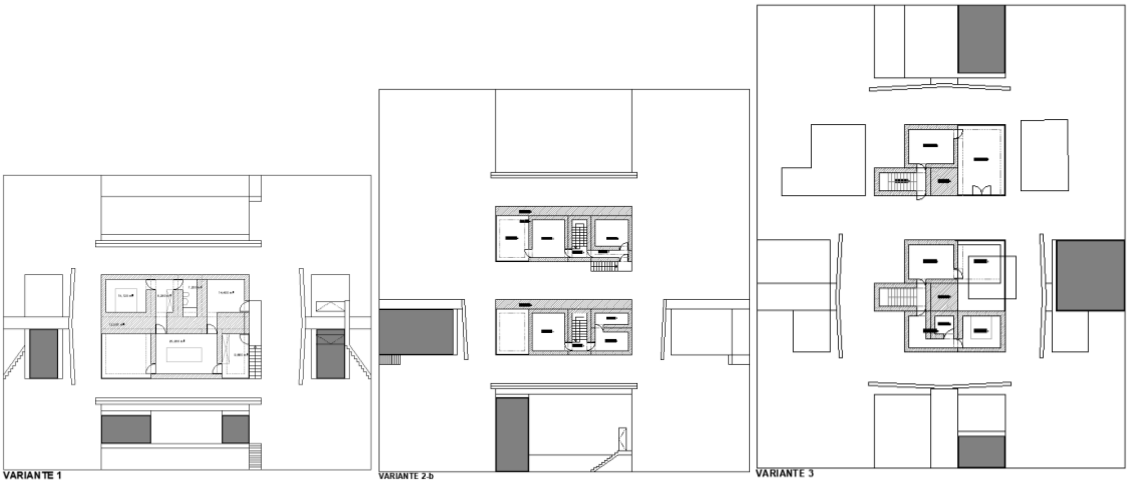

Figure 5: 3 different housing plan were evaluated. (1) Single floor suspended with concrete blade (94 m^2). (2) Two suspended floors with pillars (94 m^2). (3) Two floors compact (125 m^2).

Table 2: Case Study - Target values and project values

	Case Study	
	2100 Target values	Project
Areas of analysis	Primary energy[a] (MJ/m^2)	Primary energy[a] (MJ/m^2)
Construction (gray energy)	110	111.78
Energy needs	13	13
Mobility[b]	104	167[e]
Nutrition	98	98[f]
Total energy	325[c]	389
Total power[W]	***618*** [c]	***580*** [d]

[a] Not renewable primary energy
[b] Daily mobility
[c] Considering a swiss average of 60 m2 / inhabitant
[d] Considering the project value of 47 m2 / inhabitant
[e] Considering 2 parkings and the average public transport service in Ticino Canton
[f]Standard Swiss complete vegetarian nutrition

The study variant that presents the energy characteristics shown in table 2 (respecting the 2100 Targets values in term of Total power per capita and nearly reaching the energy requirements in terms of MJ/m^2) is the housing plan number 2 with the following general characteristics:

• The building structure must be compact, the internal surfaces limited
• Building envelope and structure should be prefabricated in wood
• Transmittance of the construction elements according to the Swiss state of the art (0.15 - 0.20 W / m^2K)
• Wood heating in central position of the house without heat distribution
• Domestic hot water heating by a heat pump
• Without photovoltaic or thermal solar panels
• Purchase of certified electricity from renewable sources (hydroelectric)

Notes:

- Photovoltaics: the annual amount of grey energy of a photovoltaic system (in the considered cases) is broadly equivalent to the annual compensation in terms of operating energy computed according to the technical norm [18]. Basically, the presence of a photovoltaic system involves roughly ca. +120 MJ / m^2 in terms of grey energy and subtracts approx. 120 MJ / m^2 in terms of operating energy (systems from 10 to 14 kWp);
- Due to the fact that in the vision Society 2000W there is the possibility of considering the certified energy purchased as full renewable, the presence of a photovoltaic system is always unfavourable (buying certified energy compensates the operating energy without having the grey energy load of the PV system).
- At this stage, for the agricultural self-production of food a surface of at least 2’000 m^2 was estimated. The area has to be cultivated through natural and regenerative agriculture which should provide self-sufficiency after 7 years with a commitment of 1 person for 4.8 hours per day.
- The targets established have not been reached in terms of energy MJ / m^2 but in terms of power per capita (W). Mobility has a certain weight in respect of the limits, however, it is a sector hardly influenced by designers because it depends on where the building is build.

4. Conclusion

Swiss energy policy has ambitious long-term goals. The way to reach them is not yet determined. This study provides a multidisciplinary approach to determine the characteristics of buildings and living-style in order to achieve sustainability goals both from an energy and a long-term environmental point of view. An innovative holistic approach, which partly concerns technical and design aspects, partly regarding behavioural aspects such as nutrition is proposed. The innovative concept of alimentation considered as building need in the energy balance, has been introduced.

The energy values (present and achievable target) for the alimentation related to the building were quantified (today 683 MJ/m^2, target 98 MJ/m^2). A proposal for a practical design limit value for the Society 2000W at 2100 is quantified (considering operating energy, grey energy, mobility, nutrition) at 325 MJ/m^2 (618 W per capita) primary non-renewable energy. A preliminary case study has shown that the values are achievable today by focusing on a low-tech approach, with low grey and operating energy, and with a fully plant based diet.

A vision of total sustainability of the buildings that will be the home of a mankind of the near future for which integration in the ecosystem with positive impacts is a moral imperative is proposed. The shift of the paradigm of the role or non-role of mankind in the ecosystem allow to reinterpret inhabitation and construction technology.

4.1. Next Steps

The next steps are:
- Calculation of the energy and emission target by year 2100 considering the global energy need (renewable and non-renewable)
- Verification of the feasibility of the target for a CO_2 neutral construction (0 kg / m^2)
- Determination of technical solutions, materials and approaches to achieve the objectives concerning the target of grey energy needs of the construction through pilot projects (construction of an experimental single-family house)

- Development of systems for integrating the production of eatable plants onto the building envelope through models in full scale
- Quantification of the objectives in the sector of biodiversity regeneration
- Development of building foundation systems and site management in order to preserve the stratigraphy of the soils.

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HYBRIDisation – a resilient strategy in times of change and transformation

Schwehr P, Schuchert C L, Winterberger F

Lucerne University of Applied Sciences and Arts, Competence Center Typology & Planning in Architecture (CCTP), CH-6048 Horw

peter.schwehr@hslu.ch

Abstract. Our built environment consists of spaces, buildings, and cities that are subject to ever-changing social, economic, ecological and cultural demands. The demand for high quality living space is becoming ever more significant for densifying urban areas. When lifestyles, modes of working and recreational activities intertwine, new concepts on all scales must follow. Consideration of resilience of all kinds is becoming an important part of planning. It requires typologies with resilient characteristics, which can also take on new tasks perhaps not yet known of today. This paper recognises such a typology in the hybrid. Hybrids possess a variety of characteristics and benchmark parameters. A code inherent in them renders them capable of reacting to various situations and differing requirements. Depending on its constitution and purpose, the hybrid code affects a variety of architecturally relevant, environmental levels, namely district, neighbourhood, building, unit, components, infrastructure and processes. "Hybridisation" describes the process of the deliberate application of this code on all levels ("design and injection"), albeit also its decoding, i.e. activation of processes of change. In this way "new genetic alliances" are created, in which differing hybrids interact. By offering advanced adaptability through HYBRIDisation, buildings become resilient to change and allow for diverse modification and development throughout their lifespan, resulting in improved learning ability. This paper explores strategies of HYBRIDisation and the consequences for the interlinked levels to enable hybrid and resilient levels of environment.

1. Initial Situation

Today, long-lasting construction is a top priority in the building industry. In day-to-day planning and on various levels, this leads to challenges for planners, buildings and processes and begs questions as to which strategies are suitable to meet them.

1.1. Demand for planning security in times of upheaval and uncertainty

Buildings and districts are subject to permanent pressure to adapt. Stressors make them fragile and force the testing of their justification for existence. If these programmes, e.g. for living or work, change, they are very often no longer compatible with the built hardware. It is precisely in times of fundamental change, like digitalization and migration for example, that programmes are written in rapid cycles, something that does not correspond with the usual 50-100 year durability of our buildings. Moreover, solving the problem with incomplete and only partially predictable knowledge in times of upheaval is business as usual in planning. One approach, which takes account of these circumstances, takes the "unknown as the basis" [1] and seeks "approaches for dealing with uncertainty". [2] We have to admit to ourselves that we can only predict future developments to a limited extent, cannot control them and most certainly cannot plan them. [3]

1.2. Demand for resilience in the construction industry

We need buildings that can stand up to "stress" [4] arising from change for the longest possible period, yet do not rule out their own development. So instead of the maxim of resistance and consequent defensiveness against development, a resilient strategy that sees in those new requirements an opportunity for continued development. Here resilience is the yardstick of a system's robustness. If it can overcome stressors, renew itself, continue to develop and emerge from transformation even stronger, then it qualifies as a resilient system. Endurance is the overlying objective, with resilient characteristics and strategies as the route to follow. An important basic prerequisite for resilience is the scope for potential action. Places and buildings in which things can be tried out and which find justification in the event of success whilst, in the event of failure, allowing other possibilities to be tried out without great outlay. [3]

1.3. Demand for intermixed "urban areas"

Studies have shown that, by 2050, about 66%, and by 2100 about 85% of the world's population will live in cities. [5] The associated necessary densification, in combination with changed lifestyles and ways of living and working, puts typologies used to date additionally under pressure and underlines the need for new typologies. By way of reacting to the anticipated population increase in cities, the "urban quarter" construction area category was introduced in Germany in 2017. This category corresponds with the "model of a city with short routes, places to work on site and good social mixture". [6] The goal is to support areas that accommodate residential space and "service and business enterprises in small-scale, mixed use. […] This mobilises additional living space where the city is at its most attractive, ensures well-functioning intermixing and makes conservative use of land." [7] These new zoning codes make it possible to build higher and more densely in "urban areas", and use an apartment as both working and living space. Consequently a new hybrid, multifunctional typology of buildings is necessary. The challenge now is to formulate structural, creative and location-specific typology approaches in such a way that they correspond with current demands and can hold their own in changing times.

1.4. Demand for multifunctional and adaptable building

New ways of working and living, alongside increasing intermixing and combining of different functions, is leading not only to new zones but also increased blurring of what were to date clear distinctions between specific typologies (home, office, school etc.). New demands for multifunctionality and 24/7/365 usage of buildings are taking over. Future usage scenarios orient themselves towards the now. No statements can be made for the long term regarding their validity or certitude. Typologies established and used to date cannot do justice to this requirement for capacity to change and react because of their specificity and monofunctionality, and are under scrutiny as to their usefulness.

1.5. Summary

The future challenge to our built environment is marked by great uncertainty in relation to future developments. We find ourselves in times of upheaval: "globalisation, digitalization, climate change, urbanisation, demographic change and migration, declining status of nation states, increasing economic power of large private companies, […]. New technologies like blockchain and Artificial Intelligence are scarcely tangible as keywords for individuals but, in actual instances of change like gentrification, segregation, Fitbits, one-click shopping, rising sea levels and self-driving cars, they are already influencing day-to-day life today...". [3] John N. Habraken put it in a nutshell with "You can't control!". We therefore need spaces, buildings and neighbourhoods that can react as an open system to changing requirements and which, despite change, are guarantors of high-quality living space. Our spaces, buildings and neighbourhoods must urge us to act and thereby to fulfil our responsibility.

Whilst the focus used to be on endurance, today it is the built environment's transformability and the ability to react rapidly that indicate a resilient city. Resilient architecture will always be open architecture that seeks to interact with its environment, enters into collaboration and uses synergies. For this there is a need for new ways of thinking and architectural systems that can enter relationships with one another at a variety of levels and overcome the isolated way conventional monofunctional typologies operate. Hybrids can make an important contribution to this, exhibiting as they do the very resilient characteristics needed in times of unpredictable development.

2. Hybrid code, hybrids und hybridisation

2.1. Definition and demarcation

In connection with multifunctional characteristics, the term hybrid was selected for the profile of requirements for future construction and processes. Supplementing Per et al, which limit a hybrid to an "opportunist building, which makes the most of multiple skills, a key player which revitalises the urban scene and save spaces" [8], the term "hybrid" gains additional scope, to the effect that hybrids indeed do not just cover the building, instead reaching over various characteristics and benchmark parameters. Among their assets, hybrids have at their command a code that enables them to react to diverse situations and different requirements. Depending on its composition and purpose, the hybrid code works on different, architecturally relevant, environmental levels. Levels are district, neighbourhood, building, unit, room, infrastructure and processes for example. These levels are summarised as "hybrids". They are comparable with layers one above the next, which are connected at some points for a certain period. Through the "transmission of stimuli", impetus is delivered, interactions are strengthened and synergies between levels are made possible. On the one hand, "hybridisation" describes the deliberate installation of the code in these levels ("design and injection") and, on the other, its decoding, i.e. the activation of processes of change. Thus, through the interaction of the more widely differing hybrids, "new genetic alliances" are created.

The interaction between hybrids and hybridisation constitutes information processing involving two information levels of the built environment. One information level relates to the genotype. Stored there are all of the information about and characteristics of the hybrid. It is activated by a second information level – decoding. Decoding leads to different characteristics of the hybrid then visibly appearing as phenomenological characteristics, the phenotype, according to arrangement and dominance. Thus, for example, the potential for an ability to adjust is lodged in the genotype, but only becomes apparent phenomenologically in the event of change. In biology, this process of activation and inhibition of characteristics is called "epigenetic imprinting" and explains "when and which contents from the genetic handbook of an organism are to be used". [9] Following this epigenetic principle, the activation of structural and procedural characteristics of the hybrid in the course of hybridisation has to be seen as decoding of the hybrid code.

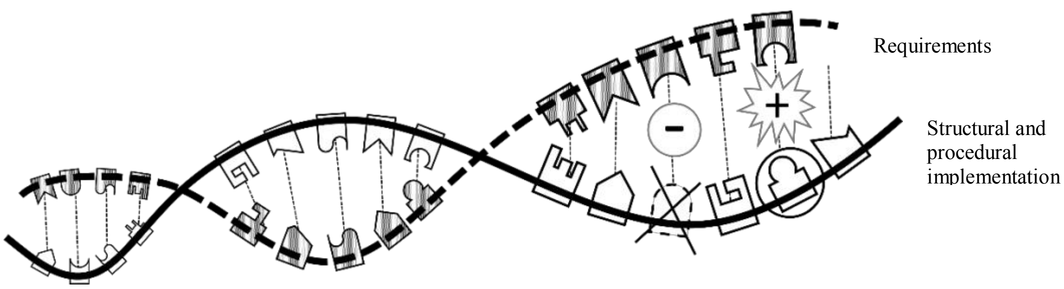

Figure 1. The characteristics of the built environment stored in the hybrid code are decoded and activated by the requirements. The structurally lodged assets of the genotype now appear as the phenotype.

Table 1. Definitions

Term	Analogy / definition
Hybrid code	**“Vaccine”** Structural and procedural characteristics that allow an architectural element to mutate into a hybrid
Hybrids (hybrid levels)	**“Recipient”:** An architecturally relevant environmental level infected by the hybrid code and inherently possessing the capability to change
Hybridisation	**“Vaccine, activation”:** From deliberate designing of the hybrid code, on through laying down its hybrid characteristics in the corresponding architectural element, to activating the hybrid. In addition, the process of interaction and cooperation between the differing hybrids is described by hybridisation.

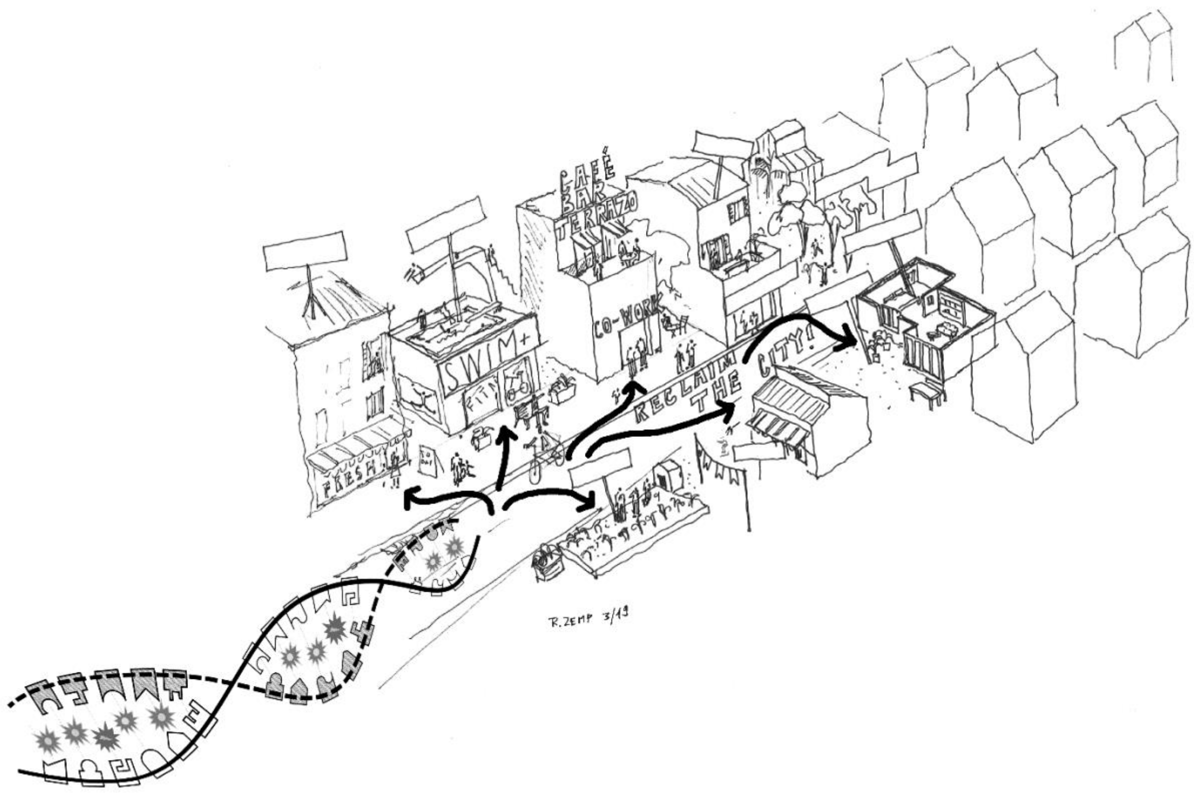

Figure 2. Effect of hybridisation

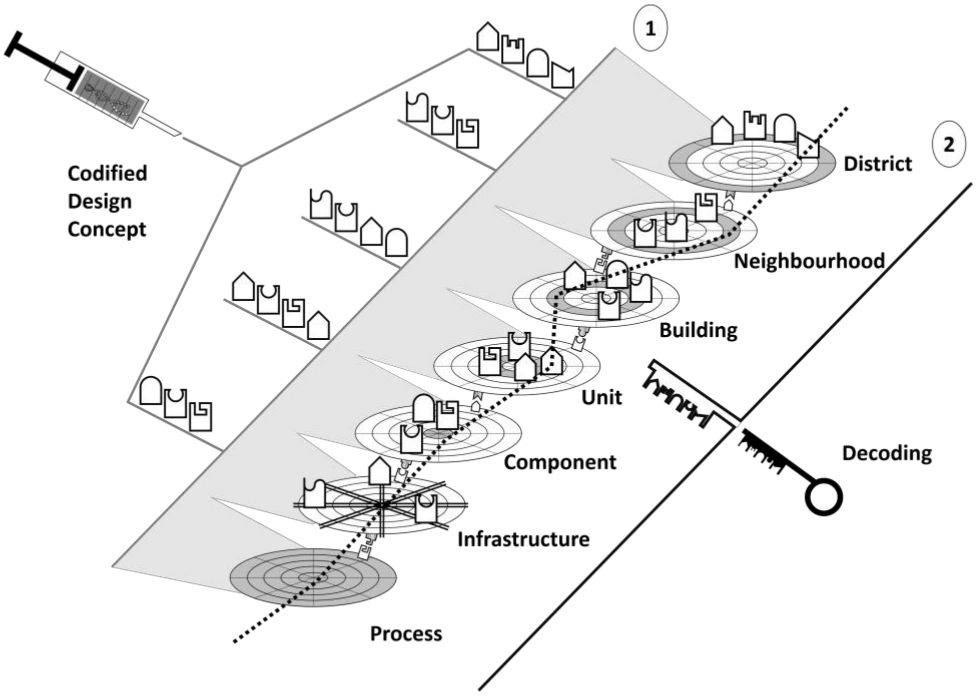

Figure 3. All levels are coded with the codified design concept, i.e. potential is laid down (1). In the event of external pressure to adapt, the code is decoded, i.e. the potential is activated (2).

2.2. Demarcation of hybrid buildings and typology

Hybrids differ substantially from conventional, specific and generally monofunctional typologies (e.g. schools, residential buildings etc.). Hybrid buildings can result from the sensible combination of requirements on various originally monofunctional typologies for example (e.g. living and work) and thereby enable multifunctional use. Thus, for example, simultaneous or staggered living and working can take place in one unit of usage, substantially raising the building's occupancy in the course of a day. This is possible if the higher requirements of one use (e.g. acoustics/living) are determining factors for the hybrid building. However, a higher ceiling for example only makes sense if the unit of usage is also used as an office. Seen from this point of view, monofunctional typologies seem more efficient than hybrid ones. But if the demands on the building change, monofunctional typologies are subject to substantial pressure to adapt, due to their specificity and efficiency alongside a dearth of buffer zones. With this in mind, resilient strategies are aimed primarily not at raising efficiency but rather their effectiveness, their efficacy, with their measures then being implemented efficiently for the sake of sustainability. This demands the sensible treatment of reserves and buffers. The combination of adequately sized and proportioned rooms with usage-neutral floor plans and unbundled building services are lodged in their genotype. They constitute the specific code for hybrid building and enable more appropriate, simpler changes of use and support the transformation of the built environment.

Table 2. Comparison between hybrid building and familiar typology characteristics

Character Hybrids	Character Typology
Application-specific	**Task-specific**
Has "unexpected mixing of functions"	Conceived for a specific use
Appropriation as a principle, scope for action	Prescribed use
Multi-used	**Mono-functional**
Oriented towards usage and changes thereof (e.g. learning)	Oriented towards function (e.g. school)
Based on unknown future	Based on tradition
Use creates form	Form follows function
Full-time activity	Part-time activity
Environment as system boundary	**Building as system boundary**
Focus impact on city	Focus on building

Sensible interaction with environment required Uses synergies	Focus on plots Self-optimisation
Open system Interconnected and open to development Anti-fragile (disruption = opportunity), fault-tolerant Great diversity From visible to undercover	**Closed system** Singular and complete Fragile (disruption = danger), fault-prone Limited diversity Visible
Changes within and outside the system through spontaneous or planned **initiation** Change can only be planned and controlled to a certain extent (e.g. appropriation by new users)	**Changes** within the system as **reaction** Change can be planned and controlled (e.g. classroom reconstruction)

An example of a hybrid which influences the whole district is the multifunctional building named Frizz23 in Berlin (D). Primary goal of the realised concept was to create "commercial with dwelling" which would be enriching for the existing neighbourhood. The city property which had recently become vacant wasn't sold for the usual market price but developed in a participatory dialog process with local stakeholders. A number of different means of funding facilitated the desired social mix. The plot was sold at a reduced price. The difference in relation to the market price was added to the price of the freehold flats and credited to the co-operative flats. This cross-financing makes affordable housing possible at a price per square metre of € 9.50 a month.

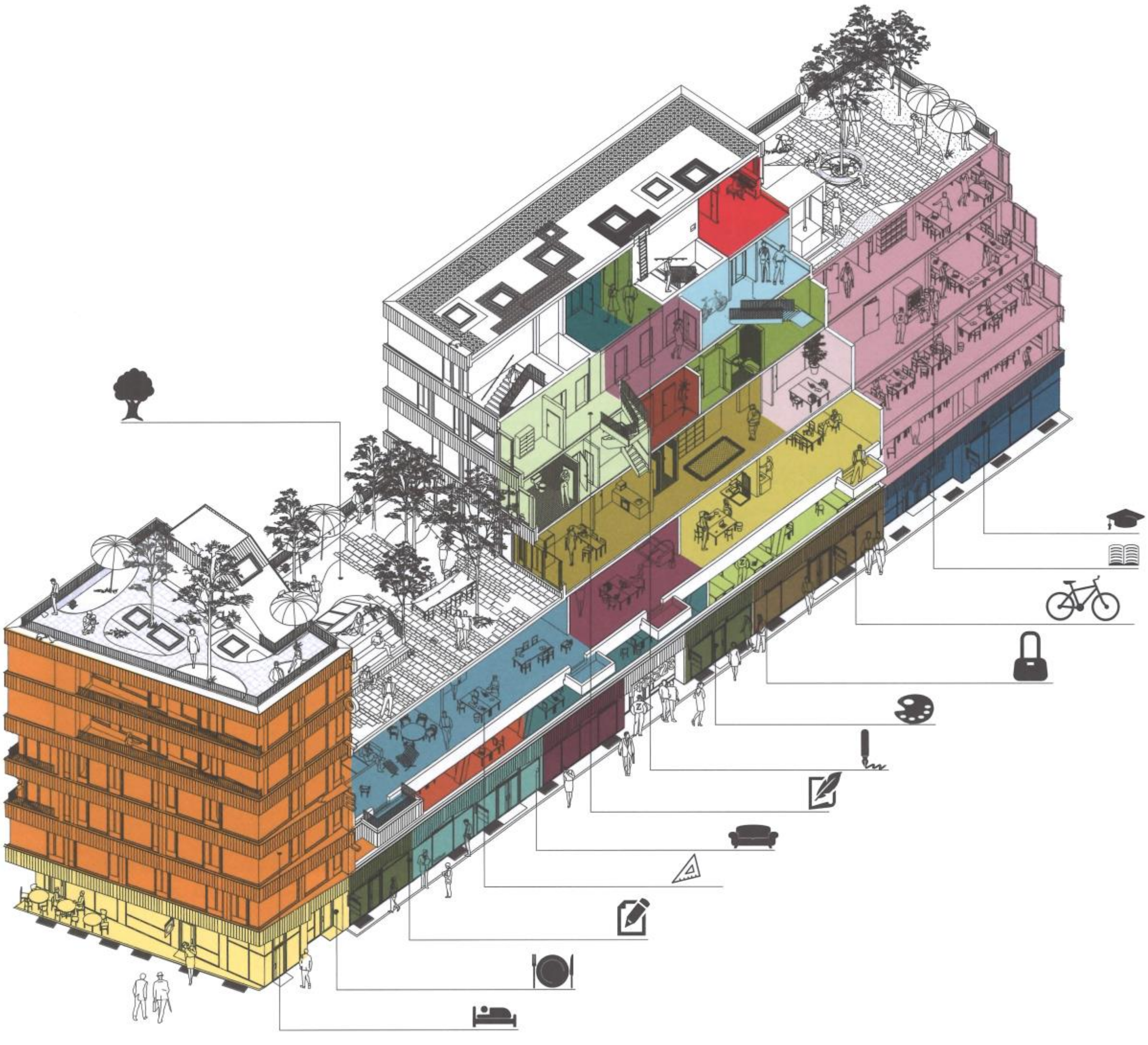

Figure 4. Frizz23, Hybrid Building in Berlin (D)
(Architects: deadline Architekten, Matthew Griffin, Britta Jürgens) [10]

A variety of floor plans and a differenciated mix of uses from trade to dwelling allows for the "self made and mixed city" [11] and makes it possible for the building to be "lively even at night". [12]

Figure 5. Social mixing through a variety of floor plans and mixed uses (by Deadline Architekten) [11]

That way, FRIZZ23 takes on the role of an incubator in the neighbourhood. It triggers developments, enables interactions, and adapts to new demands. This process of hybridisation usually takes place in several phases and at different times as will be shown below.

Phase 1: Define, Design and Inject Codified Design Concept
At the beginning, the program for the projected hybrids is defined. At the end of this phase, the requirement profile of the projected building is determined and the target agreement (e.g. space allocation plan, use, cost ceiling, deadlines etc.) is formulated. [13] The degree of hybrid character desired is defined and the corresponding structural and procedural characteristics of the hybrid are determined.

With the help of scenarios-methodology and transdisciplinary think-tanks [14], one must identify the relevant developments that will be influencing buildings in the future and formulate scenarios of possible developments. The scenarios serve as the foundation for further decisions. At the end, the design concepts are determined by mathematical spatial concepts and represented in an objective, unprejudiced manner. As a rule, plans, sketches and models serve to illustrate the outlined building concept. This serves as the guideline for the realisation of the building. [15] The building or processes are injected with the hybrid code and can now mutate into open systems, which means constructed or applied as hybrids based on the codified design concept.

The hybrid code orients itself towards the fundamental principles for resilient urban development. [3] The interaction of these principles forms the basis for a strategy to be developed specifically for each of the levels and processes involved and which is then lodged structurally and procedurally in the code. Three important fundamental principles that enable the hybrid to develop itself further according to the requirements of resilience are: it is adaptable, multifunctional and works synergistically.

Table 3. Hybrid Code – Codified Design Concept

Fundamental principles	Process-related characteristics	Structural characteristics
- adaptable - multifunctional - synergistic	- scenario-based - user-oriented - transdisciplinary - sense of responsibility - reflective - cooperative - incomplete/open/unexpected	- equivalent - usage-neutral - well-proportioned - replaceable/exchangeable - unbundled - fault-tolerant - independent (services) - offers buffer - effective - specific - appropriate / sufficient - sharing - life-cycle-oriented - recyclable - ephemeral

The fundamental principles cannot be clearly demarcated. They have a collective effect in the overall framework, differently weighted according to the specific objectives of the design, and give rise to the planned procedural and structural characteristics. Here the hybrid code is not to be seen as some panacea that is equally applicable to all environmental levels. It must be conceived specifically for each case, in order that it can act as an incubator, enabling the various environmental levels to react specifically to the pressure to adapt and amplifying their potential for further development. The hybrid code lays down the attributes for the desired resilient characteristics. The code concept is primarily about building up capabilities for the active configuration of ongoing adjustments and strategic transformations. Here the focus is not on conserving but rather it is directed proactively with the future in the sights of its strategies. As a result, the ability to react quickly and an appropriate level of effort in the process of change are important factors for successful activation and on to understanding the city as an open system.

Phase 2: Decoding

In this phase the hybrid code is decoded and hybrid activation follows. Through the scenarios considered beforehand and the resulting, specifically constituted hybrid code, the structural and procedural characteristics lodged in the corresponding level now take effect. This decoding leads to the hybrid being able to meet the new requirements as well as possible and creates new scope for action in urban development. Motivated by new societal, technological, ecological and economic changes, which act as stressors placing the city under pressure to adapt and triggering disruptions, the process of transformation is activated. The term disruptions here does not mean singular events, instead it is far more an overarching theme tending towards persistence and with a societal and global dimension. In terms of stress, they mobilise exceptional powers over a more extended period and necessitate reactive high performance. [16] As soon as the structurally lodged elements (e.g. dismantling lightweight partition wall) or processes (e.g. district management) are activated, the code is decoded and the hybrid principles can emerge specific to level. Hybrids have the ability to react with different strategies in their code.

Hybridisation is a planned process and leads to elements mutating into a “specimen of opportunity which has the mix-used gene in its code”. [8] The hybrid code was deliberately conceived for this situation. Through the process of hybridisation, impetus is unleashed towards resilient urban development. This contrasts with conventional, multifunctional building like a shopping mall located, as a rule, isolated at the city limits and making no contribution to long-term urban development. In this sense, hybrids are not separable from the process and purpose of hybridisation and take on a central role as incubators and catalysts of resilient transformation of the built environment in a city capable of development.

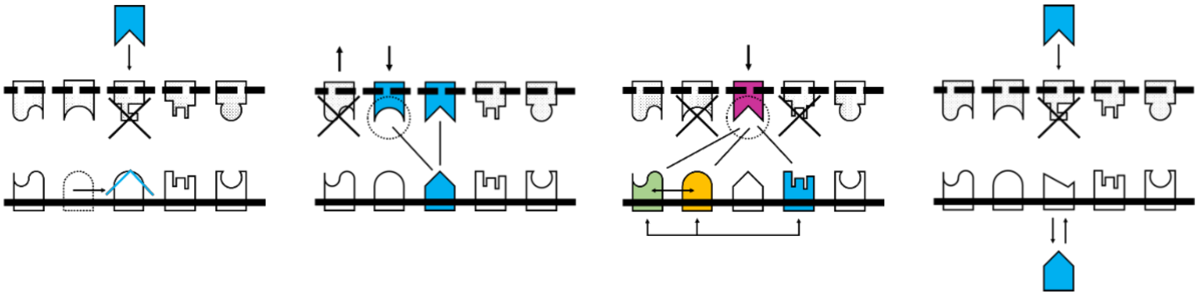

Figure 6. Principles of hybridisation in the interplay of requirements (upper strand) and structural and procedural implementation of the built environment (lower strand): adaptable, multifunctional, synergistic

Table 4. Structural and procedural implementation of hybrid principles

	adaptable – multifunctional – synergistic			
District	Special zones and areas for experimentation and ephemeral structures	Intermixed districts with corresponding compensatory spaces	Densified construction as an expression of culture of space	Scale and grading of different degrees of public space
	Interim use as activator of development	Diverse forms of construction	Renunciation of speculation and sale of urban land	Public space as a place to meet
Neighbourhood	Mix of semi-public intermediate space through placement of volume and façade design	Strengthening of neighbourly activities through provision of space and scope for action	Variety of services on offer for local shopping and sharing economy	
	High quality of intermediate space	District meeting places as incubators of experimentation and development		
Building	Diversity of residential provision through mix of typologies	House rules that do enable and don't hinder	Provision of rooms that can be additionally rented and subdivided	System of access enables different uses
	Unbundling of systems (primary, secondary and tertiary structure)	Sectional configurations and floor plans include buffers (e.g. height, riser zones etc.)	Construction and operation geared to conserving resources (including recyclability of materials used)	High degree of standardisation; modularisation and prefabrication
Unit	Rooms with equivalent proportion and orientation	Appropriation by users (e.g. completion of interior by tenants)	Neutral floor plans allowing easy adaptability	Planning based on users daily needs
Components	Application and installation oriented towards lifecycle	Design enables multiple occupancy and use (e.g. raised floor)	Robust, fault-tolerant and reparable building services	
	Simple accessibility and replaceability	User-friendly usability		
Infrastructure	Harness synergies through resource networks	Maintain independence and state control (e.g. water, public transport, power)	Polyvalent structure for use with various media	Human scale and more non-motorised mobility
Process	Reinforce the activities of those affected (e.g. volunteer agency)	No hindering of new approaches by standards and regulations	Principle of incomplete planning and permanent reflection	

	Cooperative planning culture and urban development (e.g. through citizen involvement)	Forward-looking perspectives through transdisciplinary think-tanks

2.3. Summary
What all hybrids have in common is their fault-tolerant character. As a result, they lend themselves to development and, in a figurative sense, are "adaptive". The systems involved do not have to be demolished or reconstructed with great effort. Instead, they overcome disruptions, can reorganise themselves and adapt to the new requirements. The strategies of hybridisation react to any prevailing dearth of offers or create new offers within the district on the basis of altered requirements. Consequently they are suitable for the strategic transformation of the city and create scope for action.

The great challenge here is to take account of unknowns already at the planning stage and to confer on hybrids structural or procedural capabilities that enable them to react. "This is where planners and clients reach their limits: which scenario is likely to occur? How will my client live and work in 10 or 20 years? What effect does this have on planning today's buildings? What are appropriate measures?" [17] Here we cannot avert the need to make assumptions and take a position. If the world changes, our built environment must be able to change too. This should be accompanied by winning and maintaining scope for action: The city is a "stimulating place […]. Not limited, instead complex, opening up possibilities for its occupants to make something of their lives. […] An orderly city is imposed on its occupants and limits their possibilities; a complex, disorderly city challenges its occupants to create something of their own". [18] In this process, hybrids are indispensable.

This paper arose as a result of a research focus on evolutionary algorithms in architecture. Central to the academic work is an analysis of strategic transformation of the built environment and its processes.

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Hydrological and thermal response of green roofs in different climatic conditions

Arkar C[1], Domjan S[1], Majkovič D[2], Šumi J[2], Medved S[1]

[1]Laboratory for Sustainable Technologies in Buildings, Faculty of Mechanical Engineering, University of Ljubljana, Aškerčeva 6, 1000 Ljubljana, Slovenia
[2]Knauf Insulation, Trata 32, 4220 Škofja Loka, Slovenia

ciril.arkar@fs.uni-lj.si

Abstract. The paper presents a study on the thermal and hydrological response of lightweight extensive green roofs with lightweight mineral wool growing media in different European climate conditions. The green roof heat and mass transfer model was developed and experimentally validated. It was then integrated into a developed software tool for the whole year analysis of the green roof thermal and hydrological performance. The results of performed numerical analysis showed that heat losses in heating season and heat gains in summer months of the green roof is smaller compared to the reference non-vegetated roof in all considered climate conditions and depends on thickness of lightweight mineral wool growing media and especially on the green roof's irrigation scenario. The results of numerical analyses also demonstrated that the water retention of green roofs can be considerably improved if irrigation scenario considers the weather forecast. The weather forecast based green roofs´ irrigation also improves retention at stormwater events.

1. Introduction

Green roofs gain great attention of urban planners and architects recently because of advantages comparing to other build elements of the urban environment. Besides improving urban microclimate conditions, the improved building energy performance and water retention are among most important advantages [1–4]. Because of that green roofs are gaining a predominant role in building retrofitting especially in the form of extensive green roofs because of low additional structural load, low maintenance and low cost comparing to intensive solutions [3–5]. Most common the advantages of green roofs are studied during summer time conditions [4, 6]. Beside reduced building's heat gains due to increased roof thermal resistance and high percentage of dissipated solar radiation by the foliage layer, considerable decreasing in outer surface temperature compared to traditional roof are observed [2]. Green roofs have significant impact on the thermal response of the building's envelope in the winter time conditions as well. Water in growing media enhance green roof thermal capacity [7] and can effectively store heat from solar radiation which reduces roof heat losses [8]. At freezing ambient air conditions, the process of water freezing further improves the energy efficiency of green roofs [9].

Especially in urban environment water retention is one of the key advantages of green roofs as it improves stormwater management [1, 10–12]. Green roofs, if properly designed, can retain significant stormwater and help mitigate flooding events thus addressing serious environmental impacts of excessive and uncontrolled urban runoff [10]. Selection of the growing media and plants influence green roof's retention capacity as well as evapotranspiration and thus irrigation needs. Wong and Jim [11] reported that in case when mineral wool is used as substrate considerable water retention and sufficient peak mitigation can be achieved even with a thin substrate layer. Zhang et al. [12] established that plant composition could have an influence on reduced substrate retention capacity due to created preferential flow pathways (due to plant roots) within the green roof growing media. As demonstrated in several studies appropriate irrigation water use strategy, based on weather prediction, can save considerably amount of drinking water [13–14] and it also increases retention capacity of green roofs at stormwater events [12].

As it could be concluded from the literature review thermal and hydrological response of the green roof largely depends on substrate (growing media) thickness and composition. The objective of this research is to evaluate the thermal and hydrological response of lightweight extensive green roofs with mineral wool growing media in different European climate conditions. Thermal and hydrological response of green roofs with different substrate thicknesses and irrigation scenarios is compared with reference lightweight roof to show multilateral benefits of the green roof. The potential of weather predicted irrigation on stormwater management and reduction of irrigation water use is also evaluated.

2. Green roof thermal and hydrological model

Green roofs are roof constructions that enable vegetation growth on top of a flat or low sloped load-bearing roofs. Green roofs consist of several layers such as (waterproof) root membrane, drainage layer with filter membrane, substrate (growing media) and vegetation (foliage) as it is shown in figure 1. In recent years lightweight extensive green roofs emerge in the market with some competitive advantages such as simple installation, low investment and maintenance cost as well as lower thickness and weight compared to extensive (and intensive) green roofs. The growing media thickness is between 2 cm and 10 cm and overall weight 17–40 kg/m² when dry and 42–75 kg/m² when completely saturated. Lightweight extensive green roof of system Urbanscape® with lightweight mineral wool growing media and Sedum-mix plants which thermal and hydrological performance is studied in this paper is also shown in figure 1.

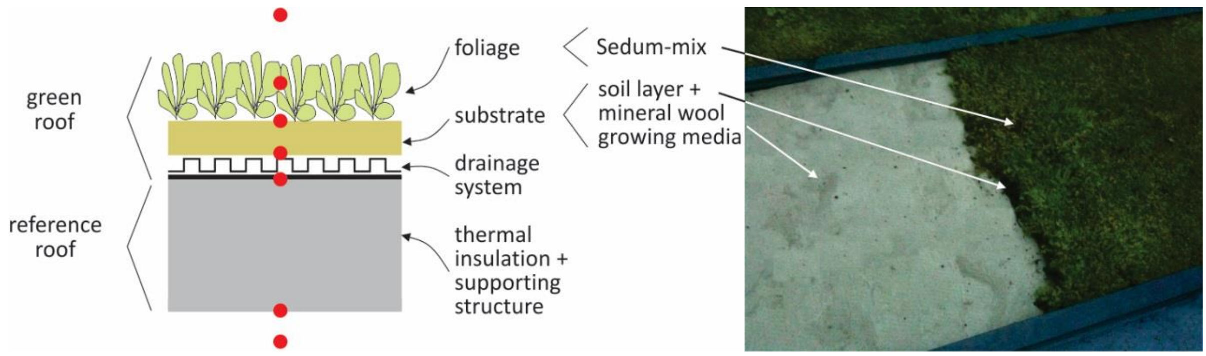

Figure 1. Schematics of reference and green roof composition (left), temperature nodes (red dots) and photo of green roof with Sedum-mix plants and lightweight mineral wool growing media (right).

To predict the green roof thermal response in summer and winter conditions and to study retention of the rainwater the quasi dynamic thermal and hydrological model of the green roof with a lightweight mineral wool growing media was developed. Because evapotranspiration process influences the heat and mass transfer, as well as green roof's growing media thermo-physical properties, the hydrological model was combined with the thermal response model of the green roof building construction. Heat transfer in the green roof is transient because of time dependent short- and long-wave radiation, outdoor and indoor temperatures and heat accumulation. Heat transfer can be determined considering one-dimensional transient heat transfer process between temperature nodes. At each temperature node energy balance equation is developed. For the greening layer (foliage and substrate) heat and mass transfer model is coupled considering two outdoor boundary planes – at the foliage temperature node and at the substrate surface temperature node, and taking into account global solar radiation absorbed by the foliage $G_{glob,0,f}$ (W/m^2) and the substrate $G_{glob,0,s}$, long-wave radiation exchange between the sky and the foliage $\dot{q}_{IR,f}$ (W/m^2) or substrate $\dot{q}_{IR,s}$ as well as between the foliage and the substrate $\dot{q}_{IR,f,s}$, convective heat flux $\dot{q}_{conv}$ and latent heat flux by evapotranspiration $\dot{q}_l$ as it is presented in figure 2. Foliage convective heat flux $\dot{q}_{conv}$ is determined according to Newton's cooling law where the convective heat transfer coefficient is calculated based on the leaf area index (LAI), aerodynamic resistance to heat transfer and leaf-air temperature difference [15, 16].

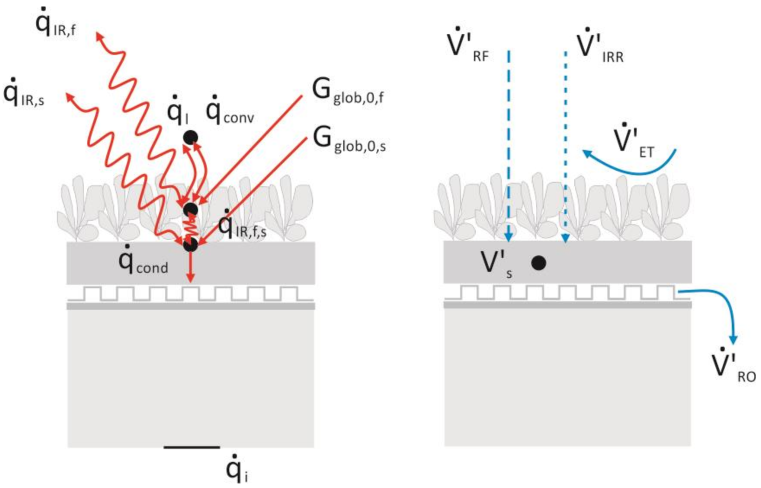

Figure 2. Heat fluxes considered in the energy balance at main temperature nodes (left) and mass fluxes considered in the water balance (right) of the green roof.

Latent heat flux $\dot{q}_l$ is determined from the evapotranspiration $\dot{V'}_{ET}$, which is calculated using Penman-Monteth equation for hourly or shorter time steps [17]. The water content within green roof substrate, in our case lightweight mineral wool growing media, has a significant impact on heat conduction and heat accumulation in greening layers as it influences material properties such as thermal conductivity and specific heat capacity; therefore, water balance must be considered. Water content in greening layer also influence evapotranspiration. For this reason, Penman-Monteth equation was upgraded for water stress conditions using results from our laboratory experiments. The substrate water content for each time step τ is determined from the green roof water balance:

$$V'^{i}_{s} = V'^{i-1}_{s} + (\dot{V}'_{RF} + \dot{V}'_{IRR} - \dot{V}'_{ET} - \dot{V}'_{RO})^{i} \cdot \tau \quad (1)$$

The substrate water content V'_s (mm/m²) is determined from the amount of rainfall $\dot{V}'_{RF}$ (mm/h m²) and irrigation water $\dot{V}'_{IRR}$ delivered to green roof in each time step (1 h) as well as amount of water lost due to the evapotranspiration $\dot{V}'_{ET}$ and runoff $\dot{V}'_{RO}$ of excess water in each time step. Runoff appears when calculated water content exceed the saturated water content $V'_{s,sat}$ of lightweight mineral wool growing media:

$$\dot{V}'_{RO} = (V'_s - V'_{s,sat})/\tau \quad (2)$$

Heat conduction and heat accumulation within the green roof growing media is calculated considering thermo-physical properties which varies with water content in the moistened substrate [18, 19]. Model also considers possible phase change (latent heat) at freezing temperature conditions [19]. Only for the loadbearing structure and thermal insulation layer (layers that are equal as for the reference non-vegetated roof) constant material properties are considered. Energy balance equations and thermo-physical properties calculation is presented in detail in [19].

For numerical model development the temperature in radiation flux equations and saturated water pressure terms are linearized. The implicit finite-difference equations are formed and they are solved using the matrix inversion method within MS Excel environment. Developed numerical model was validated with experiments as it is presented in chapter 3.

For year round thermal and hydrological response analysis, a software package "PET tool" was developed in the way that enables comparative all year thermal and hydrological performance analysis of the green roof and the reference (non-vegetated) roof. In the analysis, meteorological data from the Meteonorm 5 database are normally used. Thermal and hydrological response of the green and the reference roof is determined on the hourly time step interval whereby the indoor air temperature can be defined on monthly time scale.

3. Experimental validation

Thermal and hydrological response of green roofs have been extensively experimentally investigated since 2013 for three different compositions of lightweight extensive green roofs installed on the flat lightweight loadbearing thermally insulated ceiling of the laboratory test building [9] (Ljubljana, Continental climate). Green roofs consist of root membrane, drainage layer with filter membrane, lightweight mineral wool growing media and Sedum-mix blanket. Green roofs differ on thickness of lightweight mineral wool growing media (2, 4, 8 cm). Thermal and hydrological response of green roofs was simultaneously compared with reference roof (flat lightweight loadbearing thermally insulated construction without green roof layers). Each of the ceiling construction, called module, has dimensions of 1 × 3 m. The U-value of green roofs and reference roof is 0.157 W/m²K. A weather station Vantage Pro 2 was installed to monitor meteorological parameters. Heat flux sensors were installed on the inner and outer surface of the thermal insulation layer. Temperatures inside lightweight mineral wool growing media, thermal insulation and loadbearing layers were measured using T-type thermocouples. Rainwater runoff from each module was measured using water tank with diameter of 250 mm with pressure sensor which monitors water column high. Developed green roof numerical model was validated with all year round experimental data for green roofs with different thickness of lightweight mineral wool growing media including also short dry periods with reduced evapotranspiration due to water stress conditions. Figure 3 shows measured and with numerical model determined inner surface heat fluxes $\dot{q}_i$ for the green roof with a 2 cm thick lightweight mineral wool growing media for selected weeks during winter and summer weather conditions. Measured $\dot{q}_{i,exp}$ and modelled $\dot{q}_{i,num}$ inner surface heat fluxes differ in average less than 0.5 W/m², slightly larger differences are noticed only for daily extreme values. Higher differences are observed for summer period because a constant inner surface heat transfer coefficient was assumed.

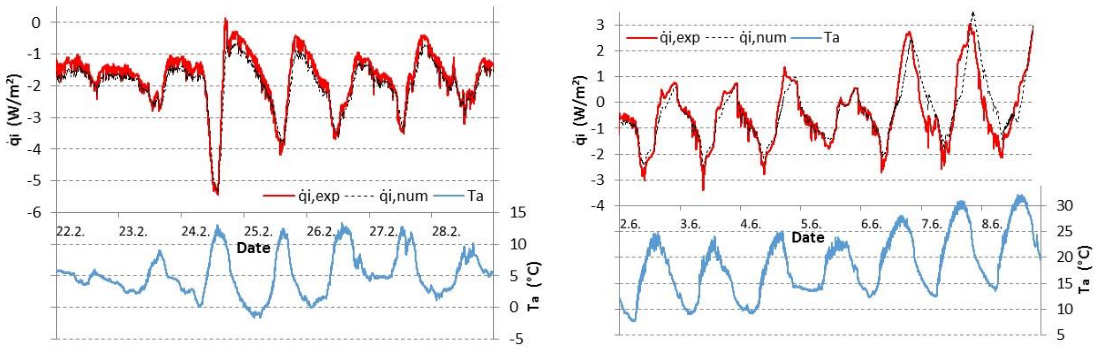

Figure 3. Measured $\dot{q}_{i,exp}$ and modelled $\dot{q}_{i,num}$ heat fluxes on the inner side of the green roof and ambient air temperatures T_a in winter and summer week.

Hydrological balance and modelling of the evapotranspiration $\dot{V}'_{ET}$ was validated with comparison of measured and with numerical model determined water runoff from green roofs. Figure 4 shows comparison of measured and with numerical model determined daily runoff water normalized on m² of the green roof area for the green roof with a 2 cm thick lightweight mineral wool growing media layer. Daily rainfall is shown as well. Figure 4 also shows with numerical model determined substrate water content $V'_{s,num}$ which indicate that water stress conditions occur (4.-5.8. and 10.-12.8.) and that developed model of evapotranspiration is adequate for such conditions as well. From the comparison of experimental and numerical results it can be concluded that developed green roof numerical model is adequate. Experimentally validated green roof numerical model was used to perform hour-by-hour whole year green roof thermal and hydrological response studies for different climate conditions.

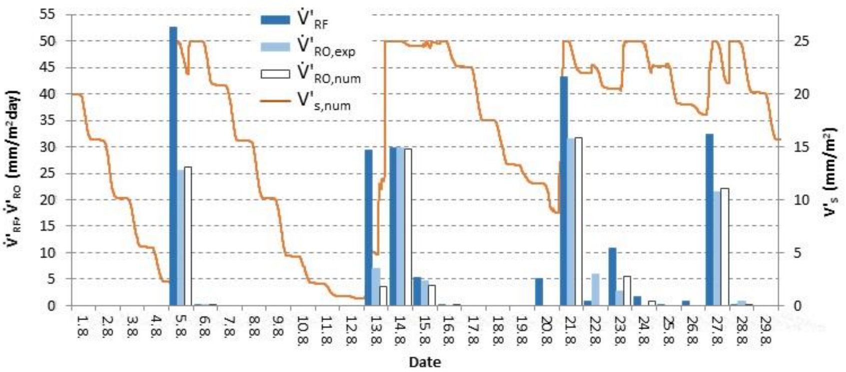

Figure 4. Measured daily rainfall $\dot{V}'_{RF}$ and runoff $\dot{V}'_{RO,exp}$, modelled daily runoff $\dot{V}'_{RO,num}$ and hourly substrate water content $V'_{s,num}$ in the 2 cm thick green roof's lightweight substrate during selected summer time period.

4. Green roof performance analysis

Heat losses of lightweight extensive green roofs in heating season as well as heat gains in summer were compared to reference roof construction for selected European cities with different climate conditions. Analysis are performed for the case of lightweight reference roof construction with 10 cm of thermal insulation and U-value of 0.34 W/m²K. Thermal response of reference roof is determined for the case of dark roof with solar absorptivity of 0.7. Green roofs with different thicknesses of lightweight mineral wool growing media (thickness of 2, 4, 6 and 8 cm) and different irrigation scenarios were considered in analysis and retention of rainwater as well as irrigation water needs are also evaluated. Maximum or saturated green roof water content depends on lightweight mineral wool growing media thickness. For the considered thicknesses (2, 4, 6 and 8 cm) the maximum water content $V'_{s,sat}$ is 25, 37, 54 and 66 l per m² of the green roof area are taken into account in the water balance (Eqs. 1 and 2). Three irrigation scenarios are considered in the analysis:

- no irrigation; maximum possible water retention, probably water stress conditions and risk of plant withering and reduced heat dissipation;
- irrigation; when substrate water content drops below 20 %; irrigation water amount corresponds to increase of the water content up to 50 % of saturated water content; in this way enabling good green roof performance and still some storage to handle stormwater events;
- irrigation considering 5 days weather forecast; no irrigation if precipitations are forecasted, otherwise regular irrigation (explained in previous paragraph).

Three cities – Ljubljana, Wien and Athens with different climate conditions (Continental high and medium rainfall and Mediterranean) were selected for analysis. Figure 5 shows average monthly ambient air temperature T_a, average daily solar irradiation on the horizontal plane $H_{glob,0}$ and monthly rainfall $\dot{V}'_{RF}$ for selected cities. It can be seen that average yearly ambient air temperatures in Ljubljana and Wien are similar (approx. 10 °C) while in Athens is over 18 °C. Yearly solar irradiation in Athens is 40% higher than in Ljubljana and Wien. The highest yearly rainfall is in Ljubljana – 1395 mm/m²a. Wien receives 44% and Athens 26% of that amount.

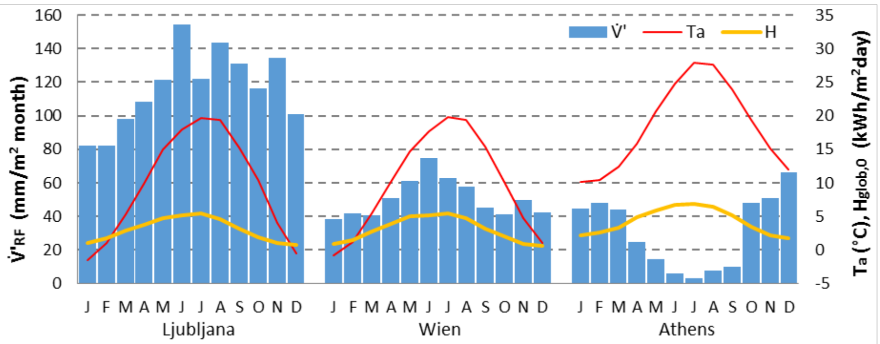

Figure 5. Average monthly ambient temperature T_a, monthly solar irradiation on horizontal surface $H_{glob,0}$ and monthly rainfall $\dot{V}'_{RF}$ for selected cities.

Indoor temperature and period of the heating and the cooling season were selected according to the city climate conditions: 20/24 °C and Nov.-Apr./June-Aug. for Ljubljana and Wien and 22/26 °C and Nov.-Mar./June-Sept. for Athens. For the reference non-vegetated roof heat losses and heat gains in defined heating and cooling period are shown in figure 6. For the green roofs reduction of heat losses Δq_h and heat gains Δq_c compared to the reference roof (absolute values) in kWh/m² in defined period are shown (figure 6) for different thicknesses of the lightweight mineral wool growing media and considering presented different irrigation scenarios: no irrigation (noIRR), regular irrigation (IRR) and irrigation considering weather forecast (IRR-wf).

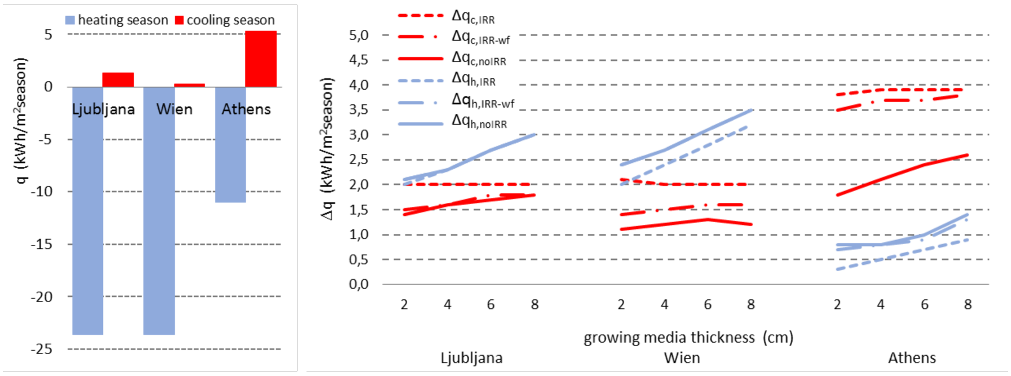

Figure 6. Heat losses and heat gains of reference roof in defined heating/cooling season (left) and reduction of heat losses and heat gains of green roofs compared to the reference roof at different green roof irrigation scenarios (right): no irrigation (noIRR), regular irrigation (IRR), irrigation considering weather forecast (IRR-wf).

It can be seen that heat losses in heating season in cities with Continental climate are almost the same, while in Athens they are more than 50% lower in spite of higher considered indoor air temperature. As expected the highest heat gains in the cooling season are observed in Athens with Mediterranean climate. Reduction of heat losses of green roof in comparison to reference non-vegetated roof is in case of no irrigation in the range from 7% to 15% for all three cities and is higher at higher thicknesses of lightweight mineral wool growing media. Green roof irrigation can influence the heat losses reduction for up to 5% in Athens and 2% in Wien, while it does have almost no influence in Ljubljana. Results indicate that although mineral wool growing media is moistened it provides some additional thermal insulation effect. In the cooling season the reduction of heat gains is the highest in case of regular irrigation thus avoiding reduced evapotranspiration due to water stress conditions. Results indicate that in Ljubljana and Wien heat gains observed for reference roof turns into heat losses for all green roofs – also those without irrigation.

Lightweight mineral wool growing media thickness (2, 4, 6, or 8 cm in the study) and irrigation scenario can be selected regarding to energy savings or regarding to retained rainwater and water needs for green roof irrigation. As it can be seen from Figure 7 green roofs with 4 or 6 cm of growing media performs much better than one with 2 cm because retained water is higher and water need for irrigation is lower. Increasing thickness to 8 cm has an effect mostly only on reduced heat losses in heating season. Nevertheless, results clearly indicate that most favourable results are obtained if irrigation based on weather forecast is applied for green roofs: retained water is practically the same as in case of no irrigation but there is no risk of plants withering; use of irrigation water can be considerably reduced, especially in case of thin substrate; and it does not influence much the reduction of heat losses in winter season and reduction of heat gains in the cooling period – with only exception of Athens with very low rainfall amount in summer months. Analysis of outflow for Wien also showed that in case of weather forecast irrigation there is no outflow from green roof with at least 6 cm of growing media (only two events in case of 4 cm) in the most rainy months from April to September.

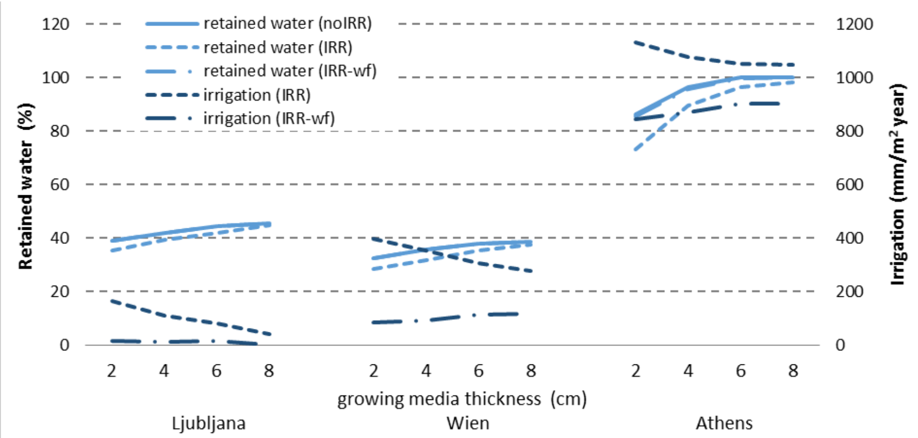

Figure 7. Retained water and water consumption for irrigation of lightweight extensive green roofs with different thicknesses of lightweight mineral wool growing media; irrigation scenarios: no irrigation (noIRR), regular irrigation (IRR), irrigation considering weather forecast (IRR-wf).

5. Conclusions

The thermal and hydrological response of lightweight extensive green roofs with lightweight mineral wool growing media was studied in different European climate conditions. In the analysis, the range of possible thicknesses of rock mineral wool substrate was considered, as well as three different anticipated irrigation scenarios. The thermal response was compared with the reference non-vegetated roof, which has, according to the calculation methodology, the same U-value of 0.34 W/m^2K. The results showed an up to 15% reduction of heat losses in the heating season. The highest energy savings were observed for the thickest lightweight mineral wool growing media, which indicates on additional thermal resistance of moistened green roof substrate. The growing media thickness does not have an effect on the heat gain reduction in summer period, as most of the heat is dissipated trough evapotranspiration. The weather predicted irrigation can reduce summertime cooling effect – on the other hand, it almost enables the theoretically highest water retention capacity – equal to that of no irrigated green roof. Analysis also showed that weather predicted irrigation can provide substantial savings of irrigation water, especially in case of lightweight mineral wool growing media thickness of up to 4 cm. The analysis also showed that the optimal green roof composition, i.e. the thickness of the substrate layer, can only be determined by taking local climate conditions into account.

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Integrating climate change in life cycle assessment of buildings: literature review

Ramon D, Allacker K

Department of Architecture, Faculty of Engineering Science, KU Leuven, Belgium

delphine.ramon@kuleuven.be

Abstract. The operational energy use and related greenhouse gas emissions of buildings are typically influenced by changes during the building service life such as climate change, technological evolution and energy mix evolution. Only few LCA studies consider these temporal variations. This paper investigates how climate change is currently considered in LCA studies. Three aspects related to the influence of climate change on the life cycle impact of buildings are focused on: (1) changes in operational energy use (heating and cooling) due to changes in the climatic context of the building, (2) changes in operational energy use due to technological evolution or climate regulations and (3) changes in energy mix due to climate regulations. All three influence the energy use and related environmental impact but the extent of the effect depends on the considered region, time step and environmental indicators. It is hence recommended to choose an appropriate time period when considering climate change in LCA and consider variations within a time period via dynamic building simulations or to include a static correction. A holistic set of impact categories should be focussed on to avoid burden shifting and the most influencing parameters should be checked via a sensitivity analysis.

1. Introduction

In 2017, buildings accounted for 36% of the final energy use worldwide and for nearly 40% of the CO_2-emissions [1]. Various studies identified that the operational energy use contributes most to the life cycle CO_2 emissions of a building [2–4]. This includes the energy needed for heating, hot water supply, air conditioning, ventilation, lighting and auxiliary energy used for pumps, control and automation [5]. Several parameters influence the operational energy use and related CO_2 emissions of buildings, such as energy equipment technology and characteristics, occupant behavior, climate conditions, energy mix and policy rules [6–10]. In addition, these parameters typically change over the life cycle of the building. Current environmental impact studies however typically do not consider these changes [11]. Operational energy use is for example often estimated based on a one-year dynamic calculation for a representative year [2,11] or a static calculation based on degree days [4,9,12,13] and standard Life Cycle Assessments (LCAs) assume a static (current) energy mix for the whole building service life.

This is confirmed by Collinge et al. [8], stating that current LCA approaches are mostly static assuming point values for flows (inputs and outputs), emissions and characterization factors. Time-related changes however do affect these variables considerably [7,8]. Dynamic LCA (DLCA) does take into account these temporal changes and is defined by Collinge et al. [8] as "*an approach to LCA which explicitly incorporates dynamic process modelling in the context of temporal and spatial variations in the surrounding industrial and environmental systems*". Only few LCA studies were found that indeed consider these temporal variations when assessing the life cycle impact of buildings.

In his paper Collinge distinguishes dynamic methods applied to the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA). Su et al. [7] follows this distinction and further divides them in four dynamics: technological progress, variation in occupancy behaviour, dynamic characterisation factors and dynamic weighting factors. The first two aspects are related to the building processes (inventory), while the last two are related to the impact assessment. Negishi et al. [6] defines three levels of which the first two (i.e. building technology level and end-user level) overlap with the first two dynamics defined by Su et al. His additional third level considers changes in the external system of the building, i.e. changes in energy production mix, climate conditions and climate regulations.

This paper focuses on one of these changes in the external system of the building, more specifically climate change. The aim is to investigate how climate change is currently taken into account in LCA studies and if any recommendations for improvement can be formulated. Three aspects related to the influence of climate change on the life cycle impact of buildings are focused on: (1) changes in operational energy use (heating and cooling) due to changes in the climatic context of the building during its service life, (2) changes in operational energy use due to technological evolution or climate regulations and (3) changes in energy mix (increase of renewable energy) due to climate regulations [14]. For example, the increased efficiency regulations lead to a shift towards electrical heat pumps being partly responsible for an increase in electricity use [14].

The next section presents the state of the art regarding the consideration of climate change in dynamic LCA considering the three aspects mentioned before based on a literature study. The influence on both the energy demand and related emissions are reviewed. The state of the art is discussed and recommendations for improvement are formulated in a final section.

2. State of the art

A state of the art is provided for each of the three aspects related to climate change and LCA as mentioned before (section 2.2 – 2.4). This is preceded by an overview of the state of the art of methods used in LCA to calculate the operational energy use (section 2.1).

2.1. Estimation of life cycle energy use and related environmental impacts

In current LCA practice, the operational energy use of buildings is calculated in different ways. A first method is based on heating and cooling degree days, applied amongst others in the research of Passer et al. [4], Isaac and Van Vuuren [9] and Roux et al. [15]. Heating or cooling is assumed to be needed from a certain external temperature onwards till a certain indoor temperature. The research of Trigaux et al. [16] defines dynamic equivalent heating degree days which consider internal heat gains and detailed solar gains. The yearly heating energy calculation includes in addition to these gains also the thermal losses through the building envelope (transmission and ventilation losses).

A second method is to use dynamic energy simulations. Komerska et al. [17] integrates thermal dynamic building simulations (i.e. DesignBuilder model) in their LCA study of office buildings in Poland to evaluate different façade solutions. A one-year simulation is used to estimate the energy consumption for the different solutions and kept constant during the building service life. Azari et al. [11] established an integrated framework by combining the Athena Impact Estimator for Buildings (LCA tool) and the eQuest energy analysis tool. The dynamic building energy simulation performed with eQuest is manually entered in the Athena framework. Similar as to Komerska et al. this is a point value in the sense that the input for Athena exists of the annual energy consumption for the different energy uses (i.e. lighting, space cooling, space heating and other).

The research of Allacker et al. [2] combines dynamic energy simulations with LCA on the building level to calculate the effect of micro-scale measures on the macro-scale and to compare different scenarios. In this study, climate datasets of three cities (Athens, Strasbourg and Helsinki) are used to represent three climatic zones across Europe. Different studies [9,18] have included multiple locations to get insights in the effect of regional climate. Again, these studies assume the climate unchanged over the building service life.

The research of Collinge et al. [8] used measured operational energy uses based on monitoring. Monthly data for energy uses and historical fuel mixes for the electricity grid and heating plant were available. The use of monitored data is of course only possible for constructed buildings and is not an option in the design phase. In his research, a dynamic mathematical model was developed considering at each moment in time the different energy uses and fuel mixes. The service life of the building is divided in two periods before and after renovation. Before renovation the detailed data is used, while for the period after renovation an estimation is made based on a model and kept constant for the remaining years. The model allows to keep constant values over the different time steps.

2.2. Changes in operational energy use due to climate change

Buildings are typically designed for certain environmental conditions but will have to deal with other conditions during their service life. The energy performance of a building will inherently be influenced by global warming. Worldwide, a reduction of the heating demand of 34% is expected by 2100 under a median climate change scenario, while an increase of the air-conditioning energy demand by 72% is expected [9]. It should be noted that part of these global changes is also caused by non-climatic drivers such as increasing income, population growth, and energy efficiency [9,19]. Globally the net effect on energy demand is expected to be relatively small compared with the total energy demand, however this highly depends on the climate change scenario (and related weather data) and assumptions made [9,18,20,21] as well as the region considered. For Europe, the IPCC report [22] states an increase of the cooling energy under a 3.7°C scenario to increase by 74% to 118% by 2100. A decrease of 0.7% per year is projected from 2010 onwards for heating energy.

In Europe, the share of cooling in the total building final energy use tripled since 1990 to 12% [19]. Most literature sources agree on the fact that raising temperatures are expected to decrease the heating demand of buildings and to increase the cooling demand [9,15,20,22–24]. However, there is more discussion about how big this effect will be depending on the region studied as well as the climate change scenario considered [19]. More specific, till 2050 a reduction is expected, followed by an increase in the second half of the century. For Europe, the reduction in heating demand is expected to outweigh the increase in cooling demand for the northern and central part at least till 2035 [9,25–27]. For the southern part, this is not the case and an increasing cooling demand will lead to a net increase. In addition to changes between heating and cooling loads, also seasonal patterns will be influenced by climate change having impacts on energy needs and mixes [9]. Winter peaks are expected to be less pronounced in future.

Looking to the related greenhouse gas (GHG) emissions, Isaac and van Vuuren [9] state a clear increase in the second half of the century on global level where India will be the most affected country. An increase of CO_2-emissions from 0.8 Gt C in 2000 to 2.2 Gt C in 2100 is projected which is about 12% of the total CO_2-emissions from energy use. Looking to heating and cooling separately, heating related emissions are stated to decrease with 36% by 2100 while the cooling related emissions are expected to increase with 72% by 2100 [9]. Heating is commonly foreseen with secondary energy sources while air conditioning in buildings is often anticipated by electricity likely leading to increased emissions and to overweigh the reduction of the heating related emissions [24,28]. Though this conclusion is very sensitive to the scenario used and the region studied [9,24]. In addition, several studies stressed the importance of the energy efficiency of the cooling system in buildings to reduce emissions [24,25,29].

The research of Williams et al. [24] presents a methodology for the early design stage which links the GHG emissions of heating and cooling energy with climate change, more specifically with changing external temperatures through a unique building fingerprint. The fingerprint is calibrated based on selection of weather years representing average, cold and warm years for a low, median and high emission scenario out of the 3000 years generated with the UKCP09 Weather Generator for different climate change scenarios. The fingerprint allows to calculate the GHG emissions for any weather year for that specific building and to consider the effect of climate change related uncertainties. Different climate change scenarios were found to influence the total GHG emissions during the life cycle to an important extent.

The research of Colling et al. [8] used energy consumptions based on utility meters between 1979 and 2009. Changes in emission factors were found to have the biggest influence. Although, the electrical energy consumption increased over this period (due to an increased building footprint), it was outweighed by the decrease in GHG emissions from the energy supply. The latter was mainly caused by a decarbonisation of the district steam production (switch to 100% gas).

The research of Roux et al. [15] considers a variable energy use (and energy mix) for different time perspectives. The building service life is divided in three periods around 2020, 2030 and 2050 for which a certain energy use (and mix) are assumed to be constant. The energy use is estimated by projecting current degree-days with a high and low climate change scenario to the respective points in time.

The research of Negishi et al. [6] proposes a five-step framework which integrates the time dimension at different steps of the LCA. In the first step a dynamic energy simulation is performed with the COMETH software as it allows to consider long-term temporal changes such as a decrease in heating demand due to global warming. Similar as to the research of Roux et al. [15], the service life is gridded in different periods characterized by constant parameters for the processes involved. By contrast, depending on the building subsystem, these periods could be limited to one year and should not necessarily encounter multiple years.

2.3. Changes in operational energy use due to technological evolution due to climate regulations

The EU has set the goal to decrease GHG emissions by 80 to 98% by 2050 [30] which requires changes in the current energy systems and hence energy mix. To achieve this, amongst others, goals are set for further efficiency measures of equipment [14]. The strengthening of energy efficiency policies is expected to result in a trend towards electrification of the heating need (i.e. heat pumps) [14,30]. Though, electrification does not necessarily lead to lower environmental impacts. The research of Blom et al. [10] shows that even though a heat pump does not use fossil fuels, it could have higher environmental impacts than a gas-fired boiler depending on the coefficient of performance (CoP) caused by the higher environmental impact of electricity than natural gas in the Netherlands. Including the materials and refrigerants of the pump even increase the difference with a boiler. In contrast, further improvement of the efficiency rate will partly compensate this difference in future.

In the past decades, policy increased insulation values for building. By consequence, the thickness of insulation improved, glazing systems develop from single glazing to triple glazing systems with coatings. However, once a building is insulated, the effect of additional insulation is rather small on the total heating energy as shown in the research of Waddicor et al. [25]. It was even found to slightly increase the cooling load due to an improved air tightness and reduced thermal bridging. Improving window insulation has an important influence on the energy demands, however a good balance should be found between reducing solar gains in summer and increasing in winter. While a good insulating value is recommended for different regions, low g-values are only recommended in hotter arid locations and could lead to higher heating loads in cold locations. His study further highlights the increase of efficiency for the chiller as the most effective measure to reduce cooling energy as mentioned by other studies before [24,29].

2.4. Changes in energy mix due to climate regulations

In addition to increased efficiency measurements, also goals are set to reduce the use of fossil fuels and increase the use of renewables influencing the energy mix. By consequence, trends such as a shift from oil to gas and electrification of heating are expected [14]. Electricity is the fastest growing form of final energy use and multiple studies stress the importance of electricity in future. In Europe fossil sources are however still used for more than 50% of its production [27]. The energy mix evolution will have an influence on energy consumption related emissions of a building [10,12,15,24,31]. However, in most of the LCA studies an average energy mix is used and kept constant for the full building service life even though this mix is subjected to temporal variations from daily to decadal scale [15]. Multiple studies were found to investigate a specific aspect of a changing energy mix (i.e. specific equipment component or mix evolution) but only few were found to study this in a building LCA.

In Europe, the increased share of renewables in the electricity mix is mainly driven by an increase of wind power [14]. The solar and biomass fraction both increase as well, but not as significantly as for wind. Multiple studies investigated the influence of climate change on the solar and wind power generation. For PV generation, it is unlikely that climate change will be a threat in Europe. Studies confirm possible decreases in the range of 15% and possible increase of some percent [32,33].

The research of Blom et al. [10] compares the use of gas and electricity consumption in Dutch apartment buildings. For the Dutch situation, the research shows a higher impact of the electricity consumption per MJ of energy than for gas caused by the low heating demand of the building. Gas is found to have a higher impact when considering the average consumption of all households in all dwelling types. Changing the sources for electricity generation influences the environmental impact, however, they should be chosen carefully as impacts could be shifted to other indicators. This shifting applies in general when reducing heat demand by increasing electric share or replacing gas by electricity consumption. A holistic approach is hence recommended to take well-founded decisions between multiple options.

The effect of the country specific electricity mix is highlighted in amongst others the research of Vuarnoz et al. [31]. For the year studied, the 17% of the electricity on the Swiss grid supplied by Germany was responsible for 70% of the GHG emission of this Swiss mix caused by the high share of fossil fuels used in the German electricity production.

Roux et al. [12,15] describe the importance of considering temporal variations in the electricity mix. In Roux et al. [15] a business as usual evolution and a scenario with the introduction of a carbon tax in France were used to predict future energy mix evolution. Further research of Roux [12] considers the hourly variation in the electricity mix. In this case, the environmental impact of the mix for that hour is multiplied by the consumed energy instead of using a yearly average environmental impact. It was found that the annual average mix leads to an important underestimation for Global Warming Potential (GWP) and Abiotic Depletion Potential mainly caused by higher shares of coal and gas power plants during winter. By using an hourly time step, differences in electricity production between on- and off-peak hours can be accounted for as well as on-site electricity production. Consistency between the energy simulation and electricity mix evaluation is hence recommended. The need for a representative hourly mix is stressed as real years could be subject to climatic or economic conditions and in consequence might not be representative for the years after. In further research [34], Roux stressed the importance of up-to-date data if electricity has an important share in the system as linked technologies and installed capacity change rapidly (e.g. increase in renewable power plant capacity).

3. Discussion

A literature review showed the relevant impact of climate change and climate regulations induced changes on the energy use and related GHG emissions. Based on the reviewed researches, LCA studies should be performed for an appropriate spatial context (e.g. full country or specific region or even city) as climate change impacts on buildings and climate policies could differ to a large extent from region to region. Further, three aspects are highlighted to be considered when performing a building LCA which are discussed in the following subsections: (1) considered time step; (2) holistic approach; and (3) uncertainties.

3.1. Time steps within service life of a building

As stated by Su et al. [7] ignoring time-varying influences decreases the accuracy of the assessment results. Time-varying influences can be defined on the short-, mid- and long-term perspective. When considering effects of climate change and long-term energy mix evolution, time steps of 20-25 years come forward as changes are mostly projected to future points in time (i.e. 2030, 2050 and 2100). Dividing the service life in two or three periods as proposed by Roux et al. with a certain energy use and energy mix for that period seems a good option to encounter these changes. Alternatively, linear interpolation could be used between different scenarios in time. However, as both climate change and mix evolution do not change linearly, it would not necessary give an improved accuracy. For the energy mix defined, it was found that considering daily, weekly and seasonal variations are important. Instead of using an annual average mix, it is recommended to use per time period a yearly profile encountering these variations.

Technological changes rather evolve year by year. Replacement of elements will moreover intervene with these longer periods defined for climate change effects and energy mix. A shorter time step, as suggested by Negishi is more suited for the replacement of technical equipment.

Ideally changes in energy use due to climate change and technological evolutions are encountered by multi-year dynamic building simulations. If impossible or unworkable, the authors suggest to consider the change by technological improvement by applying a correction on the estimated energy use due to climate change (e.g. 5% reduction due to increased system efficiency of the heating system).

3.2. Holistic approach

A holistic approach is recommended to avoid burden shifting when considering changes between different end-energy uses, energy mixes and technologies. Other indicators than GWP should be focussed on such as acidification and terrestrial ecotoxicity. The shift towards more electricity use instead of fossil fuels has a significant negative impact on those indicators. Not considering those could lead to burden shifting.

3.3. Uncertainties

As all the studied changes will happen in future, it is important to consider the related uncertainties to come up with robust choices. Firstly, the influence of the climate change scenario chosen was highlighted multiple times in the reviewed literature. Considering multiple climate change scenarios as done by Williams et al. is recommended by the authors to get insights in the spread of energy use and related emissions. The multiple climate models available can be used to investigate the spread across different climate change scenarios. As this could be time intensive, a thorough study based on one scenario with a sensitivity study based on a worst case and best-case climate change scenario could already provide relevant information about the most sensitive components of the building LCA model.

Secondly, it is unsure when certain shifts (e.g. higher cooling than heating load or shift from gas to electricity) will happen and this might highly depend on the building characteristics and location. Multi-year dynamic simulations are recommended to get insights in these dynamics.

Lastly, evolutions in energy mixes and energy efficiencies are often driven by policy goals. It is however uncertain if these will evolve linearly towards those goals or not and whether they will be reached within the foreseen timeframe. If the goal of the LCA study is to get insights in the influence of changes, the authors recommend to assume linear trends. If the goal is to see which reductions in GHG emissions are needed by when to avoid further climate change, a sensitivity study on time steps is recommended to identify the necessary changes and their time steps.

4. Conclusion

This paper investigates changes in operational energy use and related emissions caused by climate change and how these are currently considered in building LCA studies. Three aspects are focused on during a literature review: (1) changes in operational energy use (heating and cooling) due to changes in the climatic context of the building during its service life, (2) changes in operational energy use due to technological evolution or climate regulations and (3) changes in energy mix (increase of renewable energy) due to climate regulations. All three were found to have an important influence on the energy use and related emissions, though the extent of influence depends on the considered region, time step and environmental indicators. The authors recommend to choose an appropriate time step for the investigated influences and to allow for changes within different time steps by means of dynamic building simulations (preferable multi-year simulation) or correction. Further a holistic approach is recommended to avoid burden shifting and to make well-founded decisions. Lastly, uncertainties are inherently linked with future projections. Therefore, sensitivity analysis with at least best- and worst-case scenarios is recommended for the studied parameters to obtain robust design decisions.

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″PET tool″ – a software tool for lightweight extensive green roofs performance analyses

Arkar C[1], Domjan S[1], Majkovič D[2], Šumi J[2], Medved S[1]

[1]Laboratory for Sustainable Technologies in Buildings, Faculty of Mechanical Engineering, University of Ljubljana, Aškerčeva 6, 1000 Ljubljana, Slovenia
[2]Knauf Insulation, Trata 32, 4220 Škofja Loka, Slovenia

ciril.arkar@fs.uni-lj.si

Abstract. Due to energy, environmental, and social benefits, green roofs are recognized as a bioclimatic technology and sustainable construction systems and are becoming a predominant solution in connection with urban planning and building envelope retrofitting. To support design and marketing of Urbanscape® lightweight extensive green roofs a special software tool was developed, which is presented in the paper. Performance evaluation tool (PET tool) is validated based on extensive and continuous 5-years in-situ monitoring of thermal and hydrological response of different Urbanscape green roofs. The key performance indicators of Urbanscape green roofs are evaluated based on calculated thermal and hydrological response. To emphasize the advantages of green roofs thermal response and performance indicators are determined also for non-vegetated roof for the same boundary conditions. PET tool enables i) evaluation of Urbanscape green roofs' whole year thermal and hydrological response, ii) to search for the optimal design of the Urbanscape green roof system in terms of energy and water performance, iii) evaluation of comparative advantages compared to non-vegetated roof, iv) energy savings and CO_2 emission reduction analyses for heating and cooling season. Analyses can be made for arbitrary worldwide climate conditions since meteorological parameters are gathered from Meteonorm database.

1. Introduction

In the past, the primary role of greenery on the building envelopes – green roofs and green facades – was its aesthetics, while their impact on the building and the external environment has become the subject of research in the last decade [1]. Nowadays, green building envelopes are recognized as having a high positive influence on urban microclimate and living comfort in cities, since they address many environmental issues, such as urban heat island mitigation, water retention and detention, sink of CO_2 and other pollutants [2-3], all resulting from the impact of global climate change and urbanization [4]. The survey of research activities and state of the market reveilles that among green building envelope technologies green roofs (both extensive and intensive) are the most developed and established technology. Due to energy, environmental, and social benefits, green roofs are recognized as a bioclimatic technology and sustainable construction systems [2, 5] and are becoming a predominant solution in urban planning and an increasingly used alternative at building envelope retrofitting especially in the form of extensive green roofs because of low additional structural load, low maintenance and low cost in comparison to intensive solutions [2, 6]. Green building envelopes are part of the green infrastructure, which is quoted in numerous strategic documents, initiatives and directives of the European institutions [7-10] and city administrations, where they are recognized as technology that contributes: to improving the energy performance of buildings, to stormwater and water resource management, to achieving greater biodiversity and to the transition to a climate change neutral Europe.

Green roofs are adaptive (and even multifunctional) building envelope constructions, so their characterization, selection and evaluation of thermal performance can not be based on standard/basic building construction thermal performance metrics e.g. steady-state thermal transmittance (U-value), which is easily recognized by building designers, stakeholders and experts [11]. Due to lack of suitable performance metrics for static and adaptive building constructions the advantages of green roofs, in comparison to non-vegetated roofs are most commonly studied experimentally or numerically using developed numerical models [12] and considering equal boundary conditions. Green roof models were also developed for building energy simulation tools EnergyPlus and TRNSYS [12] however they firstly do not consider latent heat of water at water freezing ambient conditions, which considerably influence green roof thermal response and secondly they are not adapted to lightweight mineral wool growing media, which has a very high water retention capacity and low thermal conductivity and density (equal to mineral wool thermal insulation) in a dry state.

Due to limitations of existing green roof models in building energy simulation (BES) tools a software tool named 'PET tool' was developed to enable yearly thermal and hydrological response analysis for arbitrary climate boundary conditions. Software tool was made based on the developed and thoroughly validated green roof and non-vegetated roof numerical models. PET tool is designed in a way to support design and marketing of Urbanscape® lightweight extensive green roofs. It's functionality and performance metrics are presented in this paper.

2. Green roof performance evaluation tool

PET tool is a user-friendly software tool, developed within MS Excel, intended for comprehensive analyses of Urbanscape green roofs' thermal and hydrological performance and presentation of their advantages compared to existing non-vegetated flat roofs. PET tool, its features, functionalities, performance and analyses are the result of collaboration between Knauf Insulation, Urbanscape Green Solution Team experts and stuff of Laboratory for Sustainable Technologies in Buildings, Faculty of Mechanical Engineering, University of Ljubljana. PET tool is one of the results of a five-year industrial research project [13-14] financed by Knauf Insulation, Škofja Loka, Slovenia.

Instructions for proper use of PET tool and correct interpretation of presented results can be accessed from the PET tool welcome screen (figure 1a). Instructions (figure 1b) provide also further calculation examples and interpretations of results according to frequently asked questions of customers.

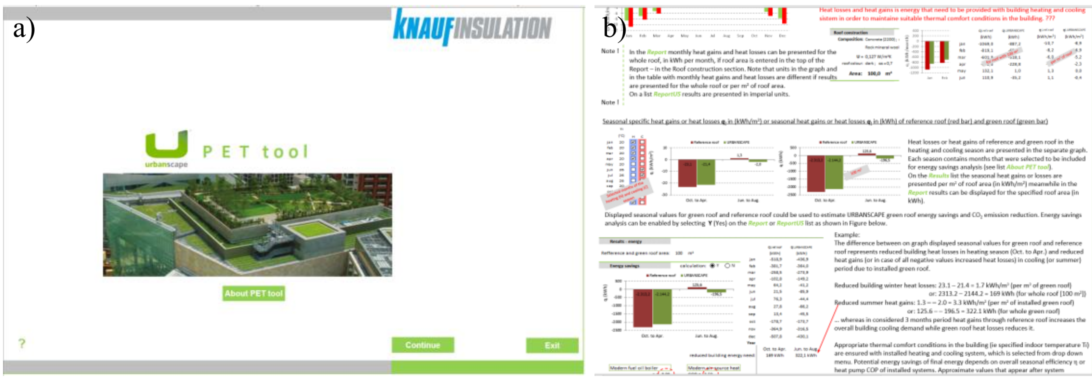


Figure 1. 'PET tool' welcome screen (a) and screenshot of PET tool instructions for use and results interpretation (b).

2.1. Numerical model and model validation

Green roof energy and hydrological performance is determined with developed one-dimensional transient heat and mass transfer numerical model, which considers main heat fluxes that influence green roof thermal response as well as green roof's water balance. The green roof model is presented in detail in [12]. Compared to existing green roof models it also takes into account heat transfer phenomena at freezing temperature conditions – a latent heat accumulation in green roof's lightweight mineral wool growing media. As demonstrated in [12], latent heat accumulation considerably alters the green roof's thermal response; peak heat flux as well as heat losses are also reduced. Green roof's numerical model equations are solved within MS Excel environment using the matrix inversion method. Number of temperature nodes is fixed to 32, where 6 of them are being used for the green roof growing media. Specially developed algorithm determines optimal number of nodes for each roof layer, according to the layer thermal resistance, in order to achieve optimal accuracy of numerical calculations. Thermal and hydrological response of the green roof is determined using a time step of one hour, which equals the time step of meteorological data, which are obtained from Meteonorm 7 software [15]. Alongside with the green roof numerical model also a numerical model of reference (non-vegetated) roof was developed in order to enable comparative green and reference roof performance analysis.

PET tool was validated based on extensive and continuous 5-years in-situ monitoring of thermal and hydrological responses of different compositions of Urbanscape Green Roof Systems performed on Faculty of Mechanical Engineering, University of Ljubljana. Experimental green roofs were installed on a flat roof of a laboratory test building presented in figure 2. There are four modules, each with dimensions of 1 × 3 m, one of them representing the reference non-vegetated roof. Until now 8 different Urbanscape green roof compositions were tested, each with in-situ monitoring period of at least 1 year. One green roof composition remains unchanged since 2013 for evaluation of long-term effects on thermal and hydrological response. Results of PET tool numerical model validation are presented in yearly reports [13-14] and published research papers [12].

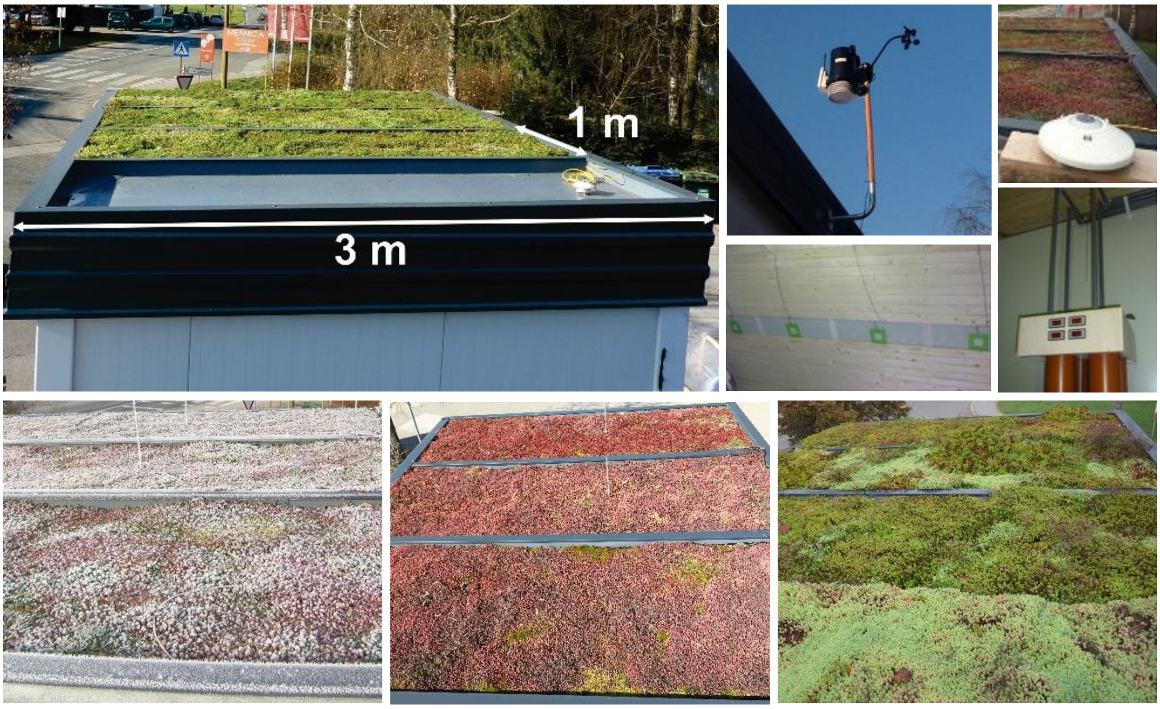


Figure 2. Lightweight extensive green roof modules on a roof of the laboratory test building after installation in 2013 (top left), some used measurement equipment (weather station Vantage Pro 2, pyrgeometer Kipp&Zonnen CG1, heat flux meters, developed outflow volume-flow meters) (top right) and green roof vegetation (Sedum-mix) appearance in different periods of the year (bottom).

2.2. Definition of roof compositions and boundary conditions

PET tool is a MS Excel .xlsm file with separate .xlsx file with Meteonorm meteorological data for several worldwide locations. The screen that appears after the welcome screen is shown in figure 3a. At first, the composition of a loadbearing construction (i.e. the ‘Reference roof’), on which Urbanscape Green Roof System is placed, is defined. Up to 6 layers can be defined, from drop-down boxes where materials are organized in groups. For each layer thickness needs to be specified and U-value is displayed at the top of the screen. For the reference roof the absorptivity of solar radiation also need to be selected. Follows the selection of Urbanscape lightweight extensive green roof system composition. As a vegetation layer a Sedum-mix blanket with 2 cm soil layer is added automatically. For the green roof the overall thickness and maximum water content are displayed on screen. Irrigation scenario – N/Y and at which water content green roof is irrigated – needs to be also specified. In the numerical model it is set that at each irrigation event 30% of maximum water content is added. At the end the climate conditions are specified by firstly selecting the country and then the city. Data that are imported in PET tool and are needed in numerical model are hourly values of ambient air temperature and relative humidity, wind speed, rainfall and solar and incoming longwave radiation on horizontal plane.

The second PET tool screen presents graphically and numerically meteorological parameters (figure 3b) what helps the green roof expert to define indoor temperature in heating (winter) and cooling (summer) season and to select months that are going to be included into seasonal energy savings analysis. Months that are not selected are not considered in seasonal energy performance analysis. Displayed meteorological data are valuable also for optimization of green roof composition and irrigation scenario.

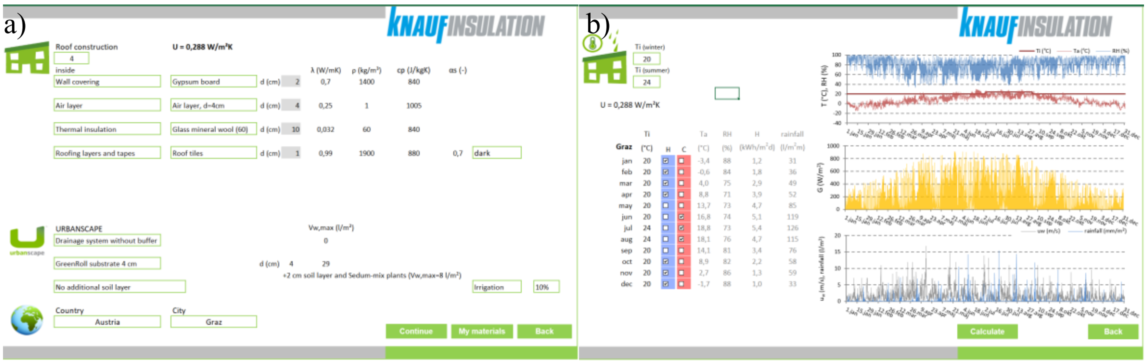


Figure 3. Screenshots of ‘PET tool’; definition of reference roof composition and lightweight extensive green roof composition and irrigation and selection of site meteorological parameters (a) and indoor boundary conditions definition and selection of months for seasonal analysis and graphs presenting meteorological parameters (b).

2.3. Presentation of performance indicators

When boundary conditions as well as heating and cooling season are defined thermal and hydrological response is calculated with validated numerical models of lightweight extensive green roof and reference roof. In the PET tool calculation progress is shown by displaying calculated monthly values. Thermal and hydrological response calculations do not end at the end of the year. Calculations are repeated in order to balance initial conditions. Calculations stop when calculated values does not differ from those obtained in the first run. Figure 4 presents screen with displayed results where hourly, monthly, seasonal and yearly values are presented for the green and the reference roof. The first graph (top-right) presents hourly values of specific heat flux $\dot{q}i$ in (W/m²) on inner surface of reference roof (red line) and green roof (green line). It enables comparison of peak heat fluxes which directly influences required heating and cooling power. Graph also visualizes green roof heat flux attenuation due to increased roof heat capacity, shading and evapotranspiration as well as due to latent heat accumulation in green roof substrate caused by water freezing and melting at freezing ambient conditions. On the left hand side of the screen monthly average specific heat values are presented as an indicator of monthly heat losses and gains. The difference between reference and green roof value indicates the potential monthly energy savings. The same graph presents also monthly peak heat fluxes what indicates the expected peak heat losses and gains in each month. Numeric values are listed in the report (section 2.4).

For the months that were selected for heating and cooling season the seasonal specific heat gains or heat losses qi in (kWh/m²) are presented for the reference roof (red bar) and for the green roof (green bar). These values can be used to evaluate Urbanscape lightweight extensive green roof energy savings as well as for green roof composition optimization.

One of the recognized advantages of green roofs is also urban heat island mitigation. This benefit of green roof in comparison to the reference roof can be evaluated from the graph in the middle of the screen (figure 4), which presents hourly values of calculated outdoor surface temperatures of both roofs. Lower outer surface temperatures indicate other environmental and social benefits of green roofs. This graph also enables evaluation of water stress conditions on temperatures and heat transfer.

Green roof water balance is presented at the bottom of the screen with presented results (figure 4). Right graph shows hourly values of green roof substrate water content (orange line), outflow from green roof (green line) and green roof irrigation (blue line). From this graph green roof expert can analyse influence of different irrigation scenarios and different drainage systems (with/without water storage) on retained water and water for irrigation. One can evaluate green roof also regarding to the stormwater management.

Yearly hydrological performance of Urbanscape green roof system (on the bottom left graph in figure 4) presents dark blue bar showing yearly rainfall from meteorological data what in analysis equals the outflow from the reference roof. Next to outflow from Urbanscape green roof is presented with green bar and above both bars the share of retained water in case of green roof installation. Estimated amount of water for irrigation of each m² of green roof is shown in light blue bar.

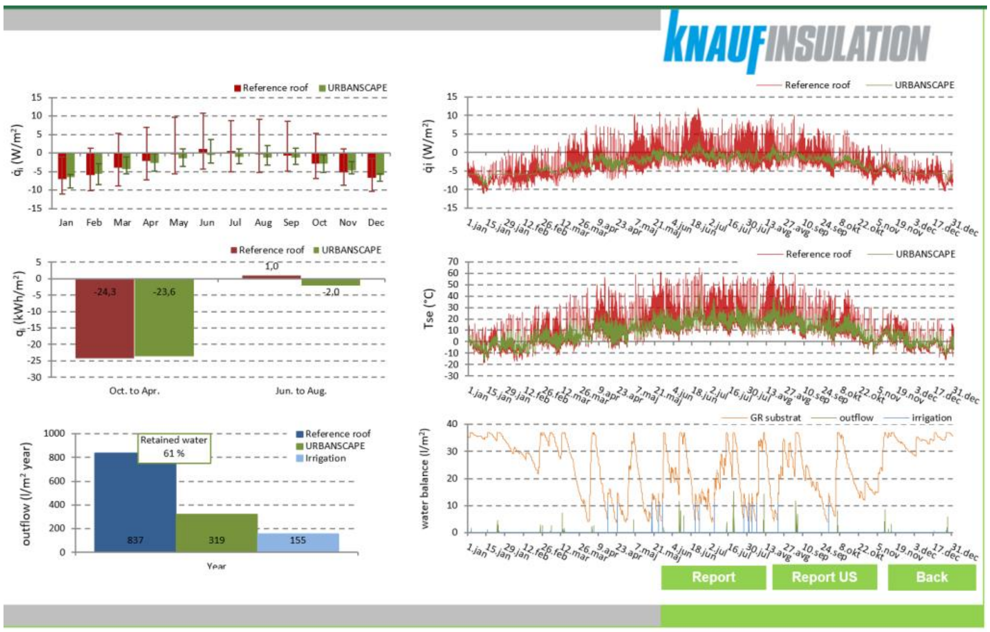
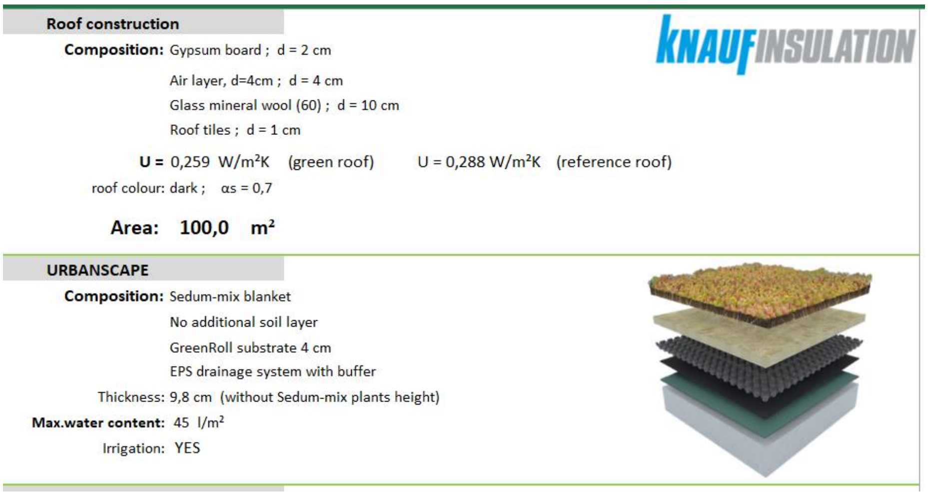


Figure 4. Screen with results of numerical calculations in the form of graphs presenting hourly, monthly, seasonal and yearly values of calculated parameters.

2.4. Report

PET tool report enables further analysis and presentation of additional results like numerical average monthly heat flux values and monthly water balance results. The report can be saved as a separate pdf file. As one of the purposes of PET tool is to support marketing, the results in the report can be presented in imperial units. There are also two tailored versions of PET tool in French and German language.

Report contains the information on reference and green roof composition and their U-value. In case when expanded polystyrene (EPS) drainage layer with water storage is used in green roof, also informative U-value of green roof, determined considering the calculation methodology for inverted roofs, is displayed as shown in figure 5. In case when green roof area is specified all graphs and numerical values are presented for specified roof area and not as specific values for each m^2 of green and/or reference roof.



Roof construction

Composition: Gypsum board ; d = 2 cm
Air layer, d=4cm ; d = 4 cm
Glass mineral wool (60) ; d = 10 cm
Roof tiles ; d = 1 cm

U = 0,259 W/m²K (green roof) U = 0,288 W/m²K (reference roof)

roof colour: dark ; αs = 0,7

Area: 100,0 m²

URBANSCAPE

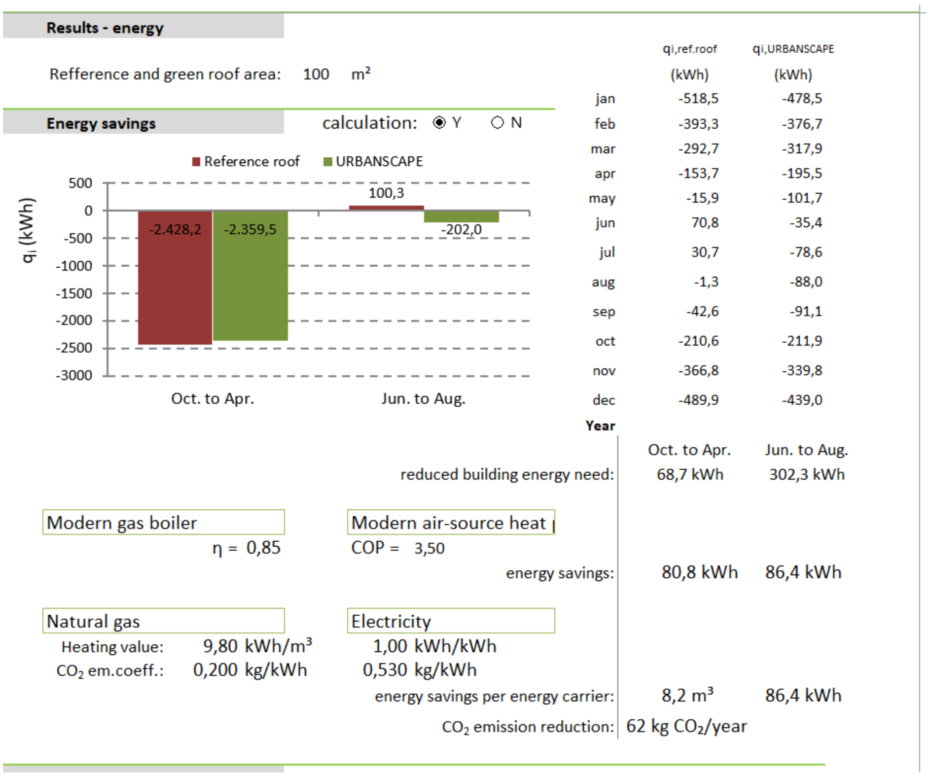
Composition: Sedum-mix blanket
No additional soil layer
GreenRoll substrate 4 cm
EPS drainage system with buffer

Thickness: 9,8 cm (without Sedum-mix plants height)

Max.water content: 45 l/m²

Irrigation: YES

Figure 5. Part of the report presenting reference and Urbanscape green roof composition and basic characteristics; in case of used EPS drainage layer U-value of green roof differ from U-value of reference roof.



Results - energy

Refference and green roof area: 100 m²

Energy savings calculation: ◉ Y ○ N

	qi,ref.roof (kWh)	qi,URBANSCAPE (kWh)
jan	-518,5	-478,5
feb	-393,3	-376,7
mar	-292,7	-317,9
apr	-153,7	-195,5
may	-15,9	-101,7
jun	70,8	-35,4
jul	30,7	-78,6
aug	-1,3	-88,0
sep	-42,6	-91,1
oct	-210,6	-211,9
nov	-366,8	-339,8
dec	-489,9	-439,0
Year		

	Oct. to Apr.	Jun. to Aug.
reduced building energy need:	68,7 kWh	302,3 kWh
energy savings:	80,8 kWh	86,4 kWh
energy savings per energy carrier:	8,2 m³	86,4 kWh
CO_2 emission reduction:	62 kg CO_2/year	

Modern gas boiler
η = 0,85

Modern air-source heat
COP = 3,50

Natural gas
Heating value: 9,80 kWh/m³
CO_2 em.coeff.: 0,200 kg/kWh

Electricity
1,00 kWh/kWh
0,530 kg/kWh

Figure 6. Part of the report where energy savings and CO_2 emission reduction (environmental indicator) due to green roof installation can be determined.

In the energy section of the report the building heating and cooling system, their seasonal efficiency and energy carrier can be specified. Based on selected or entered values the reduced final energy use for heating and cooling is presented as well as energy savings per energy carrier for each season. Additional yearly reduction of CO_2 emissions due to installed green roof is presented.

3. Upgrades and additional functionalities

With constant development of Urbanscape green roof solutions also the PET tool is being constantly upgraded. New drainage systems and new lightweight growing media solutions are added to the drop down list, while their thermo-physical properties are determined with laboratory experiments and validated with green roof in-situ thermal and hydrological response measurement results. New materials for loadbearing (reference) roof construction and meteorological data can also be added to enable analysis for specified reference roof design and location.

Further more advanced analyses are also possible with an open version of PET tool. As an example of such analysis the influence of historical weather data (observed climate changes) on green roof hydrological response is presented below. Namely, often raised question is how representative are the weather data, which are typical years for selected location. Results obtained using historical data for the period from 1985 to 2016 was statistically analysed and compared with results obtained with Meteonorm typical year for case study green roof in Mexico City. Figure 7 presents some of the obtained results. From the hydrological response graphs for selected years (typical year, 2016 extremely high and 1990 low precipitation amount) it can be concluded that typical year suitable covers the rainy periods in Mexico City.

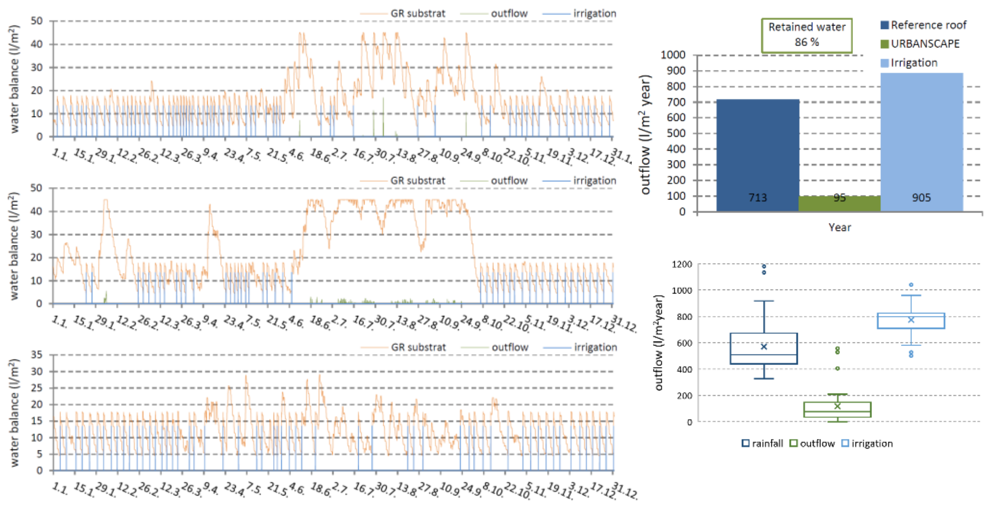


Figure 7. Results of green roof hydrological response analysis considering weather data from 1985 to 2016; water balance graph in case of typical year (top), 2010 and 1990 (bottom); yearly balance in case of typical year and box plot considering all 33 sets of meteorological data.

Box plot in figure 7, which covers all weather data sets further reveal wide range of yearly rainfall where more than ¾ of the years had a rainfall below that of a typical year. Historical data show that the amount of precipitation is increasing. Two outliers indicate two years with extreme rainfall, both appearing in last decade. One additional outlier in green roof outflow indicates that there was also one another year with high rainfall in a short period (month with extremely high rainfall). Low outflow for other years indicate high water retention capacity of case study green roof. Obtained results for required irrigation water gives indication on range that is expected regarding to the variations of meteorological conditions in the Mexico City.

4. Conclusions

Due to the lack of suitable thermal performance metrics for green roofs and limitations of BES tools that do not enable thermal response analysis of lightweight extensive green roofs with lightweight mineral wool growing media a ‘PET tool’ was developed and presented in this paper. In comparison to existing models the PET tool green roof model additionally considers different heat and mass transfer at water stress conditions and at freezing temperature conditions. As it was shown the PET tool enables: a) evaluation of Urbanscape green roofs’ thermal and hydrological response, b) to find the optimal green roof composition in terms of energy and water management performance, c) evaluation of the comparative advantages of green roof compared to existing reference flat roof and d) energy savings and CO_2 emission reduction analysis for heating and cooling season. Analyses can be made for: i) arbitrary composition of lightweight or massive reference flat roof – on which Urbanscape system is installed, ii) different composition of Urbanscape green roof system and irrigation scenarios and iii) different worldwide climate conditions.

Acknowledgements

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Assessment of urban-scale potential for solar PV generation and consumption

Pedrero J[1], Hermoso N[1], Hernández P[1], Muñoz I[1], Arrizabalaga E[1], Mabe L[1], Prieto I[1], Izkara J L[1]

[1] Tecnalia Research & Innovation, Astondo Bidea, Edificio 700, Derio, 48160 Spain

juan.pedrero@tecnalia.com

Abstract. The rise of grid electricity price and a growing awareness of climate change is resulting in an increasing number of photovoltaic facilities installed in buildings. Electricity market regulation and climatic conditions, in particular solar radiation, are the main factors that determine the economic viability of a photovoltaic facility. This paper describes a method for evaluating the potential for photovoltaic (PV) production and self-consumption for the building stock of a particular city. A GIS 3D city map is used to calculate solar irradiation. Building-level electricity use is calculated based on building type, geometry and other characteristic inferred from building age, taking the cadastre GIS as main input. The methodology identifies the realistic potential for rooftop photovoltaic installations, as well as the optimum size to be installed from an economic perspective. To represent different regulations that can affect economic viability of PV installations, calculations should adapt for the specific installation conditions and regulatory situation, as for example self-consumption and net metering. The proposed methodology is applied to a case study in Irun (Spain), where results for potential of PV generation and self-consumption for the building stock are presented. The results offer public administration a realistic view of economically viable PV potential for the city and allow to analyse different mechanisms to promote their installations. It also serves for individual electricity consumers to evaluate and optimize new photovoltaic energy facilities. Finally, it serves policy makers to estimate the repercussion of electricity market regulations on the economic viability of PV systems.

1. Introduction

Energy consumption in cities currently represents between 60% and 80% [1] of the global energy use. As the population living in cities increases worldwide, this percentage is bound to increase in the future. The expected trends for progressive electrification of heating loads and transportation, will also mean that electricity use in cities is likely to rapidly increase in the coming years, and consequently the energy supply and demand profiles in the cities will evolve.

Cities will generally need to upgrade grid and infrastructures to be able to cope with these increasing electricity demands, and this infrastructure should allow to increasingly deliver renewable electricity, if climate change objectives are to be achieved. Generation of renewable electricity on-site within the city is becoming a priority in many cities, as a solution to reduce electricity transportation and distribution losses and potentially reduce investments in grid infrastructure. From all the renewable electricity generation technologies, PV has emerged in recent years as arguably the most competitive and adequate technology for urban areas, due to its good economic and environmental performance. Costs have reduced [2] and levelized costs of PV electricity has reached grid parity in many countries [3].

Environmental benefits of PV installations are also nearly indisputable [4], as long service lives and low maintenance result on a nearly-zero impacts for their operation, and life cycle impacts have greatly reduced due to improved manufacturing processes [5].

Distributed PV electricity generation and consumption is therefore a subject of major interest for most cities, and methodologies and tools for estimation of its potential are needed to facilitate this task. This paper proposes a method for evaluation of PV potential, departing from cadastre data for the cities to create a 3D GIS map, estimate the available solar radiation, and calculate the solar PV electricity production.

As economic viability of PVs largely depends on the specific electricity market, this paper presents an evaluation for the different regulatory approaches, including economic evaluation if self-consumption or net metering schemes are applied.

2. Methodology

2.1 Calculation of building stock energy demand

The calculation of the energy demand of the building stock for the city of Irun has been done through *Enerkad,* software developed by Tecnalia in the European research project PlanHeat [6], completed and improved to allow the electricity energy consumption analysis.

The *Enerkad* tool is a QGIS based software which calculates the energy demand and consumption at the building, district or city level based on cadastral data. *Enerkad* performs a static calculation, based on the degree-day method, and obtains the energy demand for each final use: heating, cooling, Domestic Hot Water (DHW), lighting and equipment, allowing energy consumption to be obtained by type of fuel for each building. Given that the study carried out focuses on the potential of PV generation, the analysis will focus on the electricity consumption. Due to the unavailability of a representative sample of hourly electricity profiles, the national electricity consumption curve for the residential sector has been used for residential buildings [7], and an alternative profile for non-residential buildings [8].

For residential buildings the heating system is introduced in the model (gas boiler, diesel boiler, electric boiler, heat pump, etc.), in case there is an electricity need associated to heating purposes it will be considered in the electricity consumption curve.

For non-residential buildings, it is particularly relevant the fraction of electricity used for heating and cooling, which will largely vary between buildings depending on their use, age and the outside air temperature during each day.

Electricity consumption profiles are defined based on 5 main uses: cooling, lighting, equipment, heating and domestic hot water. Each one of the uses has its own characteristics:

- **Electricity for Cooling**: Covers all the cooling demand supplied by air to air heat pumps, will be mainly found in tertiary buildings.
- **Electricity for Lighting and equipment:** Covers all the electricity demand for equipment and lighting uses. The consumption profile will vary depending on the building use and the day of the week (workday, Saturday, Sunday).
- **Electricity for Heating:** Covers all the heating demand supplied by air to air heat pumps (mainly tertiary buildings) and electric boilers (some residential buildings).
- **Electricity for DHW:** Covers the domestic hot water demand met by electric boilers.
-

A complete description of the energy demand analysis methodology is presented in European projects' public reports[9] and conference papers[10].

2.2 Calculation of solar irradiation

The objective of the solar potential analysis is to quantify the potential for the integration of solar technologies on the roof surfaces of the buildings in the Municipality of Irun, considering orography, urban framework and shading resulting from constructive and natural elements

The climatic file and the Digital Surface Model (DSM) must be modified in order to adapt it to the requirements of the used tool. It is necessary a filtered DSM file, containing only the points corresponding to the roofs of the buildings and the ground. The rest of the points in the file are deleted.

The annual solar radiation per square meter (resolution of the DSM model) is obtained for any point of the municipality (roofs and urban spaces) by means of the UMEP plugin [11] for QGIS[12]. The solar map is bounded to the municipality limits using the administrative boundary layer of the municipality.

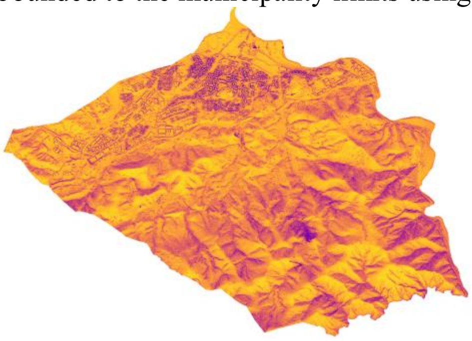

Figure 1. Annual solar radiation map of the municipality of Irun

In the solar radiation map (figure 1) all radiation levels are shown. The areas selected to study the potential PV production will have to meet several requirements and filters, as being part of the building roof and exceeding a specific irradiance threshold. To calculate surfaces where PV could be installed with a minimum economic performance (e.g. maximum return of investment period), minimum irradiance thresholds have been set and are specified in section 3.3.

2.3 Economic performance evaluation of PV installations

The economic performance of PV installations profitability and its relation with different regulations has been calculated considering that the consumer will be connected to the electricity grid, and assuming that the power term tariff will not vary when installing the PV modules. Therefore, all the economic savings quantified correspond to the energy term of the electricity bill.

For the actual electricity production, the calculation method presented in EN 15316-4-6:2007 [13] and the specification of technical conditions of installations connected to the network [14] have been used. PV production is hourly calculated for 12 days each one representing one month of the year. Irradiation values have been taken from PVGis database for the city of Irun [15].

Table 1 shows details of parameters that are used to calculate economic performance of PV installations.

Table 1. Summary of the parameters used for the economic

Parameter	Value
PV module efficiency [16]	16 (%)
Inverter efficiency [17]	95 (%)
Miscellaneous losses [18]	13%
Electricity base price for the first period [19]	0,1347(€/kWh)
Taxes on electricity (VAT) [20]	21 (%)
Annual electricity price variation rate[1]	2 (%)
Interest rate [7]	6.7 (%)
Power density of PV modules [16]	164.95 (W/m^2)

[1] Reports from the European Commission [26] show 4% annual price growth for the past years. A more conservative approach has been taken for this study. Note that higher electricity price variation rates would reduce the return period of the PV modules.

Total installation costs [21]	1.465 (€/W)
O&M costs [21]	0.02 (€/W.year)
PV modules service life [4]	25 (years)
Inverter service life	15 (years)

2.4 Economic evaluation of PV generation and consumption under different policies

There is a large degree of variations and uncertainty on the evolution of regulations for on-site PV production and self-consumption throughout the world. This paper explores three different scenarios which correspond to specific energy policies carried out or proposed in different parts of the world [22].

- **Solely self-consumption (SC)**, this first scenario reflects the current regulation system in Spain where the surplus of small PV producers is not remunerated at all. Consequently, the obligation to feed the grid with free electricity when the production exceeds the producer's energy demand stimulates smaller distributed generation facilities with no surplus electricity production and whose profitability is exclusively based on reducing the electricity bill. This approach brings on a smaller reduction of the greenhouse gas (GHG) emissions associated to electricity savings and is not able to decouple from a fossil-fuel dependent economy.
- **Net-metering,** this regulation has already been put into practice in places like California. In this study, surplus electricity is valued at retail price. Therefore, all the electricity produced with solar panels can be consumed at any other time, using the grid as a storage system. This legislation could consider different periods where the energy fed into the grid can be retrieved, daily net metering, monthly net metering, annual net metering. **Annual net metering (ANM)** is the modality chosen for the present evaluation.
- Finally, a third scenario has been represented, **"theoretical maximum potential"**. This scenario assumes that all the surface available for PV installation within the chosen irradiation threshold could be installed, and the economic return for injecting to the grid will be equal to the economic return for self-consumption. This scenario could represent regulations where electricity transactions with nearby buildings or electricity users could be allowed, or some regulations with feed-in tariffs.

3. Case study characterisation

Irun is the second largest city in the province of Gipuzkoa in the Basque Autonomous Community, Spain. It is located in the border between Spain and France and inhabits 59.508 citizens [23]. The municipality takes part in several sustainability programs and has already published its second sustainability action plan.

3.1 Origin of the data

To carry out the analysis of the potential of solar energy implementation on the roof surfaces in Irun, the following geospatial data are used:

- Digital Surface Model (DSM): 1m^2 resolution, from Geoeuskadi ftp download service [19].
- Climatic information of the study area: The climate model of the city of Donostia (15km west) available in Energy plus format (epw) with hourly resolution [24] has been used.
- Reference cartography: Cadastral basis of the buildings for the municipality of Irun, provided by the City Council of the locality and layer of administrative limits of the Basque Country obtained from Geoeuskadi [25]

3.2 Building stock electricity consumption characterisation

Based on the GIS built from cadastral data, the total rooftop area has been obtained and is shown in Table 2. As this study focuses on the study residential and tertiary buildings' energy consumption, the industrial rooftop area will be neglected. Nevertheless, it represents a significant potential area for PV installations.

Table 2. Rooftop area by building type in the city of Irun

	Rooftop area (residential and tertiary)	Industrial and other rooftop area	Total
Total	774.336,70 m^2	428.017,64 m^2	1.186.305,93 m^2

Table 3 presents the results from the electricity consumption simulation done with *Enerkad* tool [9], [10], as explained in section 2.1.

Table 3. Building stock energy characterisation for the city of Irun

	Unit	Value
Total electricity consumption	kWh/year	124.050.535,95
Cooling	kWh/year	1.145.746,85
Lighting and equipment	kWh/year	71.174.294,34
Heating + Domestic Hot Water	kWh/year	51.730.494,76

3.3 Calculation of surfaces with a minimum solar irradiation threshold

To determine PV installations that would have a minimum economic return under optimum circumstances (all electricity used or sold at cost price) two different irradiation thresholds have been selected. Table 4 shows the thresholds and their estimated return of investment, considering energy savings, installation and maintenance costs,

Table 4. Return of investment periods for different irradiance thresholds

Irradiance threshold (kWh/ m^2 year)	Return of investment (years)
1100 (kWh/ m^2 year)	<10 years
925 (kWh/ m^2 year)	<12 years

As it can be seen in figure 2, most roofs with North and even with west slopes are automatically dismissed in the upper threshold, due to the shades associated to their orientation.

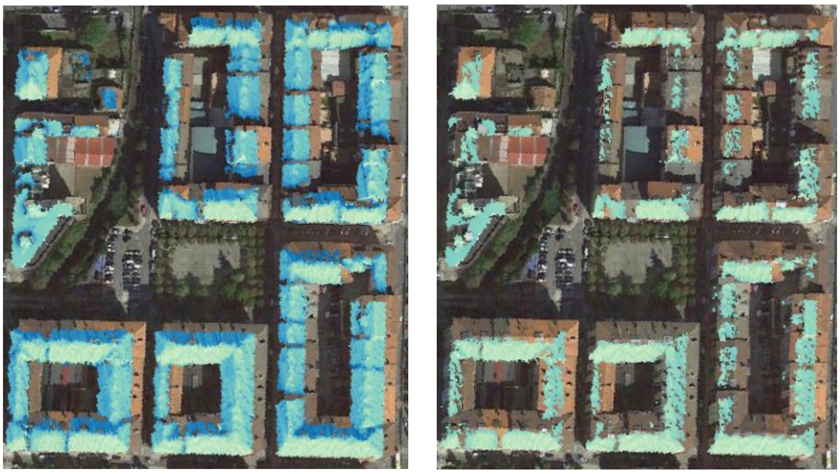

Figure 2. Solar radiation considering different thresholds (left: 925 kWh/m^2 and right: 1100 kWh/m^2)

Crossing this data with the cadastral base layer of the municipality, 2 parameters will be calculated: the roof surface with a radiation greater than the established threshold and the average radiation in the surface in which the radiation is greater than the stablished threshold. Based on the average solar irradiation and available roof surface, solar production potential will be calculated building by building.

3.4 PV optimization based on economic performance and possible legislations

Since solar resource is not available on demand and must be exploited during a limited period of time, the correct planification and dimensioning of the facility is of great importance to pursue its maximum profitability. National regulation for distributed generation plants has a direct impact on the design of the facility, as it determines the economic revenue of the installation, or the size of installation to achieve a minimum profitability.

For the calculation of the energy balance to determine the optimum profitability of a PV installation, a standard building, representative for Irun has been used as a reference. The building consists of 32 dwellings divided into 5 floors and it is oriented north to south with a flat rooftop. For the purpose of this study, the solar electricity production will be shared by all the dwellings in the building.

Taking such building as a reference, the energy consumption and PV production curves have been calculated for each month of the year. Then, the costs and savings for the PV facility have been calculated and a sensitivity analysis performed to find the optimum peak power of the PV installation.

When considering the legislation in the calculation of costs and savings, it is necessary to study the coupling of the electricity production and consumption, especially in the "self-consumption only" case, where all the surplus electricity would be lost without obtaining any profitability. In figure 3 the generation and consumption coupling can be seen for two PV installations cost-optimized for both regulations (optimized based on the results from the sensitivity analysis shown in figure 4).

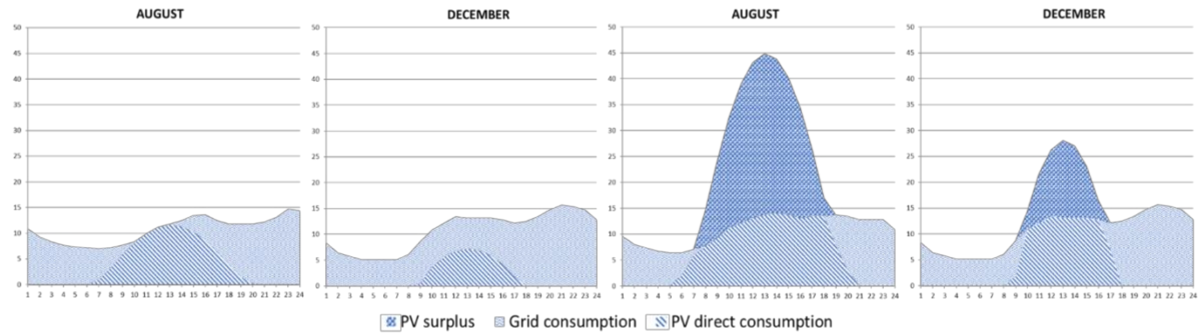

Figure 3 Comparison between the month with the highest electricity surplus (August) and the month with lowest electricity production (December). Installation designed for an optimum profitability under Self-Consumption and Annual net Metering regulation according to results from figure 4.

As the installed power of a PV facility increases or decreases, the energy balance pictured above varies, consequently varying the amount of surplus electricity and savings. In Figure 4 it can be seen how this modification on the size affects the benefits and how the profitability starts dropping once the energy surplus increases. The optimum point for a PV power plant stands as for 1kW per dwelling in case of self-consumption regulation and about 2,25 kW per dwelling in case of annual net metering regulation.

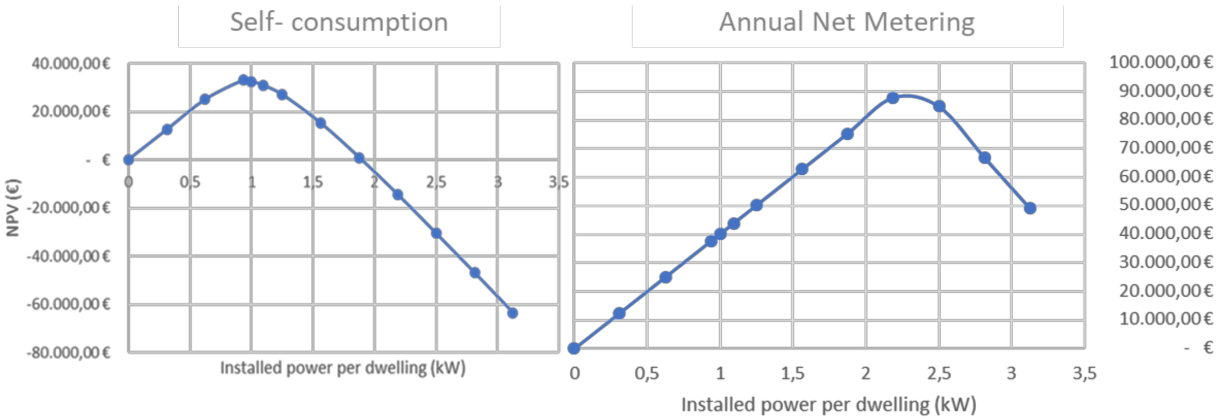

Figure 4. PV plant dimensioning NPV curve for Self-consumption and Annual Net metering regulations.

The optimum points from the NPV curves presented above follow the next behaviour:

- **Self-consumption:** the optimum case consumes 100% of the electricity consumption. No electricity in injected into the grid and **29,23%** of the annual electricity demand is met by PV panels.
- **Net metering:** In this case the grid is used as a storage and the optimum PV installation should be able to feed a **100% of the total annual electricity demand** of the dwelling, even if only **48,90%** of the electricity produced by the PV panels is **instantaneously consumed**.
- **Theoretical maximum potential: 100%** of the electricity produced by the panels could be indistinctly used and sold, with the same economic return.

For the analysis of the economic profitability of PV installations, maximum size of PV installation will be therefore determined as follows, for the different irradiation thresholds:

- Self-consumption: 29% building demand
- Net metering: 100% building demand
- Theoretical maximum potential: 100% available building roof surface

4. Results

Combining the calculations presented in the previous sections the optimized PV potential of the city of Irun has been calculated. These results show the available area which complies with good solar irradiance and sufficient economic profitability, considering also the current legislation.

Table 5. Installable surface for investment return period under 10 years

	Theoretical maximum	Self-consumption only	Annual net metering
Installable surface	269.822 m^2	149.039 m^2	248.452 m^2
Percentage of rooftop surface in the city	35%	19%	32%
Approximate installable power	44,50 MW	29,73MW	40,99 MW

Table 6. Installable surface for investment return period under 12 years

	Theoretical maximum	Self-consumption only	Annual net metering
Installable surface	550.287 m^2	207.098 m^2	439.466 m^2
Percentage of rooftop surface in the city	71%	27%	57%
Approximate installable power	90,79 MW	34,17MW	72,51 MW

In the following table the energy share of PV power in the city is calculated.

Table 7. Solar power energy share. Percentage of building stock electricity consumption fed by solar PV.

Threshold	Theoretical maximum	Self-consumption only	Annual net metering
1100 kWh/m^2.year	32%	17%	29%
925 kWh/m^2.year	59%	24%	48%

For PV installations to have a return of investment below 10 years (irradiation above 1100 kWh/m^2.year), with current regulation in Irun (self-consumption), only 19% of the roof surface could be installed, and 17% of the total electricity use of the building stock could be produced and consumed. If regulation would evolve to an annual net-metering scheme, 32% of the available roof surface and up to 29% of the electricity use in buildings could be supplied by PV. The theoretical maximum potential of PV installations in the city for this 10-year return of investment could reach 35% of the roof area and provide 32% of the total electricity use.

These numbers largely increase if the return of investment is extended to 12 years (irradiation above 925 kWh/m^2.year, as many other roof surfaces would become available. As it can be seen in Table 7, for this case up to 24% of the total building electricity use could be supplied under self-consumption scheme, 48% for annual net metering, and 59% for the theoretical maximum production.

5. Discussion and conclusions

This study has shown a methodology to calculate the potential for PV electricity generation and consumption in cities. The methodology allows the calculation of potential for installation of economically viable PV generation systems in buildings across a city, under different regulatory schemes such as self-consumption or net metering. This type of study is expected to be very useful for city energy planning, as it allows to estimate PV generation potential in roofs, which could represent a significant share of the total building energy use in the cities.

For the presented sample case of Irun city, located of North Spain with an average annual radiation of 1,300 kWh [15], which is one of the lowest for a Spanish city, up to 24% of the total building electricity use in the city could be supplied by PV panels under current self-consumption regulation. This percentage of building electricity supply would rise up to 48% if annual net metering were in place, and to 59% for the theoretical maximum production of PV panels in roofs. These calculations are for profitable installations with a return of investment of 12 years, which equals a IRR of 7%, taking into account that these installations have a service life of 25 years. With this attractive economic performance, business models and financial schemes should be explored to promote the progressive and rapid deployment of installations and make use of this solar resource currently unexploited.

Even though cities embark in sustainable energy strategies and climate change mitigation action plans, it is important to note that in coming years building electricity use is expected to increase, due to the progressive electrification of transport and heating loads. It can be expected that a larger share of the available solar PV surfaces in the roofs in the city could be used for building self-consumption. The implications of this PV generation on the electricity grid would in principle be beneficial, as would mean practically no changes to the current electricity grid and can reduce new infrastructure requirements for the grid.

Acknowledgements

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Building physics design of urban surfaces

Leistner P[1, 2], Kaufmann A[1], Koehler M[1], Würth M[1], Hofbauer W K[1], Dittrich S[1]

[1] Fraunhofer Institute for Building Physics IBP, Institute Stuttgart
Nobelstraße 12, 70569 Stuttgart
[2] University of Stuttgart, Institute for Acoustics and Building Physics (IABP)
Pfaffenwaldring 7, 70569 Stuttgart

andreas.kaufmann@ibp.fraunhofer.de

Abstract. Structural-spatial form and urban land use are among the main transformative fields of action of cities. Quality of life and environment, identity and individuality as well as participation in local society are significantly influenced by urban surfaces. Most urban surfaces have so far been designed for the long-term fulfilment of individual purposes, but offer greater scope for design in terms of functionality and adaptability, quality and efficiency. It therefore makes sense to develop, evaluate, technologically expand and test the potential of urban surfaces in terms of building physics as a whole. In view of growing stress on urban structures due to climate-induced influences, such as flooding, extreme weather conditions or heat islands, new possibilities, processes, systems or materials are needed to improve resilience. The article presents exemplary developments that can be supplemented and combined. Hydroactive surfaces can buffer rainwater and release it with a time delay to reduce heat and flooding equally. Green façades improve city climate and air quality. Sound-absorbing façades reduce inner-city noise. Innovative transparent foil enclosures provide equally visibility and an optimum weather protection of objects to be protected throughout the year.

1. Introduction

Essential transformative fields of action for cities are their structural-spatial design and urban land use. They are of particular relevance for the sustainable development of cities and urban districts, as they have a decisive influence on the quality of life and environment, on the identity and the participation in local society. At the same time, there are inseparable interactions between the design and use of urban areas and other fields of action, including resource and energy efficiency, climate resilience and mobility. The focus of most settlement, traffic and, above all, building surfaces has so far been solely on the long-term fulfilment of individual purposes. For the exploitation of a multitude of further design and action options, it is necessary to unite the aspects and actors that originate from all parts of urban society in a structured and moderated interdisciplinary and interest-spanning process. The fact that local authorities are highly affected by permanent climate changes and extreme weather events alone makes it clear that these challenges can only be met with coordinated contributions. These contributions include the holistic development and technological expansion of the building physics potential of urban surfaces. Figure 1 illustrates the effects and interactions in the context of the current situation and design goals.

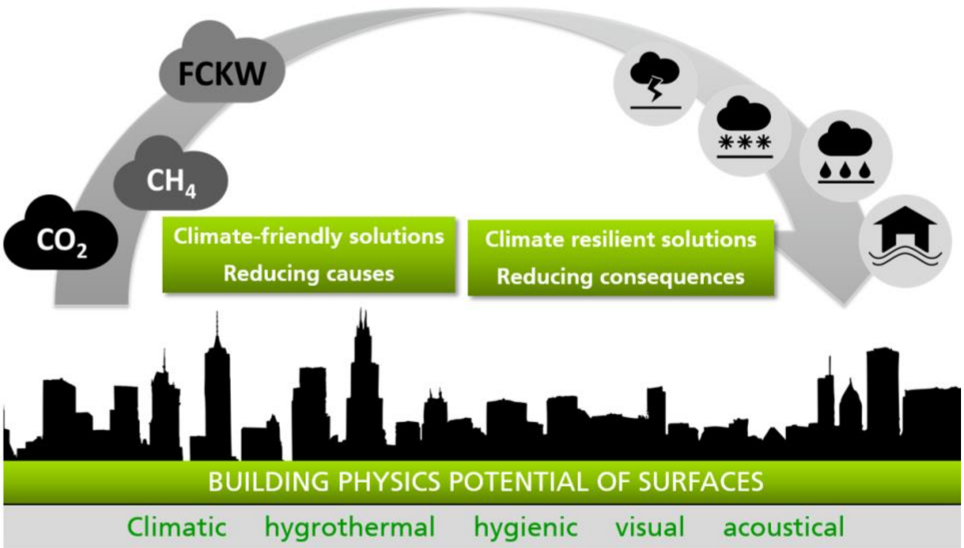


Figure 1. Building physics potential for the design of urban surfaces with climate relevance and for sustainable quality of life and environment in cities.

The current state of knowledge clearly and frequently demonstrates the need for action, but also shows concrete options for action that can be used effectively and economically, e.g. to react to specific consequences of climate change and to the increased dynamics of weather phenomena (water, snow, temperature). In practice, however, there are often barriers that are cross-use, cross-interest and cross-disciplinary. In order to be able to extend the system concept to large urban surfaces, e.g. to include aspects of urban safety (disaster and fire protection), systematic physical land management is necessary, as illustrated in Figure 2. Sustainability is the basic principle and standard of the design.

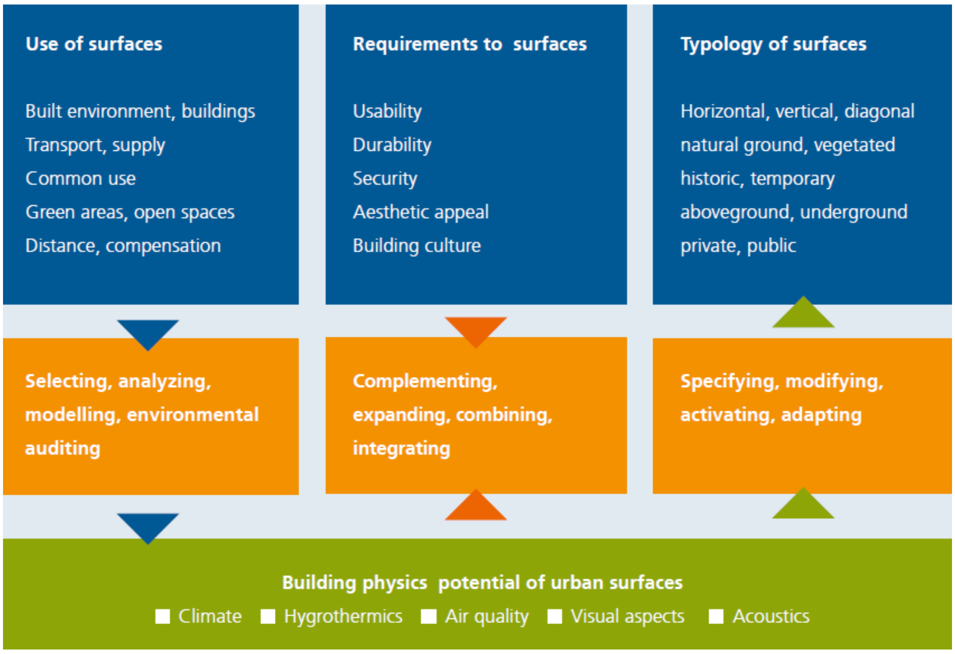


Figure 2. Systematic consideration and treatment of urban surfaces in the sense of physical land management.

The experimental determination of the properties of urban surfaces, the (quarter and city) model description with planning tools and, of course, the evaluation were and are the subject of research and development in order to develop the building physics potential. The Fraunhofer IBP is working on these topics since a couple of years in several projects. Currently there is a comprehensive project running at the IBP to develop both solutions for an enhanced climatic resilience and an improved sustainability of urban surfaces. Exemplary results of the IBP developments and their interrelated consideration are reported here. The examples given are chosen to show the wide scope of options.

2. Hydroactive traffic and open spaces

In metropolitan areas, the proportion of sealing increased to over 90 percent of the total area, which increases and accelerates precipitation runoff on the one hand and reduces the amount of water available for evaporation, latent cooling and groundwater recharge on the other hand. Since the lack of buffer areas leads to overloading of the sewer system, municipalities can limit the maximum discharge donations from properties and, for example, prescribe retention options on the property [1]. However, particularly in highly dense settlement structures there is often no space for open indentations, e.g. trough-trench systems with high infiltration and evaporation rates. Therefore, urban surfaces are in demand which serve to prevent heat and flooding equally [2]. One approach is the so-called "sponge city" principle [2] [3], in which urban surfaces are increasingly used for the intermediate storage of precipitation. The aim is to approximate the water balance of built-up areas to that of undeveloped areas, i.e. essentially to reduce the peak discharge values after heavy rainfall events and to increase the proportion of local evaporation and infiltration for groundwater recharge in the urban water cycle.

The horizontal roof and traffic areas, which have so far been largely fallow, as well as selected façades are of particular importance for potentially hydroactive areas [4] [5].

For decades, paving surfaces have also been able to be designed as infiltrable coverings. Usually, paving structures with a porous structure or seepage openings with a regular profile are considered. Alternatively, the joint between the paving stones is filled with coarse-grained material. In order to enable complete drainage in the vertical direction, all layers in the substructure must be permanently permeable in addition to the surface layer. Due to the resulting lower mechanical load-bearing capacity, it is only used on traffic areas with low loads, e.g. service roads, pedestrian zones and permanently used parking areas with low truck and bus traffic [6] [7]. So far, initiatives to use traffic areas as summer urban heat sinks have been rare [8]. While commercial products are not yet available, field measurements show that a temperature reduction of the order of ten Kelvin is possible, depending on the boundary conditions. This corresponds approximately to the temperature difference between a dry concrete surface and a grass area at noon. Figure 3 shows a field test with different water-storing concrete pavements.

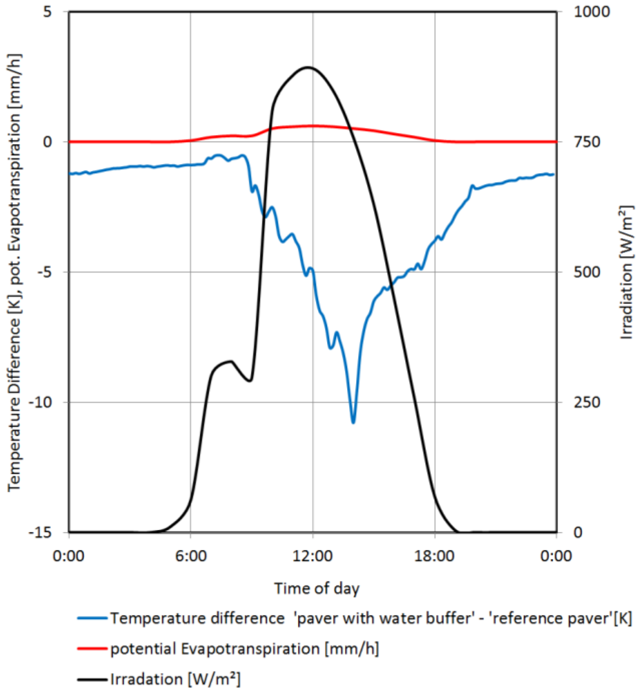


Figure 3. Field test with different water-storing concrete pavements (left: test field, right: measured temperature reduction of a storage stone compared to a standard concrete paving under summer conditions [8]).

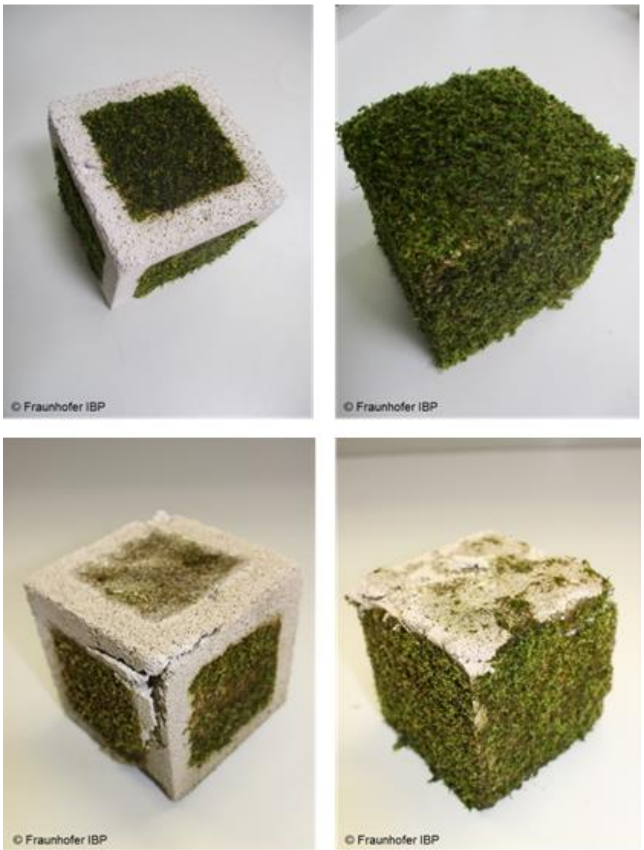
3. Greening of façades

With the "Weißbuch Stadtgrün" [9] the political goal is pursued to promote green in the city and thus also green buildings and façades. An obvious argument is the effective medium to long-term CO_2 binding and thus the contribution to climate protection.

In the manner of a "natural air-conditioning system", evapotranspiration through vegetation can have a cooling effect in the sense of reduced summer heating, sort of reducing heat stress in urban areas [10]. Comparative measurements of conventional and greened façades show that the latter have a cooling effect in summer and an insulating effect in winter, as well as balancing the humidity directly in front of the wall. For example, the evapotranspiration of an 850 square metre "living wall" is approx. 1,800 liters with the corresponding cooling capacity [11]. Façade-bound greenery thus reduces the effort required for air-conditioning of the buildings because it keeps them cooler.

In terms of air quality, model observations [12] show a reduction of nine percent NO2 and 13 percent PM10 (Particulate Matter $\leq$ 10 µm) in incoming air pollution when large-area green walls are placed in street canyons under average conditions. Within a street canyon, reduction values of up to 15 percent NO2 or 23 percent PM10 are possible, which can increase by up to 40 percent for NO2 and 60 percent for PM10 at low wind speeds. Data on concrete filtering performance of climbing plants are only available in isolated cases. In the case of ivy (Hedera Helix), for example, this is four to 8.4 percent of the total dust in the vegetation period or 1.8 to 3.6 percent per year. Of these, 71 percent are smaller than 15 micrometers and only ten percent smaller than 5 micrometers [13] [14]. With the Boston ivy (Parthenocissus tricuspidata) a binding of up to 80 percent of metals from the coarse dust was determined [15]. All these results prove that green façades can cause a local reduction of dust pollution. The examples also show, however, that systematic investigations with practical relevance are urgently required in view of still incomplete information on the potential effects.

While green roofs are already comparatively well developed and numerous systems for the most varied tasks and requirements are already established on the market, there is still a need for optimization for green façades. Many systems are fragile and also costly to install and maintain. Extensive greening must be carried out with site-specific plants, e.g. for certain mosses, and must include targeted control and promotion of surface colonization. This is the only way to achieve a visually appealing growth that is regularly and homogeneously distributed. At the same time it promotes the native flora and expands the niche offer for numerous animal species.



In addition to innovative design and implementation, a key to success also lies in selecting the right plants for the respective application and planning situation. For example, mosses with up to 30 times larger surface areas have a higher fine dust binding potential than many grasses.

Since further investigations are necessary, a new method is currently being developed to settle moss on building surfaces. First results are both promising and essential for future development steps. The condition of the test specimens in Figure 4 after winter weathering in the open shows that the moss was able to establish itself on the surfaces protected from driving rain. The used building material, on the other hand, has obviously been strongly affected by frost-thaw changes, which is why further investigations with different building materials are necessary in order to find an optimal correlation here.

Figure 4. Three-dimensional test specimens of 10 by 10 by 10 cm AAC block and planted with moss (two different shapes). Test specimens before (top) and after winter weathering (bottom).

4. Sound absorbing façades

The unchanged high attractiveness of cities also leads to increasing acoustic demands on urban systems and structures. With regard to the perception of sound in an urban context, the reflective behavior of façades is the main focus. In distinct street canyons, the hard building surfaces amplify all sound events, but of course the shielding effect of buildings is also perceived. Before functionally extending façades to influence acoustics, especially in noisy urban spaces, it is important to emphasize that this should never be at the expense of their function as sound-insulating building envelopes. In practice, there are still deficits and development needs. The acoustic functionalization of façades certainly cannot solve urban problems on its own. In order to take up the proof and the economic efficiency of acoustic façade functions for urban areas, a systematic consideration is the first step. The practically relevant acoustic categories can be summarized as follows:

- Sound generation / sound radiation: Today, façades emit considerable and above all completely expendable noises. Ventilation openings, movable sun protection systems or wind noises on acoustically sensitive façade elements are just a few examples of avoidable noise exposure.

- Sound screening / sound diffraction: These terms are essential for the already mentioned shielding effect of buildings in urban environments. There is the possibility of a targeted influence on the propagation of urban sound through structured façades, balconies, overhangs, roof connections and the like.
- Sound reflection / sound diffusion: Together with shielding and diffraction, they contribute to the amplification and distribution of sound. On the other hand, however, there is a great variety of elements, structures and urban design scope to consciously direct sound into less sensitive areas, even if it cannot be stopped or absorbed.
- Sound absorption: The actual reduction of sound energy once generated only is possible by absorption or dissipation of sound waves. Materials, layers and structures as well as openings and gaps offer numerous possibilities without having to invent a new façade. Almost all façade types can be functionally upgraded or converted to achieve high sound absorption levels.

A concrete example of a possible modification is the "rear-ventilated curtain façade". The system has been established for a long time and proven in practice, is characterized by a high degree of design diversity, is accepted by building owners and architects and is in itself unproblematic in terms of building physics functionality (moisture, heat and fire protection). However, the goal-oriented implementation in practice requires knowledge of the optimum relationship between flow resistance and other properties of the (outer) layers. Figure 5 schematically shows a façade structure with a sound-permeable (e.g. perforated) outer layer and its sound absorption if three different underlay sheets are used in front of the insulating material. The main difference is the flow resistance of the underlay variants, which certainly still meet the requirements of DIN EN ISO 13859 [16]. The sound absorption coefficients show the effect of clever modification of individual parameters. If typical inner-city noise spectra are used, highly absorbent noise protection façades can be achieved with variant 3 in Figure 5.

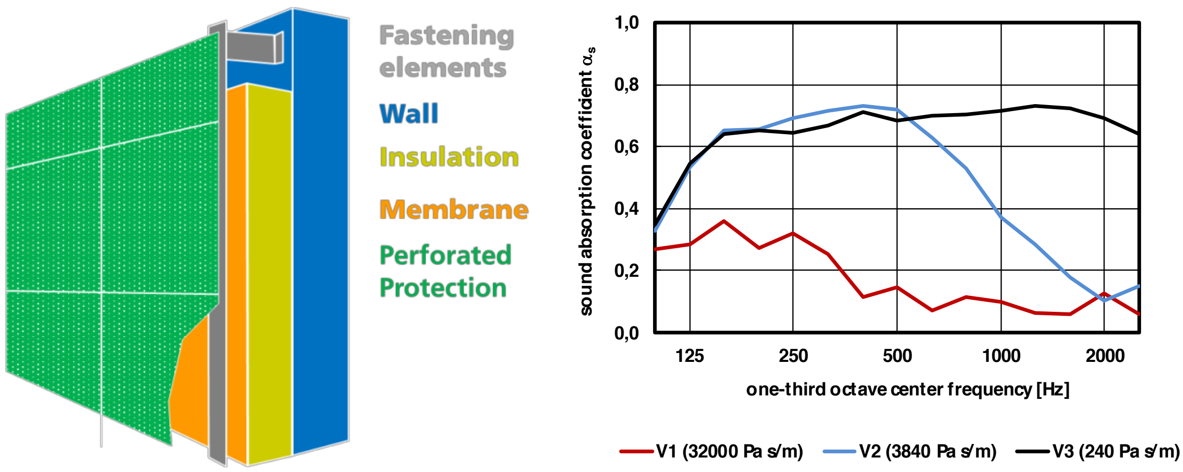


Figure 5. Acoustically modified, rear-ventilated curtain façade (left: schematic structure, right: measured sound absorption coefficient at vertical sound incidence and use of 3 underlays with very different flow resistances).

Based on this sound absorption effect, its impact on the urban environment can be calculated and evaluated. For the exemplary quantification of the potential, Figure 6 shows the building situation with buildings aligned parallel to the source (motorway, dark blue area on the bottom right), flanked by vertically positioned buildings and a side street. The standardized frequency-dependent calculations were carried out according to DIN ISO 9613-2 [17], the street (traffic figures) was characterized as a line source in octave bands with noise spectra from pass-by measurements. Geometry and topology are based on real, in detail simplified data and the façades were mathematically clad with sound-absorbing material. The results allow the comparison of weak absorption effect, e.g. a normal exterior plaster (Figure 6, left), and highly absorbing ($\alpha_w \geq 0,75$) material (Figure 6, right), as e.g. with the layer variant 3 according to Figure 5. The level differences are clearly recognizable and concern not only the individual points (figured level values), but considerable zones of the area.

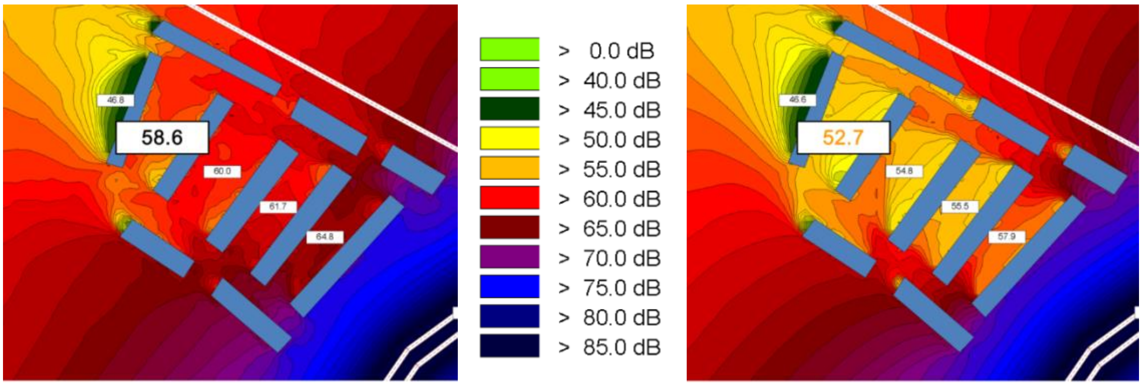


Figure 6. Sound immission calculation with low (left) and high (right) sound absorbing façades of the buildings. The single values in the maps are sound pressure levels (sum levels in dB(A)) at selected points.

Of course there are still some questions, e.g. after the comparison with noise barriers or after the additional costs. The answers will be differentiated and will lead to concrete advantages and disadvantages depending on the situation. With a view to the future, it is therefore important to recognize, evaluate and treat the acoustic environmental influences in almost all, including urban, living spaces.

5. Transparent enclosure systems

Every autumn thousands of fountains or stone sculptures are hidden, mostly under wooden enclosures, to protect them from the winter climatic conditions. However, this measure makes a large number of culturally valuable objects invisible for almost half the year. These temperature-damping opaque enclosures offer a comparatively constant indoor climate, but with a consistently high level of air and material humidity and without completely preventing frost-thaw changes, which contributes to the damage to the cultural assets. The solution of using transparent enclosures made of a steel and glass construction to ensure the visibility of the objects to be protected enhances the quality of the urban space. Nevertheless, on the one hand these constructions are associated with increased costs due to the choice of materials and the logistical effort involved, on the other hand the combination of glass housing and solar input creates a "greenhouse effect" which results in high fluctuations in temperature and humidity and puts considerable strain on the object to be protected [18], not to mention possible glass breakage.

Scientists from the Fraunhofer Institute for Building Physics IBP and the Technical University of Munich have therefore developed and investigated an enclosure system made of transparent membranes which, by damping the amplitudes of temperature and relative humidity, enables a climate favourable to the object to be protected [19]. Further goals of this system are, among other things, the avoidance of the essential damage mechanisms for stone objects, especially frost-thaw changes at high material moisture levels, thermohygric deconsolidation and organic growth as well as favourable assembly, transport and storage properties and sufficient durability. In addition, the design should pay attention to optimum regulation of the ventilation system. When the ventilation is too high, the external climate also becomes apparent in the interior and leads to moisture ingress and condensation on the stone, whereas too little air exchange can trigger a permanently high air humidity and consequently frost splitting and organism growth.

The transparent enclosure system under investigation consists of a framework with braced stainless steel profiles, into which a prefabricated polyvinyl chloride foil cover is suspended. This system is characterized by various advantages. On the one hand, it can be easily dismantled into its individual parts and reduced to a small storage volume, and on the other hand, the support frame has good durability. In addition, the film is easy to replace in the event of attrition and, among other things, offers high tear and UV resistance combined with "non-crease" transparency even after repeated construction and dismantling. In addition, the high moisture content of the material at the time of enclosure can be dissipated to the outside via heating due to solar radiation in conjunction with controlled air exchange, while moisture entry by re-condensation is prevented.

Figure 7. Newly developed foil enclosure in field test.

The results of the measurements carried out prove that with these systems a faster material drying is achieved than with previously used opaque wood enclosures. In addition, organic growth is largely avoided and the material to be protected is kept dry. The innovative transparent foil enclosures with controlled ventilation are an interesting alternative to the opaque wooden enclosures currently in use especially because they provide equally visibility and optimum weather protection of the fountains or stone sculptures that characterize the cityscape throughout the year.

6. Outlook

Although the challenges of urban systems are not equally distinct in all cities, the impact of elementary urban structures can be found everywhere. This also includes the chronic and acute consequences of climate change at the local level, such as water shortages or flooding, unusually hot and cold weather conditions, heat islands and haze bells. Urban surfaces will play a major role in the reaction and transformation of cities, and their building physics efficiency is significantly higher than it has been exploited yet. In the future, innovations and investments will be just as necessary as regulations, incentives and information. The aspects and examples presented show that the building physics of urban surfaces can make valuable contributions to this.

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Sustainability of innovative urban surfaces – a new approach of assessment

Henzler K, Horn R, Jäger M, Maier S D

Department for Life Cycle Engineering (GaBi), Institute for Acoustics and Building Physics, University of Stuttgart, Pfaffenwaldring 7, 70569 Stuttgart, Germany

KristinaHenzler@gmx.de

Abstract. The physical design of urban surfaces determines the management processes that are required to ensure that their intended functions are fulfilled within a set period of time and influences their linked material flows. Those flows are causing numerous environmental, economic, and social impacts. In the field of urban surfaces, there is a broad variety of innovations available that has the potential to contribute to a more sustainable environment and quality of life in cities. However, before implementing any kind of innovation, it is important to quantitatively and qualitatively assess its sustainability impacts in a holistic manner. While current assessment methods provide a suitable framework for the sustainability assessment of products and services, without modification, they cannot be applied to urban surfaces and related management processes.

The herein introduced methodological approach is designed to overcome this problem by not only being tailored to the sustainability assessment of innovations in the field of urban surfaces but also by combining life cycle thinking with a holistic approach. By integrating SDGs, it will provide insight into the possible impacts of an innovation in all three dimensions of sustainability at the municipal level. This knowledge can be used to support the municipality in its decision on the design of urban surfaces and management processes by showing whether or not it is advisable to implement an innovation from a sustainability point of view. The focus of this publication is on the development of a general life cycle of urban surfaces and its interaction with product innovations.

1. Introduction

Leistner et al. [1] highlight the importance of the design of urban surfaces for the environmental quality in cities and their resilience to climate change. They show that urban surfaces have a considerable building physical and sustainability related potential and that innovations are essential for realising it [1]. It is pointed out by Leistner et al. that by conducting a Life Cycle Assessment (LCA) on the various management processes of urban surfaces, it is possible to determine their sustainability and to identify potential starting points for the optimisation of the partly large quantity of material flows in cities [1]. By systematically assessing the sustainability of urban surfaces, another perspective is taken as usually complete sustainability assessments of cities overlook their potential. All three dimensions of sustainability are essential for sustainable development [2], and not only environmental but also economic and social impacts are expected from the implementation of the aforementioned product innovations. Current sustainability assessment methods cannot unmodified be used for the analysis of innovations in the field of urban surfaces, as, e.g., they do not allow the practitioner to take into account the comprehensive use phase of the urban surface and the interaction of the life cycle of the innovation and the surface. Therefore here, a holistic approach for the sustainability assessment of innovations in the field of urban surfaces is proposed, using life-cycle thinking and indicators in line with and based on the Sustainable Development Goals (SDGs). Thus, such a method can be used to support municipal decision-makers with regard to potential sustainability impacts before implementing innovations for urban surfaces. The SDGs are accepted as a basis for the development of sustainability assessment methods and are used on a municipal level, e.g., by Maier et al. [3] and Wang et al. [4].

2. State-of-the-art of sustainability assessment methods

Several existing methods have been analysed regarding their suitability for the assessment of innovations in the field of urban surfaces.

The LCA uses the concept of life-cycle thinking [5], however, attempts to apply this to urban surfaces have shown that it is not sufficient to take into account the multitude of processes that occur during the use phase of urban surfaces. This leads to an entanglement of different processes and therefore, life cycles. This requires a new approach, different from the establishment of one general life cycle. Besides, various requirements are placed on urban surfaces concurrently [1], yet they cannot be considered with the concept of the functional unit provided in the ISO-LCA. Moreover, different stakeholder perspectives can be taken when assessing innovations in the field of urban surfaces, as, e.g., in the case of costs: on the one hand, there is the municipal budget and on the other hand, the income of the workers. Besides, as the LCA only allows for an assessment of possible environmental impacts [6], it is inevitable to go beyond this concept for a holistic assessment. Therefore, indicators must also be selected and adapted to the system of the urban surface to be investigated.

The concept of Life Cycle Sustainability Assessment (LCSA) presented by Klöpffer [7] allows the three dimensions of sustainability to be taken into account by combining the methods of LCA, LCC, and SCLA [6]. However, for the social dimension, there is no scientific agreement on indicators [8]. Hence, here, the SDGs are used to select indicators for a holistic assessment. Moreover, the methods of LCA, LCC, and SCLA are developed to different degrees, which can cause difficulties in the application of this approach [8]. Wang et al. [4] have shown that rather than the LCSA as presented by Klöpffer [7], the Life Cycle Sustainability Analysis (LCSA) Framework (hereinafter: LCSA Framework), which is one of the results of the CALCAS project [9], provides a good foundation for the development of a holistic sustainability assessment method.

The LCSA Framework builds on the ISO 14040-standardised LCA, but goes beyond it in three dimensions of broadening and deepening, thus enabling the practitioner to conduct an assessment of impacts in the environmental, economic, and social dimension of sustainability [9]. However, it must be noted that it is not a guide [10]. Rather, it is described as "[. . .] *a transdisciplinary integration framework of models rather than a model in itself*" [9]. Consequently, it first needs to be made operational [9]. So far, the LCSA Framework has not been used for the evaluation of urban surfaces. Hence, the herein presented method adopts the fundamental structure of the LCSA Framework but relies on other methods and concepts in order to make it applicable to the case of urban surfaces.

The ex-ante sustainability assessment methodology for municipal solid waste management innovations developed by Wang et al. [4] provides a sound basis for the development of the new method. Its appealing features are the operationalisation of the LCSA Framework, the integration of the SDGs in the assessment, based on the approach by Maier et al. [3], and the sustainability assessment of innovations in a specific field before their implementation [4]. Thus the method of Wang et al. [4] plays a decisive role in the operationalisation of the LCSA Framework for innovations in the field of urban surfaces: its way of implementing the Framework and making it applicable to innovations serves as a basis for the design of the individual phases of the new approach. It needs to be modified to fit innovations in the field of urban surfaces and related management processes.

In conclusion, there is currently no method available that can directly be used for the sustainability assessment of innovations in the field of urban surfaces prior to their implementation. As has been shown above, not only the scope of application of existing methods but also the special features of urban surfaces, such as their extensive use phase, make it necessary to develop a new holistic methodological approach, which is tailored to the analysis of product innovations in this area. The method of Wang et al. [4] is used as a starting point for the development of the new approach. By this, the LCSA Framework is made operable for the assessment of urban surfaces. One of the main challenges in developing the new approach is the lack of application of life cycle thinking to the concept of urban surfaces. Thus, this newly developed framework serves as the underlying basis for the sustainability assessment of urban surfaces based on life cycle thinking and the SDGs.

3. Methodological Approach

The methodological approach for the sustainability assessment of urban surfaces is based on [3] and [4], depicted in figure 1. The adaptation of this framework allows the indirect assessment of SDGs across different impact category groups, including the selection and definition of appropriate SDG-based indicators. As the new methodological approach will allow a sustainability assessment of innovations in the field of urban surfaces, firstly the terms *urban surface* and *innovation* have to be defined in the context of sustainability assessments and life cycle thinking, and secondly, a general life cycle of urban surfaces must be developed. Thus the focus of this publication is on the introduction of a life cycle of urban surfaces and accordingly on the first stage of the methodology, the goal and scope definition. The generalised life cycle will make it possible to identify possible starting points for an innovation. Building on this first stage, a holistic sustainability assessment of an innovation can be conducted by proceeding with the phases of modelling and interpretation.

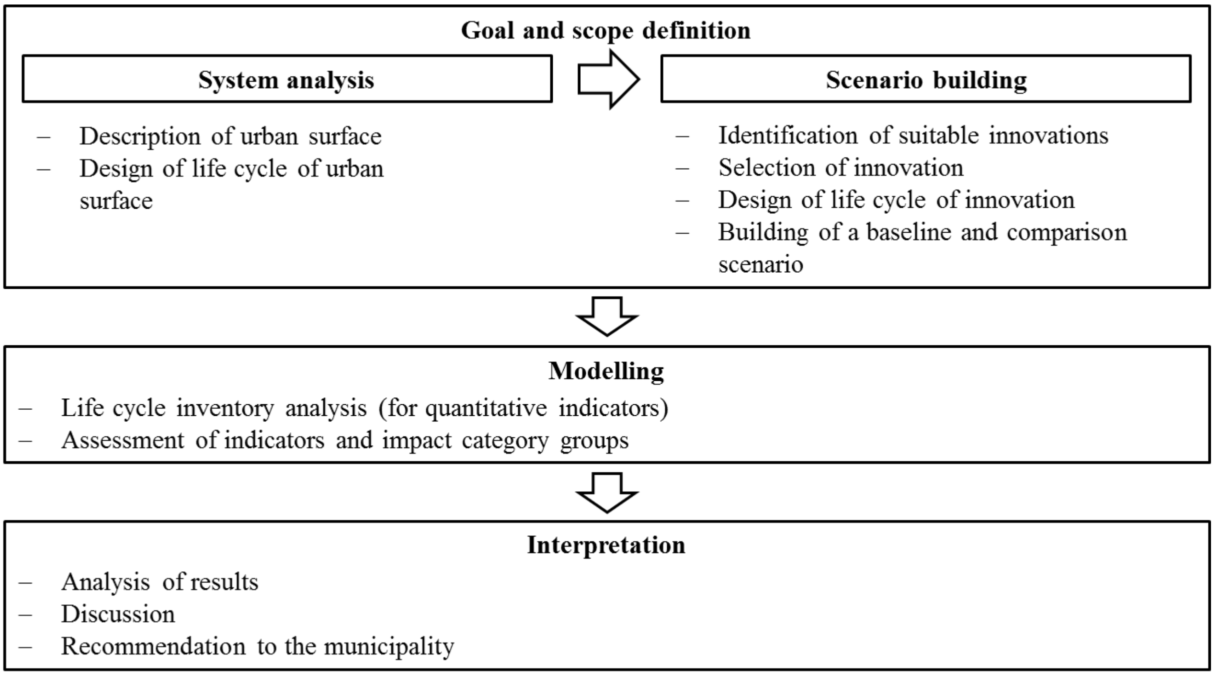

Figure 1. Sustainability assessment of innovations in the field of urban surfaces, based on [3] and [4].

3.1. System analysis

3.1.1. Urban surfaces, management processes and material flows. The term urban surfaces was coined by Leistner et al. [1]. This paper attempts to refine this concept by specifying the scope of its applicability and proposing a general categorisation of urban surfaces suitable for the herein proposed methodological approach for sustainability assessments of urban surfaces based on life cycle thinking.

Here urban surfaces are defined as surfaces that interact in public outdoor spaces within an urban context. Therefore areas such as public parks, streets, and facades are regarded as urban surfaces while indoor spaces and underground infrastructure, e.g., the municipal sewage system, are not included within this concept. A surface is considered as an urban surface as long as it keeps interacting in the same way as at the point under consideration, regardless of its geometrical dimension. As Leistner et al. [1] have shown, areas in cities are used for numerous purposes, amongst others, for buildings, traffic, and green spaces. Therefore urban surfaces are made of a variety of materials, such as concrete, grass, and cobblestone. Different requirements are placed on them, e.g., accessibility, usability, safety, and aesthetics [1]. Hence the combination of surface material, function, and requirements imposed on the surface by users or legal regulations is used here to differentiate between different types of urban surfaces. Figure 2 shows the combination of material, function, and requirements for the case of streets.

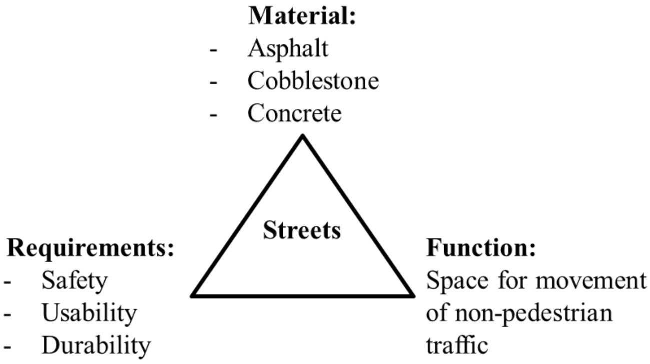

Figure 2. Triangular categorisation of streets.

From this, a categorization of urban surfaces is derived. For example, the categories of green spaces, building spaces (roofs/ facades), traffic areas, squares, and barriers are distinguished. Those can be further disaggregated into subcategories, e.g., in the case of green spaces into playgrounds, parks, and nature reserves or in the case of traffic areas into roads, cycleways, and footways. Thorough management is required in order to ensure that urban surfaces fulfil their functions within a set period. While the necessary management processes depend on the type of surface, it is common that most surfaces require several processes with varying frequencies during a year. The following is a brief, non-exhaustive overview of management processes in the field of urban surfaces. The maintenance of green spaces involves processes such as the removal of weed and foliage, watering, fertilising, and lawn mowing. Traffic areas require processes such as cleaning, winter service (gritting and snow clearance), and road marking works as well as repair, replacement, and modernisation processes. For other surfaces, e.g., barriers, repair and cleaning processes need to be performed. Derived from Leistner et al. [1], material flows that are applied to a surface during a management process, such as gritting salt, water, and fertiliser, are called input flows. Output flows are considered in this paper as a result of management processes and include, e.g., green waste and dust.

3.1.2. Life cycle of urban surfaces. As urban surfaces are considered as infrastructure, the building life cycle in DIN EN 15978 [11] is transferred to urban surfaces to design their life cycle. For this purpose, a building is considered as consisting of several urban surfaces. Consequently, the surface material is understood as equivalent to the construction product/ component in the standard DIN EN 15978 [11] and the surface as equivalent to a part of a building. The adapted life cycle does justice to the complex use phase of urban surfaces, in which, as is the case with buildings, several management processes for their maintenance, repair, and so on are carried out. It should be noted that for the assessment of urban surfaces a functional equivalent shall be formulated in accordance with DIN EN 15978 [11] in order to be able to take into account the fact that as aforementioned several requirements are placed on urban surfaces simultaneously, such as usability, safety, and aesthetics, and to ensure the comparability of the assessment results [1, 11]. It could be defined, e.g., as ‘Providing 1m^2 of footway for 1 year that meets its functional and technical requirements', with the reference unit [m^{2}a]. It reflects the previously introduced categorisation of urban surfaces based on their material, function, and requirements. Figure 3 shows, based on DIN EN 15978 [11], a proposal for the modules of the life cycle of a new urban surface, for which information should be provided to assess its sustainability. The four phases of its life cycle are briefly explained below.

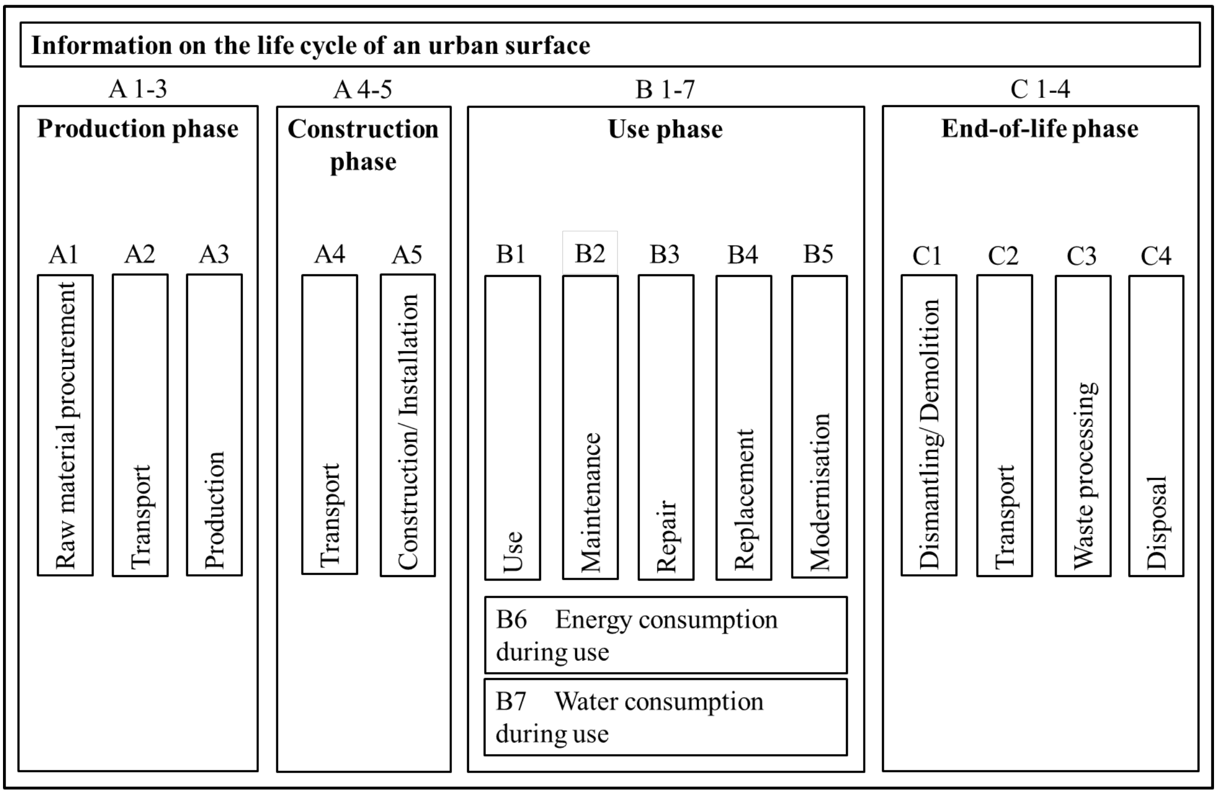

Figure 3. Information on the life cycle of an urban surface, based on DIN EN 15978 [11], technical terms adapted from [12].

A 1-5: Analogous to DIN EN 15978 [11], the processes leading to the installable surface product, e.g., wooden battens, should be taken into account in the production phase. The construction phase should contain processes for the surface materials from their production site to the completion of the construction of the surface, such as the transport of the wooden battens to the construction site and their installation [11].

B 1-7: Adapting the boundaries set in DIN EN 15978 [11], here the use phase comprises the time between the construction and the dismantling/ demolition of the urban surface. In module B1, it is taken into account that substances can be released into the environment during the use of the urban surface [11]. As previously pointed out, various management processes are performed in the use phase of an urban surface. These processes can be assigned to different modules within this phase. Following the standard DIN EN 15978 [11], the boundary of the module B2 should contain processes such as street cleaning, and lawn mowing. The repair processes necessary in the event of damage are considered in the module B3 [11]. While a replacement with the same surface material (even if it is undamaged) is taken into account in module B4, a replacement with another material should be considered in module B5 [11]. Analogous to DIN EN 15978 [11], energy and water flows that occur in the use phase of the surface, e.g., in the process cleaning, are assessed in the modules B6 and B7.

C 1-4: For buildings, the begin of their end-of-life phase is considered to have been reached as soon as they are getting decommissioned, and no further use is planned for them [11]. For urban surfaces, e.g., the end-of-life of a park which is being transformed into a residential area, the disposal of parts of a surface and waste such as lawn cuttings are considered in the modules C 1-4.

The four-phase structure that is suggested here for the life cycle of urban surfaces is, in principle, the same for different types of surfaces; however, their modules differ concerning the processes they contain. For this reason, the life cycle needs to be adapted to the surface to be assessed.

3.2 Scenario building

3.2.1. Innovations for urban surfaces. In order to optimise urban surfaces from a sustainability point of view, different types of innovations can be introduced in the city. This study relies on Rogers [13] to define an innovation as: "[. . .] *an idea, practice, or object that is perceived as new by an individual or other unit of adoption*". With regard to urban surfaces, the *idea, practice or object* is related to an innovation that has the potential to optimize urban surfaces and the *unit of adoption* refers to the municipality. Thus, based on the work done by Leistner et al. [1], in this publication we differentiate between three different types of innovations in the field of urban surfaces: a) innovative surface materials, e.g., sound-absorbing facades [1]. This type of innovation directly influences the material composition and structure of the urban surface itself; b) innovative machines/ technologies, such as gritting vehicles with a hybrid drive or battery-powered hedge trimmers. This type of innovation is related to the technology that is used to manage an urban surface; c) innovations regarding the management processes of urban surfaces, e.g., a new weed removal process. This type of innovation refers to an innovative way in which a particular management process is carried out. In any case, it is necessary to assess the potential sustainability impacts of an innovation before its implementation to facilitate an informed decision regarding its introduction [4]. In this paper, the focus is on the assessment of surface material innovations and innovative machines, both product innovations, since process innovations are not considered as tangible. The innovations are used for designing a comparison scenario which can be compared to a baseline scenario reflecting the state of the art of the urban surface and its management in the respective municipality [4]. The delta between the baseline scenario and the comparison scenario is calculated to assess the sustainability impact.

3.2.2. Life cycles of innovations. Depending on the type, the innovations intervene in different modules within the use phase of an urban surface. As in Maier et al. [3], the system boundary of the innovation is based on the concept of life cycle thinking in order to be able to consider the sustainability impacts along the entire life cycle of the innovation – this makes it possible to identify a shift of burden in all three dimensions of sustainability between the life cycle phases or processes and to take countermeasures prior to their implementation [5]. Therefore, the life cycle of a surface material innovation or innovative machine, both product innovations, should be designed after ISO 14040 [5]. For the life cycle of products and their innovative versions, respectively, a cradle-to-grave approach is chosen; consequently, impacts are assessed in the raw material and fuel acquisition, the production of precursors and the final product as well as in its use and end-of-life phases [6, 14].
An (innovative) machine is used in the respective management process of the urban surface, which in turn is performed in the use phase of the surface. For example, a common gritting vehicle and an innovative road sweeper would be used in module B2 (maintenance) of the urban surface. An innovative surface material, such as easy-to-clean cladding, would be installed in module B5 (modernisation) of the surface. As a result, the life cycle of a product and product innovation, respectively, and the life cycle of the urban surface interact. This finding is illustrated in a greatly simplified manner in figure 4. This relation reminds of the interactive life cycles introduced by Labuschagne and Brent [15]. Figure 4 shows that in the use phase of an urban surface, in addition to modernisation processes, such as process 2, also several other management processes, for example, the maintenance processes 1 and 3, are carried out, in which different products or product innovations can be used.

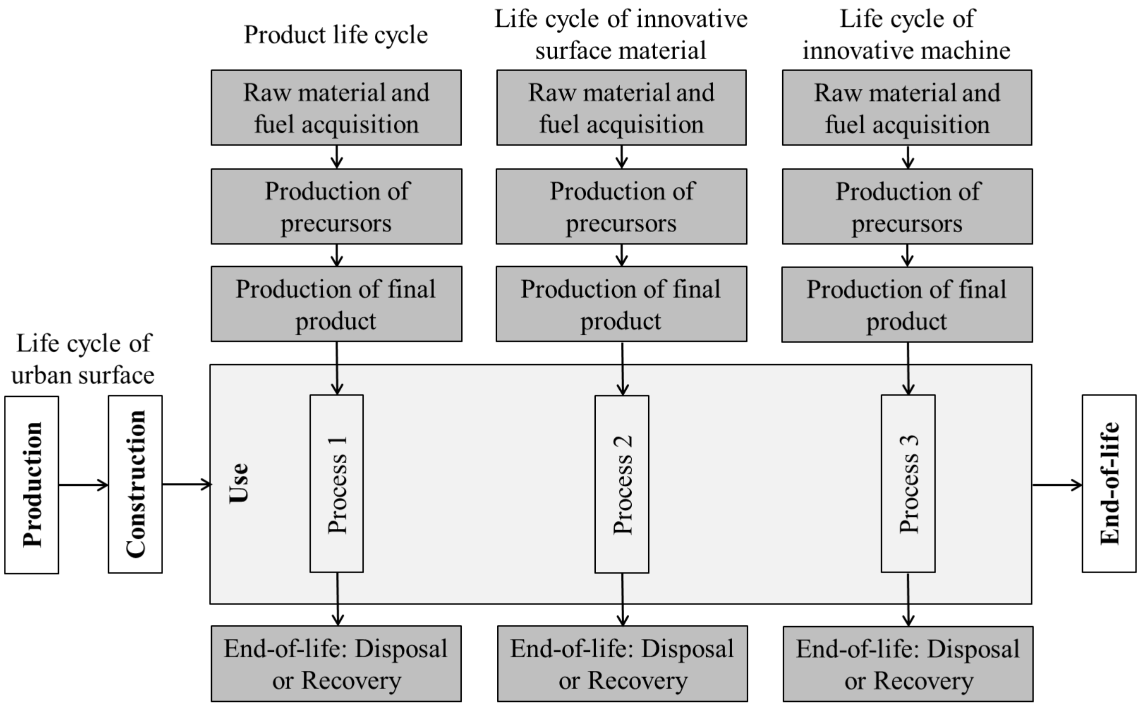

Figure 4. Exemplary illustration of the interaction between the life cycle of an urban surface and the life cycles of products and product innovations, respectively.

Based on the approach of Wang et al. [4], this exemplary, simplified scheme should be modified and tailored to the urban surface, its management processes and innovation in question to model a baseline and comparison scenario for the ex-ante sustainability assessment. In the modelling phase, it should be taken into account that, e.g., a surface material innovation can not only impact on the management process and material or energy flows it is aimed at, but also on linked processes and flows. Consequently, in addition to the other life cycle stages, all management processes and flows occurring in the use phase must be included in the sustainability assessment to grasp the full impact of the innovation. It should be noted that this methodology is designed for the assessment of innovations that optimise existing functions, but not, e.g., innovations that change functions of an urban surface.

4. Application

This section gives an example of the application of the sustainability assessment framework and the life cycles shown in figures 3 and 4 to a highway. It also makes clear how the SDGs are integrated into the assessment. In the first step of the goal and scope definition, the road is characterised, following figure 2. The highway is made of concrete and serves as a space for movement of non-pedestrian traffic. It needs to meet requirements such as safety, usability, and durability. Based on this information, it is possible to design the life cycle of the highway in question. Following figure 3, the phases of production and construction contain processes concerning the provision of concrete and the building of the road. In the use phase, maintenance processes such as winter service (gritting and snow clearance), road cleaning and repair processes are carried out (non-exhaustive list). In the end-of-life phase, besides the demolition of the highway itself, the processing and final disposal or recovery of the demolition waste and output flows, e.g., sweepings and dust, need to be included. In the scenario building, suitable innovations are identified and selected for the assessment. An innovative snow plough was chosen to improve the sustainability of the process of *snow clearance*. The life cycle of the innovation is built using the life cycle thinking in ISO 14040. Then the interacting life cycles of the highway and the currently used and innovative snow plough, respectively, are designed.

Figure 5 illustrates for the case of the innovative snow plough the embedding of the introduced life cycle scheme in an LCSA Framework operationalising assessment system and the integration of the SDGs into the latter. Thus it is possible to conduct a holistic sustainability assessment of the innovative snow plough. To make the assessment system easier to follow, the life cycle of the highway is not fully depicted in this figure. Looking at figure 5, it is essential that the practitioner analyses the sustainability impacts of the highway's use phase with (comparison scenario) and without (baseline scenario) the application of the innovation and additionally the entire life cycle of both ploughs. In this way, it can be determined if the potential advantages of the innovation regarding the sustainability impacts of the road's use phase outweigh the impacts linked to the innovation's provision. As shown in figure 5, the herein presented assessment system is built on the SDG-integrating approaches by Maier et al. [3] and Wang et al. [4]. Their SDG-based indicator systems are adapted to the assessment of innovations in the field of urban surfaces because as Maier et al. [3] point out, it is crucial that the indicators fit the innovation under question. Hence impact category groups from the indicator systems of Maier et al. and Wang et al. that are thematically uniting the SDGs, e.g., *poverty*, *climate* and *health and safety*, as well as suitable indicators are used to assess the potential impacts of an innovation in the three dimensions of sustainability [3, 4]. Amongst the criteria guiding the selection process of the indicators is their ability to assess likely impacts caused by innovations in the field of urban surfaces.

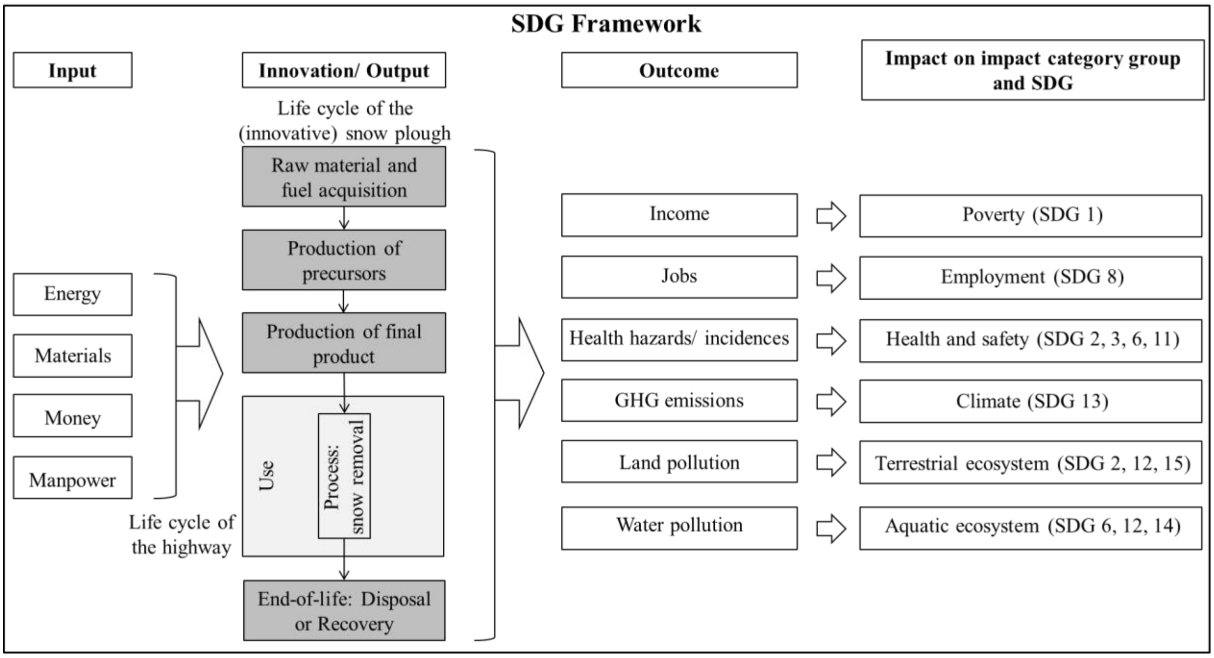

Figure 5. Embedding of the life cycle of the (innovative) snow plough in the SDG-integrating sustainability assessment system, adapted from Maier [16].

5. Discussion and conclusions

The herein introduced generalised life cycle of urban surfaces and its proposed interaction with the life cycles of product innovations provide a good starting point for a life-cycle based sustainability assessment of innovations in the field of urban surfaces. However, there is still a need to extend the proposed life cycles to make it possible to assess process innovations and to consider potential interdependencies between different management processes. Furthermore, while the methodology can be used for the assessment of innovations that optimise existing functions, it needs to be further developed so that it can be used, e.g., for the evaluation of innovations that change the functions of an urban surface, such as multifunctional materials. The next steps are to select and adapt indicators from the SDG framework to the urban surface system and to illustrate the practical applicability of the newly developed methodology by applying it to a case study concerning a specific innovation.

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conceptualization, K.H.; methodology, K.H.; validation, K.H.; formal analysis, K.H.; investigation, K.H.; writing—original draft preparation, K.H.; writing—review and editing, K.H., R.H., S.M.; visualization, K.H.; supervision, R.H., S.M.; project administration, S.M., M.J.; funding acquisition, R.H., S.M., M.J.

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Land resource management of coastal areas in Indian cities: comparative assessment with prevailing methods

Dhiman R[1], Kalbar P[1, 2], Inamdar A[2, 3]

[1]Centre for Urban Science and Engineering,
Indian Institute of Technology Bombay, Powai, Mumbai, 400076 – India
[2]Interdisciplinary Program in Climate Studies,
Indian Institute of Technology Bombay, Powai, Mumbai, 400076 – India
[3]Centre of Studies in Resources Engineering,
Indian Institute of Technology Bombay, Powai, Mumbai, 400076 – India

rdhiman@iitb.ac.in

Abstract. Indian coastal cities, enriched with a variety of marine resources, are a major driver of economic growth where the Indian coast provides shelter to a large part (~49%) of the total population in India. Proper planning of coastal resources is crucial for sustainable development, which can be achieved through advanced planning methods. Current methods for the planning of coastal landscapes in Indian coastal cities are ineffective in sustainable utilization of coastal resources and need improvements. This paper evaluates the application of the new planning method for classification of coastal landscapes in Mumbai city. The new method incorporates geospatial technology and multicriteria decision-making approach. The existing method of coastal area classification is based on Coastal Regulation Zone (CRZ) notifications by the central government, which has ambiguities in implementation. In the new method, coastal areas of Mumbai city are classified based on the physical eligibility of the coast for management of coastal resources and spatially compared with prevailing unscientific classification of coastal areas. The most dense urban area is considered for quantitative comparison of prevailing and new classification approach. Results of coastal area classifications by both methods disclosed the significant differences among different classes of coastal land. The results are validated with field visits and ground truthing along the coast of Mumbai. The findings of this study will enable the stakeholders to utilize available coastal land resources in an efficient manner for developmental and conservational activities at regional and neighborhood scale.

1. Introduction

Coastal areas are recognized as vital support to the regional and global economy around the world. Researchers are emphasizing the challenges of coastal resource planning at present due to the continuous increase in anthropogenic pressure along the global coastline [1]. Dynamics of geomorphological, climatic, and socioeconomic changes are altering the coastal system at spatial and temporal scale resulting in degradation of ecosystem services, biodiversity, and infrastructure [2]. Similarly, the Indian coast is also exposed to natural hazards like tsunamis, cyclones, extreme rainfall, coastal flooding and pressure of allied developmental activities along 7200 km of shoreline [3]. Indian coastal zone is managed to control the physical and socioeconomic vulnerability with the help of coastal regulations at the central and state level. According to Coastal Regulation Zone (CRZ) notification, eco-sensitive areas are classified into four different categories, but the distinction of these categories is based on the coastal boundary of different distances (500 m or 100 m) from the High Tide Line (HTL) towards the landward side. The CRZ notification is a strategic planning method of integrated coastal governance but unable to deliver the expected because of subjectivity and ambiguity at both fundamental and implementation level [4]. Current CRZ method is inconsistent and empirical, which does not consider the physical eligibility of different coastal features at spatial and temporal scale. Coastal planning and management is a challenge for other developing countries as well due to similar unclear policies like CRZ in India [5]. CRZ method of coastal land classification tries to deliver sustainable coastal governance for land management with limited capability. However, this CRZ method has been ineffective and failed in the past to achieve the aim of integrated coastal management at the Indian coast [6,7]. Therefore, an objective based robust classification approach for coastal areas is required to improve the coastal planning in India. It is essential to have a robust solution to address the conflicting interests of associated stakeholders during coastal land classification.

In this study, we demonstrated the application of Coastal Area Index (CAI) method, which is quantitative and capable of addressing the current challenges in existing CRZ method [8]. CAI method is applied to the coastal area of Mumbai city in India. Furthermore, a comparative assessment of the spatial extent of different categories classified by the existing CRZ method with the CAI method is carried out. Feasibility and advancement of the CAI method over CRZ method are validated by field visits and ground truthing at the selected location.

2. Methods

This study presents the application of a newly established quantitative method (CAI) for the classification of coastal land, which is based on geospatial science and multicriteria decision-making approach. We selected the coastal stretch of Mumbai city for classification into different categories based on the CAI method. Mumbai city in India is a coastal megacity of regional and global importance, located at the west coast of India and the unique dynamic coastal environment of the city represent all important geomorphological features [9]. Mumbai, an Island city, is surrounded by the Arabian Sea along the west coast and a large Thane creek in the east representing a large natural mangrove cover and associated biodiversity. Additionally, key reason for selecting this study area is the availability of signatures of ecosystem degradation related to coastal pollution, coastal flooding, the significant increase in urban development along the coast and violation of current existing CRZ method [10,11].

This study uses primary remote sensing data for quantification of physical coastal features. Important geomorphological variables representing physical coastal features are pre-processed and converted into raster format at 30m pixel level, as shown in Table 1. Land Use Land Cover (LULC), Digital Elevation Model (DEM), Normalized Difference Vegetation Index (NDVI) and coastal slope (%) are processed and classified using remote sensing data whereas soil and geology types are processed based on secondary data from central agencies namely Survey of India (SOI) and Geological Survey of India (GSI) respectively. CRZ areas are digitized using digital vector maps sourced from the State Coastal Zone Management Authority (SCZMA).

2.1. Comparative assessment of CRZ and CAI method

CAI method is developed by coupling GIS and multicriteria decision-making techniques; these techniques are well recognized and accepted in literature for land classification and policy-oriented conflict resolution among decision makers [12]. According to the CAI method, subclasses of physical coastal features are converted into utility functions based on the relative importance of particular feature towards environmental sensitivity followed by overall weight assignment to an individual layer of a coastal feature. Linear weighted sum method is used to generate the CAI by multiplying the layer weights with the respective utility value of the particular feature. Final CAI is obtained on a scale of 0-10 and classified in three distinct categories representing low, moderate, and high sensitive areas for developmental activities. CRZ classes are also demarcated according to the digital maps and converted into vector graphics in GIS tool for quantitative comparison with the areal extent of classes derived by

CAI as shown in Figure 1.This selected area is a predominantly urban area having inhabitants and commercial activities in 90% of the total area.

Table 1. Description of data types and processing.

Data layer	Source	Sub-classes
Land Use Land Cover	LANDSAT 8 (30 m)	built-up and fellow land, saltpans, vegetation, cropland, mudflats, marshes, mangroves, water bodies
Coastal slope (%)	SRTM (30 m)	< 25, 25-50, 50-75, <75
Elevation (m)	SRTM (30 m)	<1, 1-5, 5-10, >10
NDVI	LANDSAT 8 (30 m)	water, barren land, sparse and dense vegetation
Geology	GSI	rhyolite, trachyte, AA and compound flows, intertrappean, alluvium, agglomerates tuff, mud
Soil	SOI	backfilled, fine, clay, mud
CRZ classes	SCZMA	CRZ I, CRZ II, CRZ III

2.2. Validation method

Field visits are conducted at the selected site for validation of different classes by CAI and CRZ method. For this, a small area of 0.2 km^2 at the mouth of Mahim Bay, Mumbai is selected by considering the physical access to the site. This area is visited personally during clear weather. Visual observations are documented, and geotagged pictures are captured for meaningful interpretations.

3. Results

The coastal area along the coast of Mumbai city is classified and compared using CAI and CRZ approach to identify the better and more appropriate land classification method as presented in Figure 1.

3.1. Validation

Selected location near Mahim Bay in Mumbai is considered and visited for field validation, as shown in Figure 2. The visited area is demarcated with a white box in Figure 2, and satellite imagery of a particular area is shown. In Figure 2, the CAI classifies this area as low to moderately sensitive, whereas presently, this area is in CRZ II. This area is fully urbanized, and validation exercise shows the agreement between both methods. We observed the open defecation and solid waste pollution activities along the HTL which need immediate interventions from governing authorities.

3.2. Spatial extent comparison of classified areas by CRZ and CAI approach

Field visits combined with CAI and CRZ classification presented the effectiveness of CAI method for coastal land classification. Comparative results of the spatial extent of different classes are presented in Table 2.

Table 2. Spatial extent comparison of classes in CRZ and CAI for the selected site.

Classes	CRZ Area		CAI Area	
	km^2	(%)	km^2	(%)
I	1.6	7.8	0.9	4.6
II	18.5	92.0	8.1	40.1
III	0	0	11.1	55.3
Total	20.1	100	20.1	100

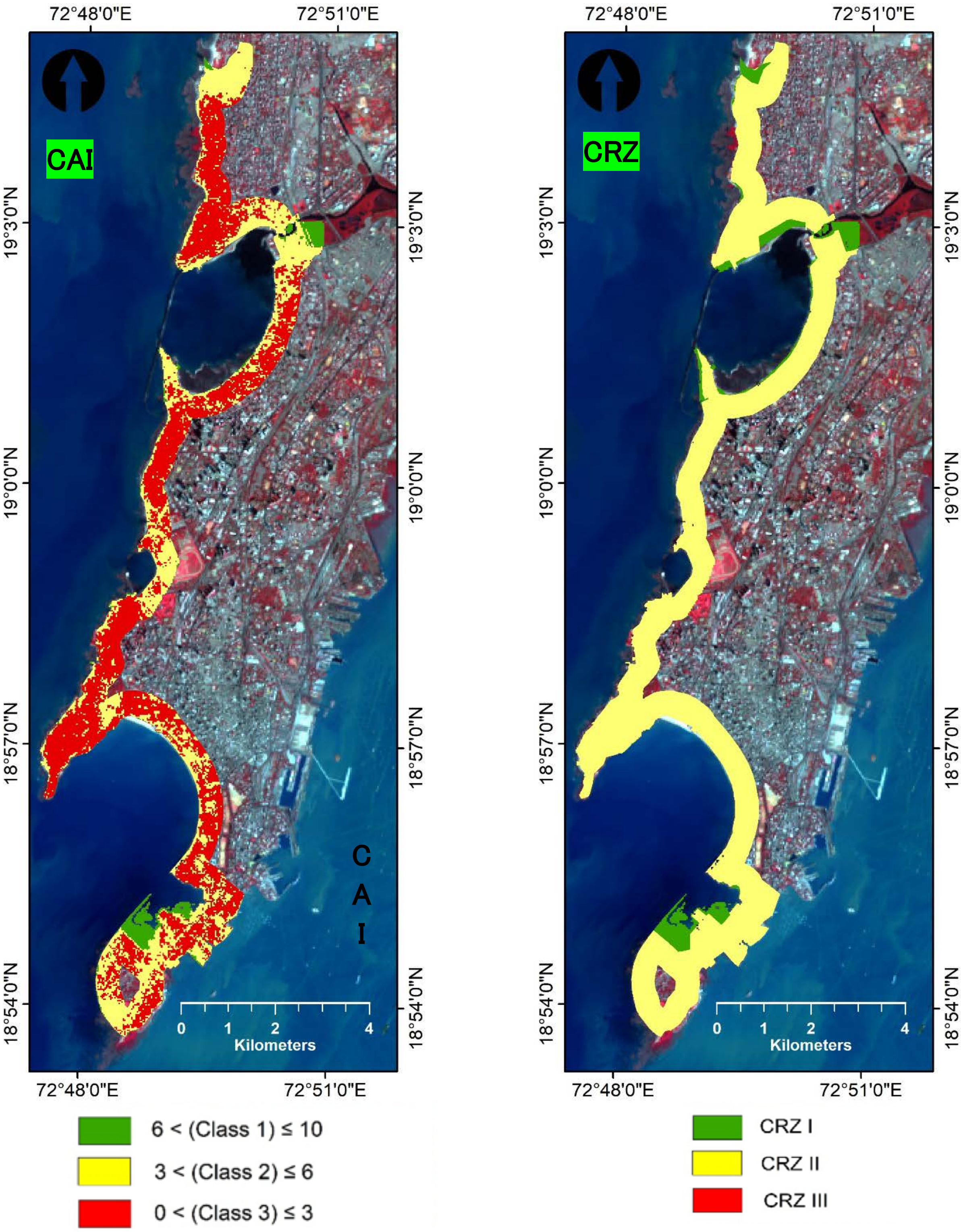

Figure 1. CAI and CRZ classification at the coast of Mumbai city for quantitative comparison.

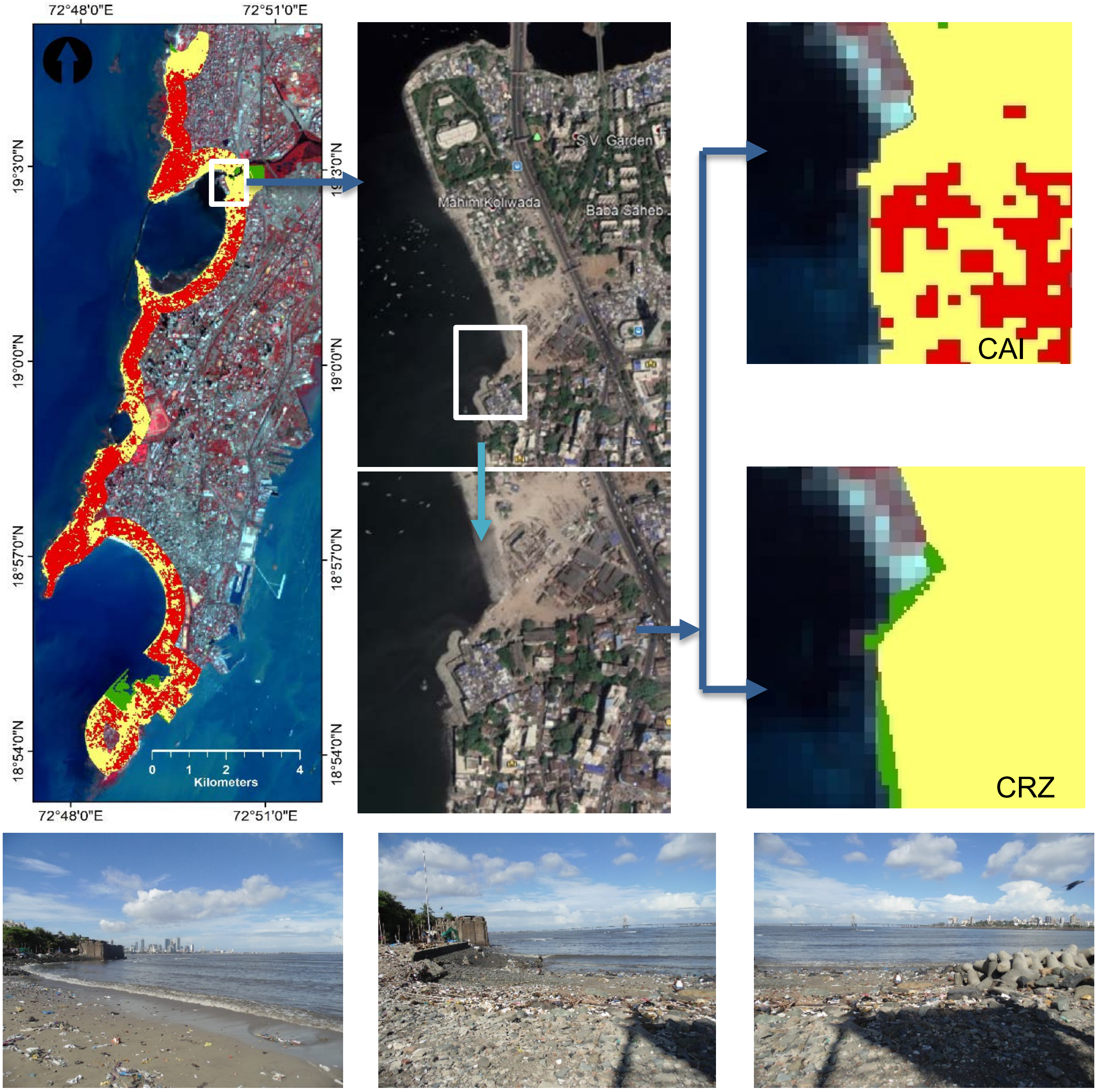

Figure 2. Validation of CAI based on ground-truthing at three selected sites along the Mumbai coast.

CAI method classifies 3.4% less coastal land in highly sensitive class compared to CRZ method as given in Table 2. The spatial extent in class two, which is moderately sensitive according to CRZ method is 52% more compared with the CAI method. Class 3, which is less sensitive in CAI, is measured 55% higher compared with CRZ. Comparison of CRZ and CAI extent shows that around 90% area is classified in a similar category of less to moderately sensitive, and the results of both methods are aligned with each other.

Results of the comparative assessment show the ability of the CAI method to classify coastal areas quantitatively at the pixel level by incorporating the physical characteristics, whereas CRZ method demarcates the fixed boundary at any given geographical location. CAI is a more robust decision-making method for coastal land classification, and the potential of this method for integrated coastal management in coastal urban areas is demonstrated in this study. Suitable applicability of CAI method will synergize the coastal protection and development by addressing the limits of current prevailing CRZ method.

4. Conclusion

The current method of coastal land classification needs to be replaced by a coherent solution to achieve effective planning of built environment from available coastal land resources. Demonstrated method of CAI is quantitative and suitable for land classification in coastal cities. Proposed CAI approach is efficient, robust, and easy to implement at a city scale. The classification differences of the spatial extent by CAI and CRZ method might be useful for coastal managers and researchers as the potential areas for development, built environment and environmental management are evaluated. CAI method allows the land classification at a precise scale in a transparent manner and addresses the subjectivity of existing CRZ method.

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Turning the existing building stock into a resource mine: proposal for a new method to develop building stock models

Lismont A, Allacker K

KU Leuven, Faculty of Engineering Science, Department of Architecture, Kasteelpark Arenberg 1 – box 2431, 3001 Leuven, Belgium

karen.allacker@kuleuven.be

Abstract. The construction sector is facing an important challenge to reduce its resource consumption. A promising strategy is to reduce the need of virgin resources by using the existing building stock as a resource mine. Various insights are needed to enable this. It should be clear how many materials are in the stock, when these will become available and to what extent these can be reclaimed in an environmentally and economically viable way. For this purpose a spatio-temporal building stock model is being developed and tested on the city of Leuven, Belgium. In a next step it will be assessed how these flows can be reclaimed in an environmentally and economically viable way. This paper provides a review on the methods used for building stock modelling and proposes improvements on the bottom-up archetypes scaling method. Building parameters relevant to material reuse and are introduced and a new methodology for upscaling is presented, using two data analysis techniques: a clustering algorithm and an artificial neural network.

1. Introduction

The construction industry is responsible for over 40% of the total European energy and resource use [1] and 25-30% of all generated waste [2]. The European Commission (EC) has therefore labelled construction and demolition waste (C&DW) a priority waste stream [3] and put a directive into place to increase its reuse and recycling [4]. Waste management is also one of the areas in its EU Action Plan for the Circular Economy [5]. In Belgium, there already is an effective C&DW recycling scheme, keeping over 90% off landfills [6, 7]. This however mainly consists of energy intensive recycling processes such as melting of metals and grinding of mineral waste (e.g. bricks, concrete, ceramics) into aggregates. The latter is especially wasteful as it degrades high-grade materials into low-grade variants [8]. According to the NGO Rotor DC, reuse of deconstructed building components is limited to about 1% of all material. Deconstruction (rather than demolition) is a logistically, economically and legally complex process [9, 10] and hence only a few companies offer this service. To scale the current initiatives from the small markets to a more significant part of the construction industry in a sustainable way, knowledge about the material flows resulting from deconstruction and refurbishment is needed. This requires insights in the material composition of the existing building stock, the demolition and refurbishment activities and related material flows and the environmental benefits related to potential recycling or reuse paths. This is a complex topic with highly disaggregated data that need to be connected to identify opportunities for a circular economy. Insights in the current state of the art regarding the main methodological aspects (environmental modelling of the building stock, urban mining and geographical data analysis) are elaborated in the subsequent section. Based on these insights a new modelling approach is presented in section 3. In a final section conclusions are drawn and the further outlook is described.

2. Building stock modelling - state of the art

2.1. Building stock modelling and urban environmental impact

Two main approaches can be distinguished in the field of building stock modelling: top-down and bottom-up approaches. Top-down approaches, such as input/output modelling and urban metabolism studies [11, 12] allow to gain global insight in the systems at work, but are unable to uncover the mechanisms of its subsystems (essentially keeping the city as a "black box") [13]. Bottom-up approaches [13, 14, 15] subdivide a city in its various components which are assessed separately and then aggregated to obtain the full picture. In literature, two bottom-up approaches can be identified to assess building stocks: the archetypes approach and the building-by-building approach [14]. The former makes use of a limited set of archetypes, each representing a subset of the building stock. This trades off the benefits of a detailed analysis of these archetypes for a simplified depiction of the heterogeneous stock. The building-by-building approach models each building individually, but usually means a lower level of detail and a lower scale level (i.e. neighbourhoods) because of practical limitations.

Geographical Information Systems (GIS) provide additional insights by making the data spatially explicit. GIS allows to assess local opportunities and impacts [13, 16] and to refine the bottom-up model through a more accurate inventory of the characteristics of all buildings [14, 17].

Where earlier studies on urban systems were limited in scope (limited to material flow analysis, or greenhouse gas (GHG) emissions), more recent studies have adopted a more holistic approach using life cycle assessment (LCA) [11, 12]. The LCA method allows to account for a wide range of environmental impacts (including GHGs, human toxicity and land use) and considers all life cycle stages (production, use and end-of-life), thereby avoiding burden shifting [18].

2.2. Materiality of building stock / urban mining

As resources are becoming more scarce and environmental burdens from the production of construction materials are increasing, attention is turning towards the existing building stock as a resource mine [19, 20]. Insight in the materials available in the building stock and the related environmental implications have become important. Mastrucci et al. [21] attempted to assess the resources in an urban area through a GIS-enhanced archetype model, derived from the European TABULA project on building typologies [22]. An LCA was made for the end-of-life stage, comparing current construction waste treatment with a higher recycling fraction for concrete. The study did not include an assessment of upscaled recycling opportunities. Other studies focussed on dynamic life cycle inventory (LCI) in LCA and on temporal changes in the building stock, identifying the release of materials and volume of recycling from building demolition [23], but without considering waste flows from refurbishments and without assessing environmental impacts.

The approach is also used to assess changes in the stock due to maintenance and refurbishments [24], or due to shifts in energy supply or climate change [25]. The ongoing BBSM project includes a limited material flow model for Brussels as part of their research in urban mining, taking into account three renovation scenarios [26]. More detailed studies on the environmental impact of demolition practice and recycling potential are available at the building level [8] without providing insights in urban stocks. Innovative recovery methods for C&DW were for example investigated in HISER and an integrated approach to a circular building sector was strived for in BAMB [27, 28]. A holistic building stock model incorporating circular principles should include these developing techniques.

2.3. Data analysis in GIS

The amount and complexity of building stock and GIS data require sophisticated techniques for data analysis [29]. In that regard cluster analysis, a type of data mining, has been successfully applied to partition and analyse a heterogeneous building stock regarding its energetic characteristics [30]. While data mining is used to uncover existing patterns from data, machine learning, which is a branch of artificial intelligence (AI) and a different method of data analysis, goes beyond this and can be used to build predictive models. Applications relevant for urban mining are still scarce, but the method has recently been applied to predict the energy performance of a building stock [31]. This study used artificial neural networks (ANN), a popular method of machine learning. The benefits of this non-parametric approach over statistical prediction models (e.g. as used by Mastrucci et al. for energy use predictions [32]) are a better representation of complex relations, the ability of the model to self-correct when more data becomes available and a lower sensitivity to researcher-induced bias by pre-programmed rules [29].

3. New spatio-temporal building stock model for Leuven

3.1. Goal of the new building stock model

The aim of the spatio-temporal model of the building stock is to gain insight in which building materials can be reclaimed at what time and how this is possible in an environmentally sound way. This model should hence allow to predict future material flows and anticipate on resulting opportunities and challenges concerning their reuse and impacts. As the model should allow to simultaneously assess material flows coming from the existing stock and material needs for refurbishments and new buildings, the model should go beyond identifying quantities of flows and facilitate a high-level recovery of materials. In order to achieve this goal a bottom-up model is proposed, validated by top-down data and combined with LCA for the environmental assessment. This is further described in the subsequent section.

3.2. Case Study

The method is developed using the city of Leuven (BE) as case study. Leuven has become an internationally recognised frontrunner in the sustainability debate and in this context, various data have been collected during the past decade which are valuable inputs for this research. Moreover, the mobilisation of citizens and enterprises alongside research institutions in Leuven 2030 shows potential for the aggregation of more data and application of the study results. The datasets that will be integrated for the research are listed in Table 1, but might be further extended with additional data sources during the research.

Table 1. Available data for Leuven

Dataset	Content
3D GRB[a]	GIS-data for the Flemish Region: location, footprint, height
DHMV II[b]	Heightmap for the Flemish Region with a resolution of 1m
Energy use[c]	Energy use for the Flemish Region (on street level)
Energy Performance database[d]	Renovation permits for the Flemish Region (anonymized)
Municipal GIS-database[e]	GIS-data for Leuven: typology, floors, function, roof type

[a] https://download.vlaanderen.be/Producten/Detail?id=971&title=3D_GRB
[b] https://download.vlaanderen.be/Producten/Detail?id=966&title=Standaardproducten_Digitaal_Hoogtemodel_Vlaanderen_II
[c] https://lokaal-bestuur.fluvius.be/nl/thema/nutsvoorzieningen/open-data
[d] received directly from the Flemish Energy Agency
[e] received directly from the city administration

3.3. Categorization of buildings
To model the building stock, a set of representative buildings for both the existing stock and new buildings has been defined. In a next stepan inventory of the quantity of (reusable) materials will be made for each of these representative buildings.

3.3.1. Selection of representative building types for the stock. The various representative buildings had to cover variations in construction period, as this influences the materials used, and variations in building types, as this influences the amount of materials in a building. A literature review on archetypes of buildings identified two useful studies: the TABULA project [22] and the SuFiQuaD project [33] which provided a good basis for the characterization of the building stock. Both studies defined archetypes for the Belgian context, categorizing the stock by construction period and building typology. The archetypes have been described in detail with the aim of assessing energy use (TABULA) or environmental impact and renovation strategies (SuFiQuaD).

To define the set of representative buildings, a statistical analysis of the building stock in Leuven was made. This analysis supported the use of the five construction periods (before 1945, 1945-1970, 1971-1990, 1991-2005 and after 2005) and four main typologies (terraced, detached, semi-detached, multi-family buildings) used by both earlier mentioned studies. The results of the statistical analysis are presented in Figure 1. The four main typologies represent a more or less even share of the housing stock. The figure reveals that while terraced houses were historically more popular, this has shifted to detached houses and multi-family dwellings. For the aim of our research, the roof type of the stock was analysed to investigate if a further division of the archetypes distinguishing roof types is needed. The analysis of the data shows that the amount of flat-roofed buildings is negligible, unless for the most recent time period and the multi-family dwellings as a whole. Accounting for these, the set of archetypes has been expanded from 20 to 28 archetypes.

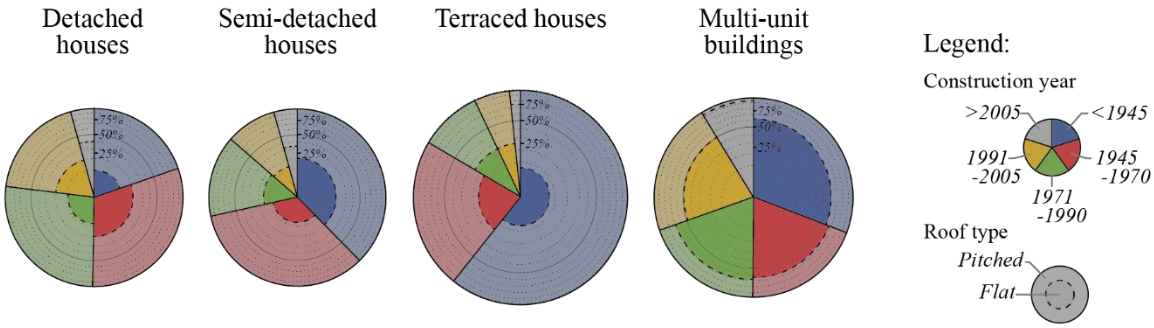

Figure 1. Categorisation of building stock in Leuven (chart sizes are weighted by total floor area)

3.3.2. Material inventory of selected types. To assess which of the materials in the archetypes can be reused, parameters are defined that determine the reusability [34], the environmental impact and economic value of materials based on a literature study and expertise of the authors. Examples of parameters are the material age, fixation method, location in the building (accessibility), embodied environmental impact and remaining technical service life. These parameters will be applied to the material inventory of each of the archetypes to determine the amount of reusable materials.

3.4. Clustering algorithm
In parallel to the manual categorization under paragraph 3.3.1, a clustering algorithm has been applied to attempt the same. A k-means clustering has been selected, where four parameters are considered: construction year, total floor area, share of exposed façades and share of pitched roofs. The algorithm defines a set amount of “k” clusters of buildings based on their similarity, as determined in the four-dimensional space defined by the considered parameters. It results in clusters of a relatively equal internal variance, which makes it a good fit for the data extrapolation. The results are shown in figure 2 and accompanied by a semantic interpretation of these results in table 2.

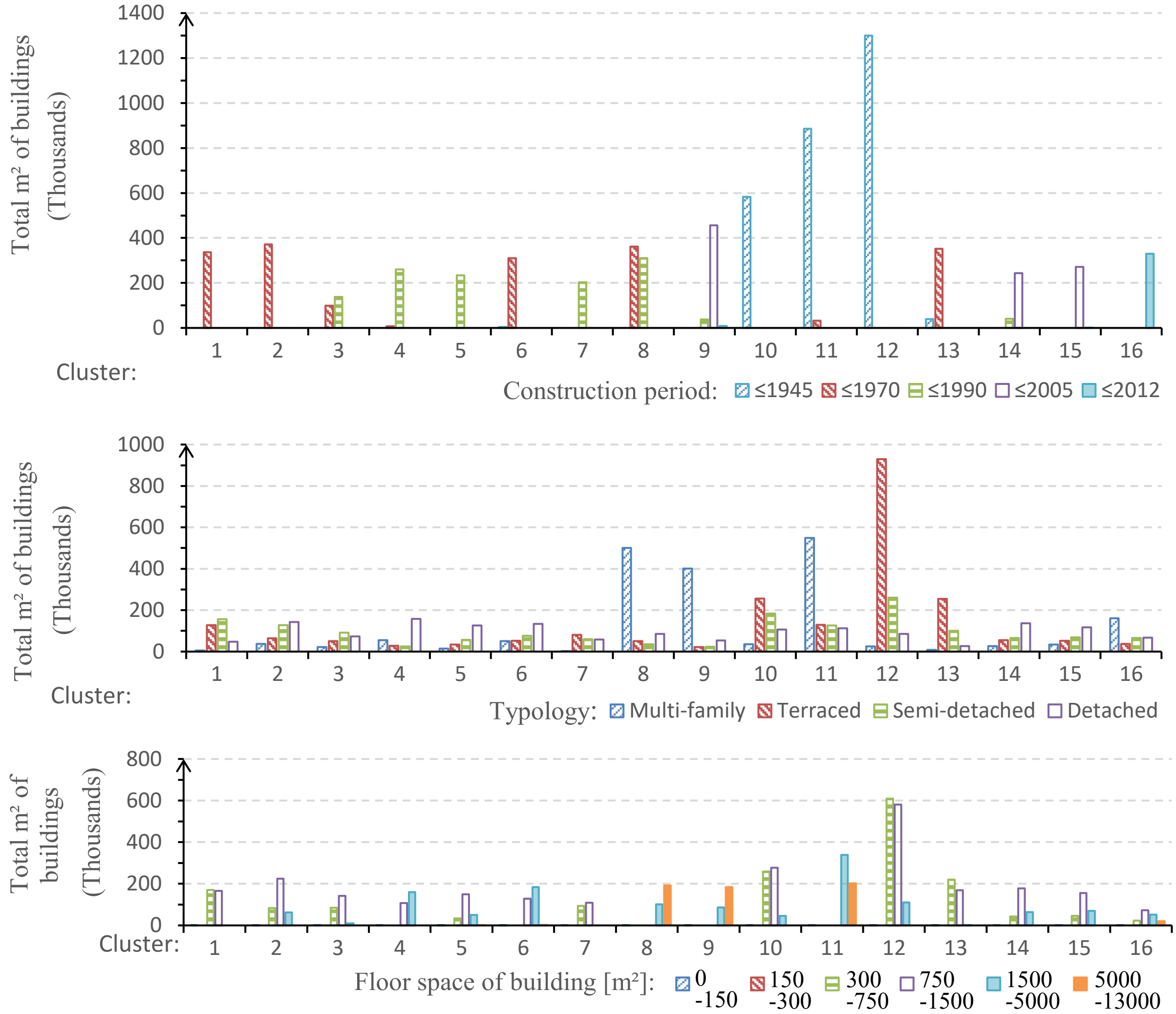

Figure 2. 16-means clustering of the building stock. The internal distribution within each cluster is shown for three parameters: the construction period, typology and floor space.

Table 2. Semantic interpretation of the clusters defined by the k=16-means clustering algorithm. Note that they are in no particular order.

Cluster	Time period	Typologies
1	1956-1970	Small, compact single-family buildings (<300 m²)
2	1946-1970	Medium single-family buildings (ca. 300 m²)
3	Ca. 1970	Small, compact single-family buildings
4	1971-1990	Large “single-family buildings” (ca. 750 m²), likely multi-family buildings
5	1971-1990	Medium single-family buildings (ca. 300 m²)
6	1946-1970	Large single-family buildings (ca. 750 m²)
7	1971-1990	Small single-family buildings (<300 m²)
8	Ca. 1970	Multi-family buildings
9	1991-2005	Multi-family buildings
10	Pre 1945	Small single-family buildings (<300 m²)
11	1921-1945	Very large buildings (>750 m²), likely multi-family buildings
12	Pre 1920	Small single-family buildings (<300 m²)
13	1940-1955	Small, compact single-family buildings (<300 m²)
14	1991-2005	Large single-family buildings (>300 m²)
15	1991-2005	Large single-family buildings (>300 m²), more pitched roofs
16	2006 and later	(Almost) all typologies

The number of clusters was determined empirically. Because of the low number of flat-roofed single-family dwellings, pitched-roofed multi-family dwellings and generally post-2005 buildings, the algorithm did not recognize these as separate clusters. Because of this the algorithm was reduced from a k=28-means clustering to a k=16-means clustering. It should be noted that there is now one post-2005 cluster (cluster 16) and that clusters 14 and 15 are similar except for their roof type.

The 16 clusters determined by the algorithm are almost completely in line with the suggested partition of construction periods, with the exception of clusters 3 and 8. Given the lack of formal delineation between these partitions, this is remarkable.

The distinction is less clear for the typologies. It should be noted that these categories in the second graph are taken from the classification by the city of Leuven. At first it would seem that the parameters of floor space, ratio of exposed façade and ratio of pitched roof do not characterize the typologies well, but the final graph adds an important nuance. It shows that floor space is an important characteristic. In fact, in the case of cluster 11, the algorithm arguably has done a better job of identifying the multi-family buildings, as buildings with a floor space above 750m² are very likely to be an apartment building instead of a single-family typology.

4. Future outlook

In a next step of the research, the inventory from the representative buildings will be upscaled to the entire urban building stock based on GIS data. In existing studies the upscaling is most often done by linking an archetype to each single building in the stock based on its characteristics. All data is then scaled linearly based on the archetype and a weighing factor, e.g. floor area. Our study proposes a new approach using data analysis algorithms. Compared to the traditional expert-based models, which use hard-coded rules, data analysis algorithms by design allow for more complex and flexible models, being able to self-adjust their criteria when more data samples are added, or when the algorithm is applied to an entirely new data set. More specifically our proposal is to support the extrapolation of the single building data through two machine learning methods: a k-nearest neighbours classification and an artificial neural networks (ANN).

4.1. K-nearest neighbours classification (kNN)

A kNN is loosely related to the k-means clustering algorithm used under 3.4, but instead of defining clusters within a set, this method works in the opposite direction: it classifies elements into categories based on the category of similar elements. This similarity is calculated in the same way as in k-means. This way it will categorize buildings under the most similar archetype. If the archetypes were to match the centroids of the earlier defined k-means clusters, the kNN classification will return categories identical to the 16 clusters. If the archetypes don't match these centroids or a different amount of archetypes is selected, the kNN adjusts, demonstrating its flexibility.

After the classification, the data obtained for the archetypes under section 3.3.2 will be extrapolated for all buildings based on their category and weighing factors determined on the available GIS-data.

4.2. Artificial neural network (ANN)

Besides the clustering approach, a second approach, i.e. ANN, will be used for the upscaling of the material inventory of the representative buildings to the full building stock. An ANN is a computing system which can learn to perform a task (e.g. extrapolate data) without using a pre-programmed instruction set [35]. There are several learning paradigms which can be employed depending on the kind of task the ANN is expected to perform. In this case, a supervised learning paradigm is selected which uses a set of training data (i.e. the cases as basis for the archetypes) to predict values for a new set of data (i.e. the remainder of the building stock). For this, inputs (known data like floor area), intermediary nodes and outputs (unknown data like present materials) form a network connected through synapses (Figure 3). Each connection represents a random non-linear transformation of the signal. These are weighted and summed to obtain an output value. Based on the feedback from the training data, these weights are then iteratively adjusted in order to obtain a good approximation of the actual output signal.

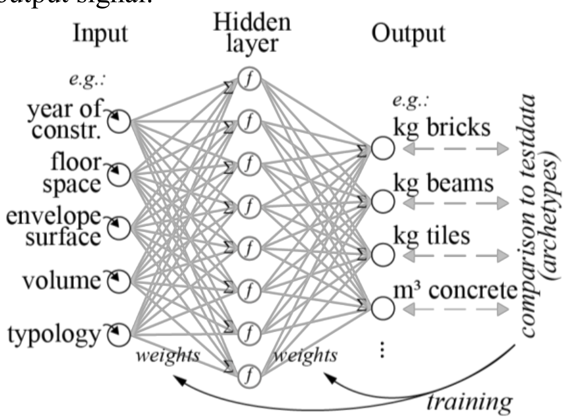

Figure 3. Concept for the proposed ANN. Data that is available for all buildings serve as input to extrapolate the unknown parameters. The network is trained on known data from the archetypes.

4.3. Interpretation of models

In the models obtained through the cluster analysis and ANN, buildings are not a priori categorised in a set of predefined archetypes, but are rather brought into relation to an expandable number of samples through their known variables. In this way, the unknown variables, i.e. quantities for the building elements, will be expressed as a sum of fractions of the inventories of representative buildings. The accuracy of these estimations can be improved through systematic interpretative workflows. The required steps will be specific to the resulting application. Relevant and feasible distinctions will be different for resource management on regional or urban scale, or even the scale of districts or building sites.

It is important to separate these interpretative steps from the development of the models themselves to assure flexibility and scalability and minimize bias.

4.4. Validation of the results of the various approaches

The results obtained through the scaling and interpretation will be validated by comparing the predictions with the reality of the building stock through test samples. Based on the outcomes of this comparison it might appear that the models require further improvements. Through an iterative process the models will be improved and more case studies will be added until the models perform well enough.

Besides validation through comparison with a random sample of buildings, the predictions of the models will also be validated by comparing these with top-down statistical data. This comparison might also reveal that one method is preferred over the other: the ANN might prove impractical in that it requires too much training data to become reliable or on the contrary demonstrates an important level of detail in its predictions. The cluster model could prove robust, but to what level it becomes inflexible for other applications because of programmed rules, remains to be seen.

4.5. Application

4.5.1. Scenario modelling. A temporal resource flow model, incorporating renewal rates of buildings and building components, allows to assess the influence of different future scenarios of expected changes in the building stock on the amount of (reusable) materials that will become available in time. These scenarios could for example represent increasing insulation levels, accelerated renovation rates or a gradual change towards the use of other construction methods (e.g. timber frame construction). The scenarios themselves will be defined based on expected future situations, covering ‘business-as-usual’, ‘targeted refurbishments’, ‘zero-energy standard’ and ‘reduced life cycle environmental impact’.

4.5.2. Quantification of building material flows. In a more straightforward application of the building stock models, near-future macro or meso-scale flows can be anticipated and the material stock on building sites can be estimated.

5. Conclusion

In the context of using the existing building stock as a resource mine, insights are needed regarding the amount of materials in the stock, their location and when these will become available. Such insights can be derived from building stock models. For this paper a spatio-temporal building stock model is being developed. The model builds upon previous research on stock modelling using a bottom-up approach. Based on a literature review, this approach was preferred over a top-down approach as the level of granularity of the latter is too low for the aim of our research. The approach proposed departs from existing approaches using building typologies which are upscaled to model the full stock. In contrast to existing studies that use a manual categorization of the buildings, a clustering algorithm is used to allow for managing the large amounts of data in an efficient way. The approach was tested on the city of Leuven to cluster the various buildings in the stock and it could be concluded that the method is deemed adequate for this use case as it aids in interpreting the large amounts of data and complex interrelations between them.

Modelling the building stock remains a challenging task as reliable information can't be obtained for all buildings. The application of our clustering analysis exposed that there can be important semantic differences to data as was the case for the typological classification. The interpretation of intermediary forms, e.g. those between an apartment block and a terraced house, can lead to very different results depending on how they are treated in the scaling from the archetypes to the rest of the stock. In the next step of this research, a better scaling method will be pursued through two machine learning techniques: a k-nearest neighbour algorithm and an artificial neural network.

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Seismic and solar performance of historical city Urban form-based multicriteria analysis

D'Amico A[a], Morganti M[b]

[a] DICEA Department of Civil, Constructional and Environmental Engineering, Sapienza University of Rome, Via Eudossiana 18, 00184 Rome, Italy
[b] Department of Architecture and Urban Studies, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy

michele.morganti@polimi.it

Abstract. The understanding of the global performance of a historical city is a complex balance of several specific issues and requires a multi-disciplinary approach to face with actual urban phenomena and challenges, such as the seismic risk and energy efficiency, that are strongly influenced by urban form. This paper focuses on the potential of urban metrics and typological indicators for describing the seismic vulnerability and the solar radiation availability of distinct urban textures, and the correlation between the two aspects. Comparative analysis at fabric scale was conducted on the historical centre of Rieti (Latium, Italy), to underline the main seismic and solar indicators. In the last decade, we witnessed the spreading of urban scale assessment and analysis tools, but seldom using an integrated approach to face the complexity of the historical city. Relying on morpho-typological indicators, the proposed method characterizes the fabrics in terms of seismic vulnerability and solar availability through a multicriteria analysis. The analysis reveals substantial differences between fabrics using three groups of indicators: *Plan*, *Space* and *Analysis-oriented*. Each group describes different features of the urban fabrics that affect seismic and solar performance and suggests improvement strategies. The purpose is to support policymaker and designer in the urban renovation process.

1. Introduction

The historical city is a complex system, and the understanding of its evolution requires specific attention to face urban actual phenomena and challenges, as natural disasters and climate changes. Nowadays, several studies in the field make use of approaches at the urban scale, rather than the building scale, in order to consider and explore all the elements that affect the functioning of a city [1–4]. Moreover, different urban forms correspond to different performances among which the seismic and the solar performances must resort to the analysis of the physical features of basic components of the built environment. In this framework, our study explores the causal relation urban form/seismic vulnerability/solar energy in the historical city through a multicriteria analysis, based on physical indicators - Urban Metrics (UM) and Morpho-Typological Indicators (MTI). The aim is to ease planning decisions for sustainable renovation processes.

The Mediterranean city represents a significant example of urban system, based on masonry construction and characterized by typological processes of growth, closely related to climate conditions and seismic events that defined its history. In terms of seismic risk, the analysis of the urban fabric focuses on the mechanical behaviour at the scale of the building aggregate [5], defined as a complex system of interrelated parts, structural units that are interconnected or in contact, which may interact under a seismic or dynamic action in general. Building aggregates generally have non-homogeneous and stratified constructive features, with different level of effectiveness of structural links between different parts. The research aimed at understanding the seismic performance of the city has developed the following approaches: on the one hand the structural-constructive approach focused on the analytical-mechanical understanding of masonry construction [6,7] and the identification of constructive characteristics linked to the reduction of vulnerability on an urban scale [1,2]; on the other hand the urban-systemic one [8,9] focused on risk assessment for the functional systems in which the city is organized. The shift of attention from the scale of the building to the aggregate and urban fabric one revolves around the morpho-typological parameters, which together with the constructive ones, are the basis for expeditious assessments of vulnerability on the urban [2,10] and territorial scale [11].

Solar energy availability is a key variable to assess buildings energy performance in the urban environment. On one hand, building's solar gains account for a significant part of the energy balance during both winter and summer; on the other hand, the potential for harvest solar energy in the urban context is directly connected to the potential for renewable energy systems to enhance energy efficiency at urban scale. Several studies reported the effect of urban metrics on solar performance [12,13]. Some of them consider real urban areas and related data in order to predict their solar potential using UM to better characterize the layout of the case studies [14,15]. Other studies focused on understanding the influence of urban morphology, described and controlled through UM, to optimize the solar potential of urban areas. The latter use normalised models derived from representative urban textures [16,17]. To perform solar energy analysis at urban scale, experts use specialised tools recently developed for the purpose, i.e. *Radiance*, *DIVA*, *CitySim* and *SUNtool*. These tools fostered the implementation of solar analysis in design practice. However, two factors still limit their widespread to urban planning and design: the specialist knowledge required to set up the simulation and the amount of time needed to realize the model at urban scale. For these reasons, this study uses the capability of UM to predict solar energy availability at urban scale. The method, based on a previous study reduces time and data necessary to carry out solar analyses, useful in the early stage of the design process [18]; this method is intended for architects and decision makers since do not require specialist knowledge and data required for the calculation are generally used in urban planning practice and are easily accessible for many cities.

In the last years, the importance of integrated approaches between energy and seismic analysis is testified by a growing number of studies. The relevance is particularly highlighted regarding the retrofit of the built heritage, implementing building envelope systems for energy, structural, and user-oriented retrofit that would significantly increase the commercial value and the life cycle of buildings, involve the users in attractive and visible solutions and, reduce the costs of energy [19]. Other studies regard the renovation of a high-rise building, focusing on the architectural quality to demonstrate the cost-effective evaluation of the convenience of the integrated approach in supporting public administration in social housing renovation [20]. On the one hand, the importance of the urban scale is nowadays recognized and investigated in several types of research for both the energy and the seismic performance, focusing the influence of urban morphology on these features [21]. On the other hand, the integration of the approaches is still focused on the building scale. The aim of this research paper is to overcome this compartmentation of knowledge, proposing a preliminary approach on integrated multicriteria analysis for the historical city, based on morpho-typological indicators in order to describe the seismic vulnerability and the solar radiation availability.

2. Methodology

2.1. The city of Rieti

The city of Rieti, located in Central Italy, is the ideal urban environment to test seismic and solar performance of historical urban form. Rieti concerned with the category of medium sized (between 5,000 and 60,000 inhabitants) local council areas, which make up about 30% of the total of Italian local government bodies and concern over 50% of the population - Ancitel on Istat database (01/01/2018).

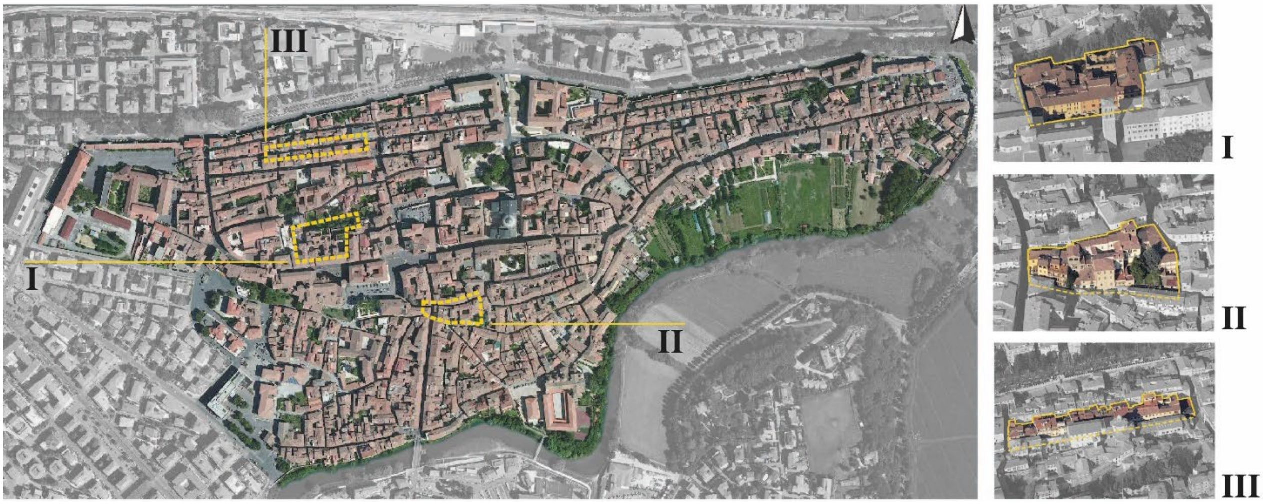

Figure 1 Aerial view of the city of Rieti and case studies identification.

The municipality of Rieti is characterized by well-conserved historic centre covering an area in proportion to its population and which falls in an area of medium-high seismic risk (zone 2), the area recently stroke by the 2016 Central Italy Earthquake. Case studies are three representative aggregates of typical urban texture of Rieti: case **I** is located in the core of the roman town, following the ancient settlement, along the *decumanus*; the aggregate, as a portion of an urban texture characterized by a clear hierarchy of streets and public space, is the result of stratification and alteration of the original seventieth century buildings; case **II**, close to the medieval walls, is part of a more articulated urban fabric with narrow streets; case **III** is located in the first medieval expansion, with a regular street pattern and mainly based on row houses, partially modified or replaced in recent times.

2.2. Metrics for urban form analysis

The range of variation of several Urban Metrics (UM) and Morpho-Typological Indicators (MTI) have been calculated. The formers have been derived from three-dimensional models of the urban textures with a level of detail LoD1 [22]. The latter have been derived from typological-observational methods, based on data of damage and vulnerability observed on previous earthquakes and normally calibrated on the use of existing databases with a level of accuracy 1 [7]. The UM taken into account have been derived from eight basic variables, widely common in urban and building studies and easily accessible (Table 1). Each metric gives information on some qualitative aspects of the urban form, such as the shape of the buildings, the plot patterns or the street network. It has been already proven that UM have a causal relation with energy performance at the urban scale [3,23]. Morpho-typological indicators are derived from the observational approach on the damage of similar structures, common in vulnerability studies for expeditious assessment at urban and territorial scale. Each indicator gives information on some qualitative aspects of the urban form and structural behaviour of the aggregate, such regularity of shape, interactions with existing buildings, transformations and interventions (Fig. 2 Table 2). The MTI analyzed are derived from the studies conducted on the case study of Nocera Umbra [24] and from the studies of Borri and Avorio, carried out on the masonry construction. In analogy with Fazzio's studies [24], qualitative indicators have a variable weight ranging from 3 to 10.

Both UM and MTI have been divided into three groups, considering their peculiarities in describing urban form: *Plan, Space* and *Analysis-oriented*. Besides, in order to facilitate the understanding and of the results, a comparison between cases has been conducted by means of normalization (Table 2). The groups collect UM and MTI with similar properties in terms of description of different features of the aggregates: *Plan* indicators are able to represent the main features on the horizontal plan; *Space* indicators describe the three-dimensional complexity; *Analysis-oriented* indicators are useful to predict solar and seismic performance at early stage of analysis.

2.3. Aggregate seismic and solar performance

The "vulnerability of the aggregates" is defined as the susceptibility to damage and loss of organization due to the complex of risk factors to which individual blocks are subjected, deriving from typo-morphological, structural and functional aspects [24]. In this study, we refer to “relative vulnerability” of the aggregates, because the normalization is carried out on the dataset of each city. Given the typological-observational nature of the vulnerability assessment methodology, the results have a greater relevance for the urban management in order to understand the vulnerability level of different portion of the urban texture.

Analogous to the cited studies, the seismic performance has been analysed thought two group of indicators, as part of a wider research [10]: descriptor parameters of the morphological and typological characteristics of the aggregate, related to the overall configuration; descriptor parameters of the general structural characteristics, related to the average characteristics of building components and aggregation methods. In this paper the first group of indicators have been considered (Figure 2).

The solar irradiation on building façades has been assessed for the selected urban aggregates of each digital model, considering urban obstructions during the whole year. We focus on the solar performance of the vertical surfaces since they are directly related to the building's solar gains which account for the most part of the energy demand in the Mediterranean latitudes. *Heliodon2* software and *Heliodon2plus* data post-processor have been used for simulations. *Heliodon2* calculates the spatial and temporal distribution of solar energy on building façades, considering a cloudless sky condition during a given period; the associated post-processor use climate data to obtain direct and diffuse solar radiation. Calculations have been carried out on the base of the latitude of the city of Rieti (42°24' N 12°51' E).

3. Results and discussion

The main results, with regards to solar irradiation on building façades and seismic performance, UM and TI evaluation are here presented and discussed in two separate subsections. The results have general implications to seismic and solar performance at urban scale in the historical city of Mediterranean climate.

3.1. Seismic and solar performance

The assessment of seismic vulnerability for the aggregates shows the most critical situations for the cases with higher Sd or TAd, which is usually reflected also on articulated geometric configurations (**I**), and for irregular aggregates with high values of PT, PTis and AT, located in complex urban fabric. The latter due to the relation with the surrounding aggregates (rSA) increasing the induced vulnerability (**II**). On the contrary, case **III** emerges as relatively less vulnerable as described by lower PT (regular linear trend) and lower TAd (mainly composed of building with a high degree of typological homogeneity). In order to complete the seismic analysis and to evaluate the relative vulnerability index, indicators based on structural characteristics are reported in Table 3.

Table 1 Urban metrics basic variables.

Symb.	Unit		I	II	III
P	[inhab.]	Population	646	382	374
A	[m^2]	Base land area	5362	3482	4396
C	[m^2]	Footprint	3693	2288	3117
F	[m^2]	Gross floor area	15095,4	9222,64	9817,41
S	[m^2]	Façade surface	10216,5	7131,4	5711,2
V	[m^3]	Built-up volume	64571	38236	37403
L_i	[m]	Interior network	0	0	0
L_e	[m]	Edge network	325	266	377

Table 2 Values of morpho-typological indicators and urban metrics regarded to case studies.

		Plan	I	II	III
FSI	[m^2/m^2]	Building intensity	2,82	2,65	2,23
FSd	[$inhab./m^2$]	Floor space density	0,04	0,04	0,04
GSI	[m^2/m^2]	Coverage	0,69	0,66	0,71
N	[m/m]	Network density	0,030	0,038	0,043
OSR	[m^2/m^2]	Open space ratio	0,111	0,129	0,130
PT	adim.	Planimetric Trend	7	10	3
PTis	adim.	Planimetric Trend Interruptions	7	10	7
		Space			
Vd	[m^2/m^2]	Vertical density	1,91	2,05	1,30
VOSR	[m^2/m^2]	Vertical open space ratio	6,12	5,97	4,47
VAr	[m^3/m^2]	Volume-Area ratio	12,04	10,98	8,51
rSA	adim.	rapport with Surrounding Aggregates	7	10	7
rTM	adim.	relation to the Territory Morphology	3	7	3
AT	adim.	Altimetric Trend	7	7	3
MVld	adim.	Mountain-Valley levels difference	7	7	3
		Analysis-oriented			
TCl	adim.	Typological Commingling level	5	5	3
STS	adim.	presence of Specific Typological Structures	7	5	5
TAd	adim.	Typological Alteration degree	10	5	7
Sd	adim.	Stratification degree	10	5	7
SF	adim.	Sky Factor	25,2	22,0	30,2
SVF	adim.	Sky View Factor	21,4	19,0	24,7

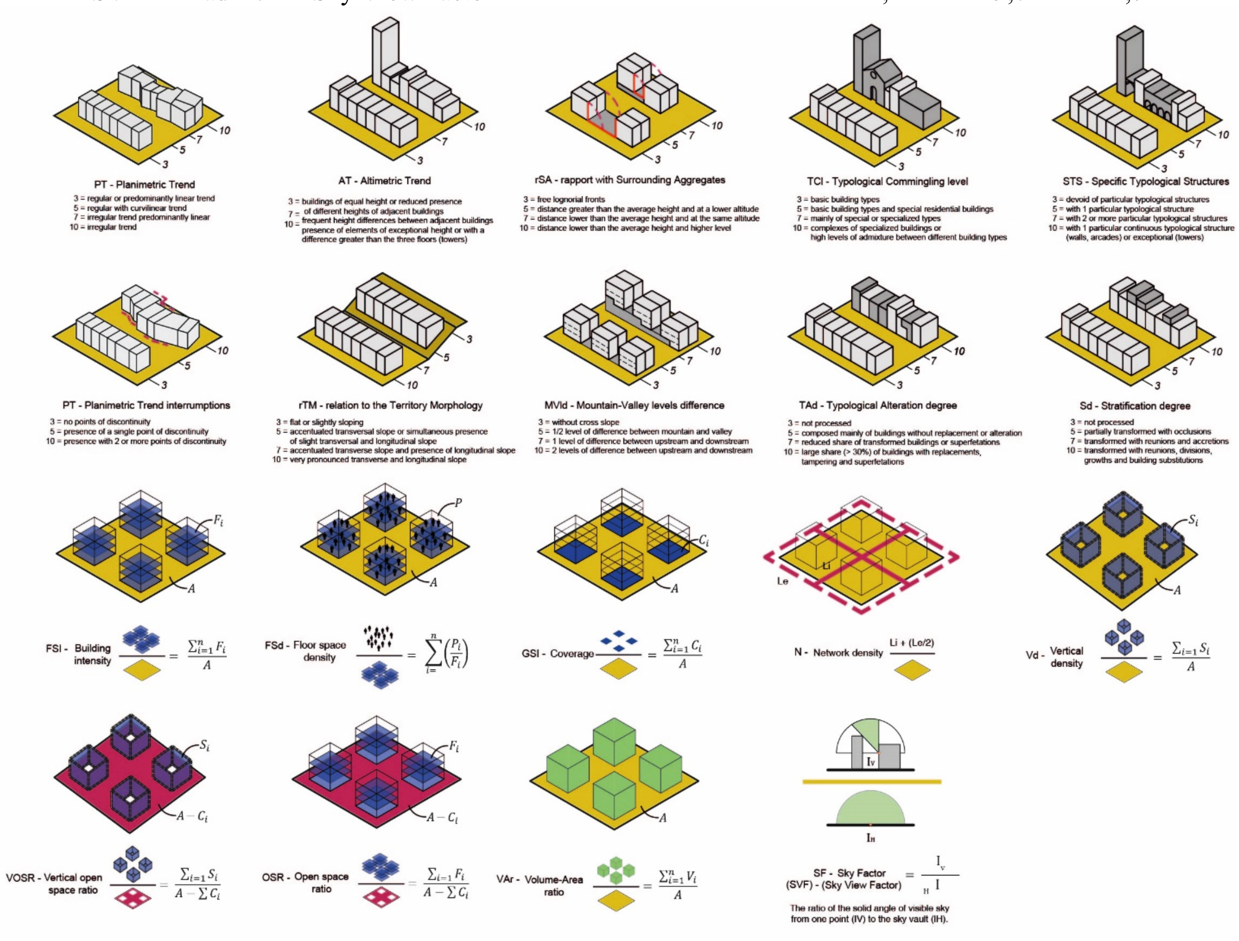

Figure 2 Description of morpho-typological indicators (MTI) and urban metrics (UM).

Table 3. Structural characteristics parameters and total values, TI total values and vulnerability index.

	I	II	III
Average conservation status of vertical structures	5	3	3
Average conservation status of horizontal structures	5	3	3
Average state of conservation of the roofs	5	3	3
Synthetic index of masonry quality	7	7	7
Presence of particular structural elements	5	5	0
Offset of floors between adjacent buildings	7	7	10
Slenderness of the wall	3	3	3
Pushing elements (arches, vaults, roofs)	7	10	7
Masonry discontinuities	7	7	5
Discontinuities or singular elements in vertical structures	1	5	1
Discontinuities or singular elements in horizontal structures	1	5	1
Discontinuities or singular elements in roof structures	1	5	1
Regularity in the arrangement of openings	3	3	7
Total indicator of structural characteristics	**57**	**66**	**48**
Total TI	**70**	**71**	**51**
Overall vulnerability index	**127**	**137**	**99**
Overall vulnerability index (normalized)	**8**	**9**	**3**

Table 4 Value of solar energy over a one-year period regarded to case studies.

	Unit	I	II	III
Solar radiation	kWh*	2.748.809	2.283.577	2.107.196
Façade energy density	kWh/m^2*	269,1	320,2	369,0
Direct solar radiation	kWh	662.113	550.052	507.566
Diffuse solar radiation	kWh	1.315.029	814.776	850.469
Global solar radiation	kWh	1.977.142	1.364.828	1.358.035
Direct façade energy density	kWh/m^2	64,8	77,1	88,9
Diffuse façade energy density	kWh/m^2	128,7	114,3	148,9
Global façade energy density	kWh/m^2	193,5	191,4	237,8
Direct solar radiation fraction		33%	40%	37%

* *Considering cloudless sky condition*

Concerning solar energy, irradiation on façades ($kWhm^{-2}y$) is directly related to a combination of high-density-related values (GSI, VOSR, Vd) and low SF/SVF values. In historical urban textures, reasons for better solar access compared to observed tendencies, are due to specific morphological features: lower urban density combined with optimal façades orientation (**III**). Instead, solar performance is in general poor for cases with high urban density (as described by each UM). Even though similar surface exposure and lower SF/SVF, case **II** receives more solar radiation compared to **I**. This result is reliably represented by UM (FSI, GSI, VOSR and VAr). Comparing fractions of direct and diffuse irradiation for case studies, we notice that differences between **I** and **III** are almost levelled by increasing of diffuse radiation (Table 4). Based on these results, it can be argued that, considering the most reliable metrics for solar analysis as indicated in previous studies [18], **II** and **III** performs better than the average. The former, due to the presence of several courtyards and higher ratios of façade surface/built volume. The latter thanks to favourable texture orientation in relation to façade exposure.

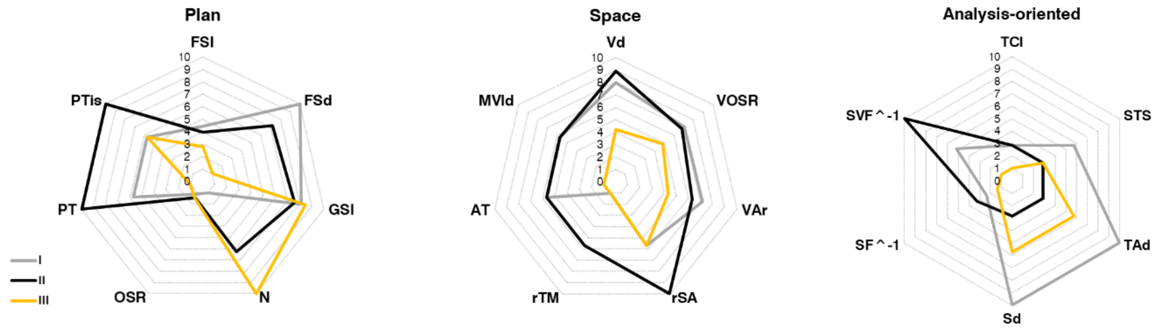

Figure 3 Comparison of normalized UM and MTI (grouped into Plan, Space and Analysis-oriented)

3.2. Urban form metrics and typological indicators

Table 2 and Figure 3 show respectively the computation of UM and MTI and the corresponding normalized values for case studies (decimal scale). The purpose of the diagrams is to visualize the urban scale performance: the higher the value of an indicator, the worse the behaviour of the aggregate in term of solar availability and seismic vulnerability. For this reason, we use reciprocal value for SF and SVF. In general, to combine different indicators helps clearly understand building density and compactness of urban fabric: compared to cases **I** and **II**, we can observe that case **III** is more compact and have less building intensity, producing openness in the urban form. By grouping different types of UM and MTI is possible to highlight urban form features of each case as shown in Figure 3. Case **III** values clearly reflect differences in urban layout and morphology of the island. Moreover, the difference between **I** and **II** appears: **II** has higher values in most of the *Plan* and *Space* metrics, while **I** has higher values in all the *Analysis-oriented* metrics. The case **I** and **II** are the aggregates with lower performances, while case **III** always covers the smaller areas of the graphs, showing as in a regular urban texture exist more favourable condition.

First-stage evaluation of seismic vulnerability and façade solar availability at urban scale can be obtained making use of the diagrams: the smaller the area on the proposed diagrams, the greater are the intrinsic capacities of the urban aggregate to perform at both levels.

4. Conclusion

Our paper presents an investigation on the capability of a multi-criteria analysis based on UM and MTI to predict urban seismic vulnerability and solar availability in the historical city located in Mediterranean climate. The Plan indicators highlight intrinsic criticalities of urban texture regarding the horizontal plan, therefore strictly related to urban form and very hard to transform without invasive action that could compromise the historical value. The Space indicators, due to their three-dimensional definitions are suitable to describe renovation strategies based on urban acupuncture and geometric regularity, taking into account the interaction with the urban surroundings. The Analysis-oriented indicators are suitable to control urban form and typology implications of solar and seismic performance and to improve them through solar and seismic sensitive design.

The proposed multi-criteria analysis model has been structured with several purposes. On one hand, it can support policy maker decisions according to the performances of urban aggregates, in order to differentiate public investments and incentives; on the other hand, it should be integrated in the early stage of design process, taking into account the solar façade availability and seismic vulnerability of urban areas to guide urban renovation strategies.

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2 DEGREES – understanding the contribution of cities to a carbon neutral society

Wittstock B, Goerke J, Blumberg M

thinkstep AG, Hauptstr. 111-113, 70771 Leinfelden-Echterdingen, Germany

bastian.wittstock@thinkstep.com

Abstract. Climate change is understood to be a factual situation to deal with and the world community has agreed with the Paris agreement of 2015 to limiting global warming to 2 °C above the pre-industrial state. Cities and urban areas are at the core of anthropogenic climate emissions. So far, however, cities are not generally recognized as major action fields for a climate neutral society. Yet, individual examples of cities with a strong climate neutral agenda prove the overall societal and economic advantage of their actions.

This study analyses 15 European cities to understand the influence and potentials, local actions and political activities as well as targets that cities can take and define to mitigate climate change and contribute to the global 2-degree goal. The empirical evaluation of the cities was conducted in 2017, using the science-based targets approach on public buildings as initial pilot. The study identifies critical internal and external success factors for effective climate engagements, particularly from the 1/3 of the cities whose strategies comply with the 2-degrees target. Criteria and levers are derived that help cities transform into low carbon communities. From that, a framework model and operational guidance are developed, binging cities in the position to develop their individual path towards the 2-degree goal.

The results of the study are demonstrated by the case of the Swedish community of Växjö, showcasing how the early and broad adoption of low carbon policies and actions results in overall economic growth and prosperity as a 'green community'.

1. Background and Introduction

The summer of 2018 lead to a fundamental change in the broad public reception of the subject of climate change. To broad parts of society in Central Europe, it became evident that climate change does already take place [1]. The global climate has warmed since the beginning of the industrial revolution of the 18th century by about 1 degree Celsius. Also, until 2013, 12 of the 14 highest annual average temperatures occurred in the time frame from 2000 to 2013 [2]. Overall, a broad consensus has been found on the need for action against climate change and even the youth increasingly raise their voice to demand for action [3].

In 2015, the parties of the Paris COP 21 conference (United Nations Framework Convention on Climate Change, 21st Conference of the Parties) agreed to limit global warming to below 2°C, or even 1,5°C compared to the pre-industrial state [4]. With ¾ of the world's population soon living in urban areas, cities are a major player for effectively mitigating climate change. For municipal administrations, however, effectively acting against climate change is a major challenge, as conventional mechanisms of administrating a city fall short for doing what needs to be done to save the climate.

This study analyzed the activities of 15 European cities to understand their current activities towards mitigating climate change. From this analysis, mechanisms were derived to help municipalities be successful in working against climate change. Obviously, cities and municipalities have a broad range of action fields to engage in working against climate change. This study explicitly focuses on the municipal building stock, as this is one of the common fields for all municipalities. Also, the municipal building stock is of special interest due to it's potential or actual function as a role model for the private real estate industry. With this focus, the relevance of other sectors like mobility and transportation should not be negated, but here, a more city-wise view into municipal activities is required. Also, some findings are believed to be applicable or transferable to other municipal activities, without further elaboration of this point in the study.

2. Empirical analysis of municipal activities

To gather information on how cities and municipalities[1] act against climate change, data from several European cities is assessed. Both, by means of a questionnaire based inquiry with the cities and by applying the Science Based Target (SBT) method [5] to understand the contributions of cities to the 2°C-target.

2.1. Methodology

Quantifying the carbon emissions of a city or municipality forms the basis for understanding or even defining a carbon reduction target for the city or municipality. The quantification of carbon emissions follows the Greenhouse Gas Protocol, more specifically the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories [6].

This protocol defines three different scopes for emissions. Scope 1 refers to direct emissions from activities and operations within the city boundaries. Scope 2 denotes emissions from Energy production and distribution, both in- and outside the city boundaries and Scope 3 relates to upstream emissions for any goods or services imported into the city boundaries. For municipalities, the three scopes analogously relate to activities and operations that are directly associated with municipal buildings and facilities or that are imported directly to municipal facilities.

For the purpose of this study, the focus lies on municipal buildings. Municipal administrations generally serve as local role models for their cities so that any climate change actions of municipalities most likely relate to their buildings and facilities. In addition to that, municipal buildings are directly available for local administrations to establish climate actions.

With the help of a questionnaire, information was collected from the involved municipalities on their approach to climate action for municipal buildings. The survey covered both, a section on a municipality's perspective on climate change and a section on their actual carbon reduction targets. The aim of the survey was particularly to understand whether the cities' current engagement in climate actions (in the municipal building sector) conforms with the 2-degree target and to identify critical success factors and barriers towards successful climate mitigation actions.

For this, the Science Based Targets method framework [5] is used. It provides a set of mechanisms that allow to derive sectoral, company- or city-specific greenhouse gas emission budgets and reduction pathways from the 2-degree target from Paris. To calculate the required changes in emissions for each of the study cities, the Sectoral Decarbonization Approach (SDA) [7] is used. This method breaks down the overall carbon emission budgets to sectors and finally to individual companies or cities.

The required emission reduction based on the SDA calculations are compared with (partially estimated) current reduction targets that the respective municipalities have defined.

2.2. Results and findings

The survey and the subsequent calculations of the required emission reductions for the cities present a diverse landscape. Some cities have actively used the Science Based Target method before to define

[1] In this article, 'city' refers to the geographical boundaries for a dedicated urban area (and this can also include an entire metropolitan area), while 'municipality' denotes the administrative bodies of a city government.

their individual 2-degree targets and act accordingly. Other cities have no targets in place that exceed national legal requirements and correspondingly have no dedicated climate actions planned.

2.2.1. Cities' current engagement in climate action. A total of 42% of the participating cities with enough data (n=12) have targets defined that comply with the 2-degree target. A much larger portion of the participating cities – 73,3% - however, consider their carbon reduction targets to be very ambitious and only 1/3 of the participants have faith in meeting the targets in the defined time frame. This also stands in some contrast to the finding that all cities state that their city is already affected by the consequences of climate change and that the effects of global warming are a relevant issue for their city.

The carbon reduction targets that cities have defined typically are derived from the current situation and are defined in a way that reaching these targets can be achieved with small or reasonable effort. Two thirds of the cities adopt targets from national or EU-targets, and 1/3 of the cities have targets that reach beyond national targets. Only 10% of the participating cities align their targets with IPCC indications.

The survey also concluded that Scope 1 and 2 emissions from cities particularly stem from fossil fuel. This leads to the conclusion that increased energy efficiency for buildings, optimizing energy systems and grids for the entire city, changing energy sources, e.g. towards biomass, and working to influence citizen behavior are among the most effective mechanisms to mitigate climate change.

In addition to that, the survey also made very clear that cities also highly depend on external factors, particularly the decarbonization of external energy supply. While some cities actively work on reducing dependency from external energy sources, for other cities, this appears to be a significant obstacle towards carbon reduction.

2.2.2. Findings from applying the Science Based Targets model. As said, the carbon emission reduction targets of 42% of the cities are aligned with the 2-degrees target. For this alignment, the cities' building sector requires an average emission reduction of 26% by 2030.

Table 1 sets the required emission reduction targets that have been calculated for each city (if enough data was available) with the Sectoral Decarbonization Approach (SDA) in relation to the cities' actual reduction targets for 2030.

Table 1. Cities' required emission reduction according to SDA & estimated current reduction pathways for 2030.

City	Required emission change (negative = reduction), based on SDA	Current reduction target (estimate) (positive = reduction)
Aachen	-32%	< 32%
Aberdeen	n/a	n/a
Aarhus	-22%	100%
Bergen	-3%	100%
Bremen	-50%	< 60%
Erlangen	-18%	7%
Glasgow	-64%	< 64%
Helsinki	-34%	< 34%
Karlsruhe	-37%	16%
Leeds	n/a	n/a
Limerick	-10%	35%

City	Required emission change (negative = reduction), based on SDA	Current reduction target (estimate) (positive = reduction)
Munich	n/a	n/a
Pamplona	-1%	8%
Plock	-55%	< 55%
Växjö	+21%	100%
Average	**-26%**	**n/a**

Table 1 (cont'd). Cities' required emission reduction according to SDA & estimated current reduction pathways for 2030.

The table shows clearly that the current ambitions of cities are higly diverse – from a 7% reduction target (Erlangen) to a complete decarbonization (Aarhus, Bergen, Växjö). One exceptional case is the one of Växjö. Due to their very early adoption of climate change mitigation actions – see section 3 – Växjö currently has a lower carbon emission profile than what would be required for a reduction path for 2030. This leads to a hypothetical additional emission budget, which is reflected by the positive number for the required emission change. Obviously, the actual effect of this situation is that Växjö has a major advantage to other cities when moving to their own target of complete decarbonization of the municipal building sector by 2030.

The table makes it clear that most cities face major challenges in the coming decade, when moving towards contributing their share to the Paris agreement.

2.2.3. Critical Success Factors. From the survey, internal and external factors are derived which have significant influence on a city's success in moving towards decarbonization. External factors, particularly the geographical location and the available natural environment have a major influence on the energy demand and on available local energy sources (e.g. availability of power generation from wind and water, availability of biomass). Also, changes in the grid energy mix cannot be easily influenced but have a major impact on the carbon emissions associated with the building sector.

In contrast to those external factors, a set of internal factors are identified as critical to success in achieving significant emission reductions. These critical success factors are

- Commitment,
- Collaboration,
- Funding,
- Capabilities.

Commitment refers to establishing a consistent thinking across all departments of a municipal administration base on developing and sharing a long-term vision. A common understanding towards decarbonization across political parties has repeatedly been reported to be essential for long-term success beyond single legislative periods. Also, higher political support for administrative actions is essential for successful execution of climate change mitigation measures.

Collaboration across departments inside the municipal administration is essential and requires efficient structures. Complex structures with a diversity of ownership and management / operational responsibility for municipal buildings, in contrast, are a significant challenge. Also, effective collaboration with non-municipal stakeholders of a city is critical for success. Available instruments need to be exercised and trained, e.g. Public-Private-Partnerships (PPP) with Energy-Service-Companies (ESCOs).

Funding refers to typically high initial investments for carbon-saving measures. Particularly if long-term financial savings from taking actions are neglected – as is typically the case – funding with available sources may be a challenge. While some funding resources from national and European programs may be available, climate change mitigation measures require sufficient initial financial resources.

Capabilities refers to the need for skilled and educated staff within the municipal administration to support changes in technologies and approaches. But it also refers to the need for (not only financial) resources, e.g. with enough skilled workers at construction companies to effectively execute measures.

3. Case Study: The City of Växjö, Sweden

One of the forerunners of urban climate actions surely is the city of Växjö in Småland, Sweden. The case of the city of Växjö is elaborated with reference to the above-named critical success factors. Växjö is a city with a population of 92.000 and an economic growth of more than 30% (GDP) from 1993 to 2015.

Commitment: The city's initial focus on environmental issues dates back to the 1960s, when the city started to take action against pollution of their surrounding lakes. In the following decades, the city continued to not only remediate polluted areas but also to step into biomass based district heating, increasing use of local renewable energy and to respond to the United Nation's program for sustainable development, the Agenda 21 [8]. The city of Växjö decided to take a leading role in sustainable development in Sweden and adopted their environmental policy in 1993 and started to monitor per-capita-CO_2-emissions.

As early as in 1996, Växjö announced for the first time the ambition to become a fossil-fuel-free city, which is now targeted for 2030, including homes, industry, and transportation – including planes taking off from the local airport.

Collaboration: Along the long-term chain of activities in Växjö, the municipal administration continuously engaged with all stakeholders in the city. This includes initiatives to influence the behavior of citizens, as well as providing support to act appropriately. Apart from providing cheap district heating (see below) from local biomass-sources, Växjö also secured attractive public transport to encourage citizens to stay away from fossil fuel powered cars, as an example.

Funding: One of the effects of Växjö's early uptake of environmental awareness and actions was that both, national Swedish and European funding was repeatedly available for new projects. Also, because of Växjö's early shift to biomass-based district heating, the city was able to offer cheap renewable energy to their citizens, when Sweden introduced a CO_2-tax in 1991.

Overall, the focus on sustainable development allowed the city of Växjö to reduce CO_2-emissions by 58% from 1993 to 2016, while securing a GDP-growth of 32% from 1993 to 2015.

Capabilities: From the municipality's feedback, it became clear that a general entrepreneurial culture and openness to try new ideas among the citizens was a very helpful basis to engage in sustainable development. Also, a general desire for independence from outside energy suppliers, fueled by the oil crises of the 1970s and 1980s, greatly supported the city's move towards local, fossil-fuel-free energy supply.

Overall, the case of Växjö nicely demonstrates how all of the named critical success factors need to be integrated in a positive way for a city to be successful in integrating sustainable development and mitigating climate change.

4. Framework model to support cities act towards the 2-degrees target

Both, the cities-survey, as well as a study from C40 Cities[2] and ARUP [9] clearly indicate that cities generally need to increase engagement towards climate change mitigation. Also, it is clear that many cities require active support to do so. Overall, required technologies to change to low carbon activities are available, yet the uptake of these technologies and the execution of climate actions is the problem.

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[2] C40 Cities is a network of almost 100 of the world's largest cities, aiming at increasing climate actions and promoting sustainable development. www.c40.org

For this means, a management plan is presented, called “Navigating the Path”. It utilizes the identified critical success factors and provides a concrete framework for bringing cities into action.

4.1. Navigating the Path
Core of this management plan is designing climate action plans. Such a climate action plan reflects a comprehensive approach to urban concepts, accounting for all aspects that matter, both directly for climate change mitigation, as well as for integrating climate actions into the municipality’s and city’s traditional activities.

Basis of the management plan is the calculation of the relative contribution of a city to limiting global warming, by using the Science Based Target approach (particularly the Sectoral Decarbonization Approach). With the derived emission reduction targets, a solid, manageable target is defined.

The actual management objectives are developed from interpreting the above-named critical success factors for the respective city. In that sense, it must be noted that a general understanding of the elements of a management plan may be generic, while the concrete management plan must be specifically tailored to a city’s situation. Any “one-fits-all” management advice were too arbitrary to provide meaningful guidance.

4.2. Critical success factor “Commitment”
As a basis, accurate and current data is required for any action on climate change. With a solid data foundation, a Science Based Target calculation can be executed. It is important to also integrate the city’s future economic development and to differentiate between sectors, in order to provide a clear picture on goals and their economic value. This will form the basis to develop a common understanding, avoiding confusion or uncertainty on the relevance of the information and the targets, bringing faith in the decisions to be taken.

One useful guidance document for setting targets for reducing carbon emissions is a set of four action areas with 12 opportunities that have been identified in a study “Focused acceleration” from C40 and McKinsey [10]. These four action areas are:

- Decarbonizing the electricity grid,
- Optimizing energy use in buildings,
- Enabling next-generation mobility,
- Improving waste management.

The study “Focused acceleration” also estimates the share of 2030 emission targets that a single opportunity may deliver. Using these action areas and the dedicated opportunities in combination with the calculated SBT-based reduction targets, a city can obtain very specific, operational targets to work against.

4.3. Critical success factor “Collaboration”
The imperative of active collaboration should not be considered to be different for climate change mitigation actions. Moreover, a general understanding of the obstacles and barriers for collaboration need to be adopted to the matter.

Important elements to operate with may be transparency on the different and potentially competing objectives of stakeholders, engaging in aligning these objectives, as well as moderating lack of understanding and the different perspectives towards a situation. Quite frequently, the involvement of external experts on the subject as moderators and solution developers is a very feasible means of improving collaboration.

4.4. Critical success factor “Funding”
With about 70% of the surveyed cities lacking the appropriate financial resources, external experts may cooperate with a municipality’s budgetary department to identify the required funding. This requires to consider all available funding sources and to develop reliable business cases for urban climate projects.

This may also include the identification and development of alternative financing instruments as well as the development of public-private partnerships.

4.5. Critical success factor "Capabilities"

For the critical success factor *Capabilities*, a direct focus on the above-named action areas helps to understand the need for the right skills. Once the specific opportunities to engage in climate actions are identified, internal and external experts can start with developing project roadmaps.

For the action area *Decarbonizing the electricity grid*, both, a thorough understanding of conventional and innovative electricity generation and storage technologies is required, as well as a solid approach to grid management and organization.

For the action area *Optimizing energy use in buildings*, often a broader perspective than the traditional view on a building, omitting user-induced energy consumption is needed. The required capabilities range from innovative processes and methods (Building Information Modeling – BIM to Lean Construction Management – LCM) to understanding the inter-dependencies of energy consumption with other aspects of buildings, typically integrated by green building certification schemes.

In the action area *Enabling next-generation mobility*, the focus will avert from the car-centric transportation planning to ease transportation without cars and to integrate novel transportation technologies.

In the action area *Improving waste management*, the focus will move from recycling or disposing of waste to real circularity in all material streams. This will increasingly include the cities' buildings and construction works to be understood as valuable resource repositories. Also, focus will grow on aligning supplier, distributor and consumer networks regionally to optimize material streams.

In addition to these action areas, the field of *Digitization* will play a vital role in changing cities' approach to new objectives such as climate change mitigation. Here, this is even more the case as climate actions intensely rely on various stakeholders and large groups of citizens to align on specific actions which are based on solid data. Hence, ICT technologies and solutions are required for a wide range of objectives, typically integrating large sets of data and providing meaningful interpretation of the data to support decision making.

5. Summary and conclusions

The empirical study done with 15 European cities on their current situation in the field of mitigating climate change shows a diverse picture. The cities' engagement ranges from essentially being compliant with current laws to thorough strategies for becoming fossil-fuel free within a decade. Only a small portion of cities have set carbon reduction targets that comply with the 2-degrees target that has been defined in the Paris agreement of 2015.

The Science Based Targets method provides a very useful framework to derive carbon emission reduction targets from the 2015 Paris agreement to the level of an individual city and dedicated sectors of the city. The Science Based Targets method is also used to estimate the cities' current position on the way to comply with the 2-degrees target and the required reduction targets.

One impressive example of how a city has developed into a forerunner of climate action is the city of Växjö, Sweden. This city has managed to achieve significant economic growth while decarbonizing the city to quite an extend already. Moreover, it has a clear plan to become fossil-fuel free (including planes staring from the local airport) by 2030.

From the survey, four critical success factors, commitment, collaboration, funding and capabilities are derived. These critical success factors must be positively addressed to enable successful climate actions.

From these insights, a management plan "Navigating the Path" has been developed, covering the critical success factors on a framework level. This management plan gives guidance on how to tackle the points raised and on how to engage in climate action to reach carbon emission reduction targets, which have been defined before.

Overall, the study clearly shows the need for cities to actively assume responsibility for their contribution to meeting the 2-degrees target. It shows that some cities did become active quite some time ago and it provides an instrument for other cities to effectively follow. With the developed management plan, cities have been enabled to break down the hard to digest objective of acting to meet the 2-degrees target into operational tasks to reduce carbon emissions.

A more elaborate report on that matter [11] is available with the authors.

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On net zero GHG emission targets for climate protection in cities: More questions than answers?

Lützkendorf T[1], **Balouktsi M**[1]

[1]Karlsruhe Institute of Technology, Centre for Real Estate, Karlsruhe, Germany

thomas.luetzkendorf@kit.edu

Abstract. Two separate, but interacting, global agendas are now leading to new, additional requirements for the future development of cities: The UN Agenda 2030, putting cities at the heart of sustainable urban development with its Sustainable Development Goal (SDG) 11, and the Paris Agreement COP21 adopting the 1.5 °C target as a basis for global emissions reductions. Regulators and researchers have widely recognized the necessity to put cities, as an important object of assessment, and city authorities, as an important actor group, at the core of climate mitigation efforts. For cities themselves this topic becomes a factor of competition among peers. In their pursuit of a low carbon future, however, they are confronted with a number of theoretical and practical questions regarding target setting and subsequent planning for mitigation. As a contribution to the current discussion, the paper initially clarifies on which principles the allocation and accounting of city-related greenhouse gas (GHG) emissions are typically based. A good understanding of the GHG sources and reduction potentials is essential for defining feasible targets and designing efficacious reduction strategies. Built on this, the paper then presents how climate targets are defined at city level and analyses the methodological considerations that arise in the case of target-setting approaches involving bringing the emissions balance to zero. Although first definitions of "net zero emission" concepts on an urban scale can be found in literature, their precise meaning and applicability still remain vague, with unclear system boundaries, calculation and assessment rules. This paper provides a definition framework for clarifying such concepts.

1. Introduction

2015 marks a historic turning point for the future development of cities: The UN Agenda 2030 with its Sustainable Development Goals (SDGs) and the Paris Agreement have put in place new framework conditions for a sustainable transition to a greenhouse gas (GHG) neutral and climate-resilient future. The two agendas cannot be achieved if tackled individually. Climate protection is an important partial aspect of sustainable development and contributes to the preservation of the natural basis for life. Conversely, long-term climate goals can and must only be achieved by sustainable means, and thus, if placed in the wider context of sustainable development. SDGs make this abundantly clear with SDG 7 "Affordable and clean energy", SDG 12 "Responsible consumption and production" and SDG 13 "Climate Action". At the same time, SDG 11 aiming to "make cities and human settlements inclusive, safe, resilient and sustainable" recognises cities as an important level of action encompassing active climate protection as a sub-goal among others.

In this sense, putting cities at the core of climate mitigation efforts is a practical imperative to achieving several SDGs. But it is also a strategic one: although cities occupy only a tiny proportion of the total global surface area (around 3%), over 70% of global CO2 emissions from final energy use can be attributed to them [1] (accounting for where emissions are caused, the respective proportion would be about 30% lower). In the absence of action, this proportion will be further raised due to the projected rise of the global population in cities to 2.5 billion plus by 2050 [2]. Today, the potential for cities to limit the magnitude of climate change through effective mitigation actions to reduce their environmental impact is widely recognized [3]. This has led to a continuously growing number of international initiatives and organisations which assist city governments in proceeding towards decarbonisation [4]. This assistance takes a variety of forms, such as international guidelines or reporting platforms (e.g. the carbonn® Climate Registry), broad catalogue of measures (e.g. C40 Cities Climate Leadership Group), or collective agreements (e.g. the Global Covenant of Mayors for Energy and Climate).

However, tapping the full potential of cities in the area of climate protection necessitates the discussion of some basic challenges: first of all, the “city” as an object of assessment and level to act is difficult to define and model due to its dynamic, complex and constantly evolving character. Cities involve not only tangible assets (e.g. buildings and infrastructures), but also intangible values (e.g. cultural heritage, social relationships, etc.) often being important determinants of, or barriers to, progress. In this regard, experts ask for more interdisciplinary collaboration between hard and soft disciplines [5]. The “city” is also a network of actors and agents of change – with the city government as the main one. Secondly, the local climate action plans that are developed and implemented need to be built on long-term ambitious targets, aligned with the global goals. Setting net zero emission targets facilitates city officials to work towards ambitious strategies that are consistent with the required greenhouse gas neutrality by the second half of the century. Nevertheless, the precise meaning and applicability of concepts related to zero emissions remain unclear. The heterogeneity of the different accounting schemes [4, 6] creates problems for target setting, action planning and monitoring of success.

The paper deals with the aforementioned challenges by answering the following questions: a) What is the definition of “city” and its role in reducing GHG emissions as part of a sustainable urban development? b) How the target of net zero GHG emissions increasingly adopted by cities can be more precisely defined? To answer these questions, the city authority’s level of influence and control in each sector and field is taken into account as a necessary ingredient for making change happen.

2. City: “actor”, “level of action” and/or “object of assessment”

A clear definition and system boundary setting of “city” is essential for identifying the different sources of greenhouse gas emissions tied to it. There is no universally applicable definition of what constitutes a “city” yet [7,8]. City is a system of interdependent subsystems that can take on a variety of forms and functions. Depending on the research discipline (i.e. urbanism, geography, economy, sociology, etc.), a city can be seen as an administrative unit, an assemblage of buildings and infrastructures, a system with energy- and mass flows, a place to live and work, a place of history and cultural heritage, a value-creating system, or a network of actors amongst others. All these definitions represent different perspectives with regard to city and exist equally side by side.

It is important to select appropriate urban-specific system boundaries based on the specific targets and research questions [9]. In the context of the present paper, where the aim is to analyse the establishment of aspiring targets for GHG-emission reductions, three of the possible perspectives are considered: (1) the city as a “system” with energy and mass flows entering and leaving its boundary (and therefore a system associated with emissions embodied in the inputs and output of its processes); (2) the city as a “place to live and work” with a corresponding demand for goods and services (demand side) that can be assigned to individual needs (e.g. housing, food and mobility), as well as with a corresponding supply of goods and services (supply side) both in and outside its boundary (i.e. a “place” associated with emissions generated from the production and transportation of products and services to satisfy the “consumers” in the city and emissions directly caused from producers in the city); (3) the city as a “network of actors” whose actions influence directly and indirectly the level of emissions.

The perspectives (1) and (2) have an influence on the way emissions sources are determined and the system boundaries are demarcated. It is not “cities” themselves that cause GHGs [7] but rather particular production and consumption activities by households, businesses, industry and institutions. GHGs are therefore allocated to cities on the basis of either a) being produced within city geographical boundaries (production-based approach (PBA) – accounting at source point) or b) being generated as a result of city actors' use or consumption of goods and services and waste generation (consumption-based approach (CBA) – accounting at end user point) [10, 11]. These two different views of how city GHGs may be accounted for are linked to the capacity and responsibility of different groups of actors (city authority, consumers) to act on limiting the sources and activities that cause the greatest impact [12]. In case a), responsibility is assigned to the producers of emissions, and therefore the actors in charge of the actual sites of the emitting processes (e.g. production facilities). In case b), responsibility is assigned to the final consumers of goods and services irrespective of where they are produced (emissions are associated with their manufacture and transport), and therefore to the actors representing the demand side.

Typically, the choice is made between an accounting procedure as per a) or b) on a macroeconomic level, with the first one being much more developed and widely adopted than the latter one [13, 14]. An exact description of the selected approach is necessary for ensuring comparability when the aim is the assessment or benchmarking of performances and practices – here double counting has to be avoided (a possible risk as illustrated in Figure 1). This was also the intention of the GPC reporting standard which outlines three scopes for the inventorying of GHG emissions [15]: Scope 1 covers the direct emissions from sources located within the city boundary, and therefore the territory-based emissions; Scope 2 includes the indirect emissions that occur as a result of the use of grid-supplied electricity, heat, steam, and/or cooling within the city boundary; Scope 3 includes all other indirect consumption-based emissions.

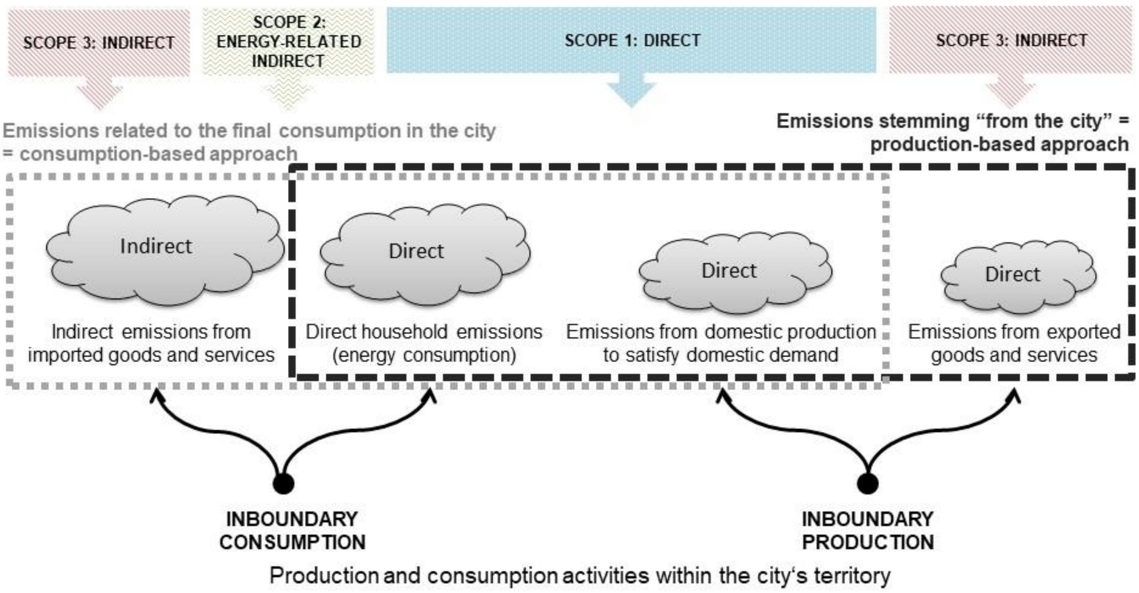

Figure 1. Illustration of the overlapping boundaries between PBA and CBA (adapted from [17]), and their correspondence with the GPC's three-scope framework [15].

For the development of mitigation strategies, the situation is different; the avoidance of double-counting is not a relevant consideration. Perspective (3) leads to the realization that actor-specific strategies are indispensable. Cities should be primarily concerned with the exploitation of all possibilities for action both on the production and demand side rather than the benchmarking of their performances. A narrow focus on PBAs – especially in the case of developed countries (and their cities) as primarily net importers of GHG emissions due to their high-consumption urban lifestyles – leads to substantial proportions of cities' GHG emissions being absent from their local emissions inventories and reduction targets [14]. This proportion can be twice or thrice as high as a city's direct emissions [16]. It is now widely recognized that effective policy-making needs to consider both approaches in a complementary fashion [12]. Only by looking at both sides efficiency, sufficiency and consistency strategies can be combined.

Once the system boundaries of the city are defined and sources and/or causes of emissions identified, the latter need to be attributed to, and therefore structured according to, key sectors (and subsectors) – when the supply side is investigated – or consumer needs (e.g. food, housing, commuting, etc.) – when the focus is on the demand side. This allows for an effective and comprehensive accounting of its GHG emissions. Already here the first difficulties arise. So far there is no uniform and generally accepted typology of sources or “polluters”. General structuring possibilities for both approaches should be worked out in standardization and harmonization efforts. However, for sector-based structures, GPC [15] can now be considered as a form of “international protocol”, since it is the one recommended by the Global Covenant of Mayors for Climate and Energy which counts more than 8000 members. For the consumer-based structures there is no “international” standard for cities, only national ones, e.g. [29].

3. The issue of target setting

The most important concept around which cities share somewhat different views and terms is the GHG (or carbon/CO2) emissions reduction target [18] as a contribution to global climate protection. Both relative and absolute targets can be used in order to assess urban-related GHG emissions and drive the design of policies and measures. Relative means to achieve a certain percentage reduction in emissions against a defined baseline, also known as “base-year target” [19], while absolute means to achieve a certain amount of GHG emissions by a target year (no need to specify a reference/baseline year in this case), also known as “fixed-level target” [19].

A global analysis by the German Federal organizations BBSR and BBR [4], which looked at 21 cities from different regions around the world, showed that many of them intent to achieve relative but not absolute reduction goals by 2030 or 2050. Some cities, however, are already shifting from relative targets to absolute global targets to guide their efforts. This category also involves conceptual targets, such as “carbon neutrality”, “climate neutrality”, “fossil-free”, “energy independence”, or “100% renewable”. Figure 2 provides an overview of some actual examples of cities with this form of target-setting. This movement towards such targets is also reflected in the emergence of a global network of cities (among other city networks operating at different scales and targeting GHG reductions in cities), the Carbon Neutral Cities Alliance (CNCA), coalesced around a shared commitment to carbon neutrality. The majority of the cities shown in Figure 2 are founding members of CNCA.

Although such absolute long-term targets provide a clear signal to all stakeholders and businesses about the city authority’s commitment to a low carbon transition, it is difficult to find clear definitions for these concepts. Focusing on the target of “climate neutrality”, according to United Nations [20], being “climate neutral” means (in general terms) to achieve net zero emissions of GHG by reducing such emissions as much as possible, while developing trade-off mechanisms to offset the remaining unavoidable emissions. Climate neutrality can therefore be used as a synonym for the scientific term “net zero GHG emissions” [21]: any remaining ton of CO_2 and non-CO_2 emissions (expressed in units of CO_2 equivalence) is balanced by the so-called negative emissions of CO_2 (i.e. CO_2 removals from biomass regrowth and/or CO_2 capture and permanent geological storage) or through offset credits.

However, although climate neutrality, as defined above, is “the goal to which all urban areas should aspire” (again according to the United Nations [20]), allowing the “balancing out” of the continued combustion of fossil fuels, without specifying minimally acceptable conditions or limits for it makes it less aspiring as “100 percent renewable”. Recognizing the dangers of leaving an unspecified room for offsets, efforts are lately focused on a more science-based perspective on the concept of climate neutrality. The negative effects of climate change can be limited if global warming remains below 1.5 °C. This possibly results in a budget of CO_2 or GHG per city or per capita. This is an ongoing discussion and the first contributions can be found at [22].

A budget-like approach has been embraced already by some cities in Germany (and Germany as a whole striving for 1 tonne CO_2 per capita and year by 2050 [23]). For example, the policy document of the City of Berlin [24] considers the ceiling per-capita budget of GHG emissions for the projected population of earth in 2050 (i.e. 9 billion people) that would keep global warming below the threshold of 2°C [25]. According to this, every person on Earth is endowed with 2 metric tonnes of CO_2eq. (life cycle-based), which means that Berlin's target should be to reduce its CO_2 emissions by 85% compared to 1990 levels (Figure 2). Another example is Munich, which, also starting from a science-based approach, sets a seemingly more ambitious neutrality target for 2050, that of 0.3 tonnes CO_2eq. per capita and year, in an effort to align as much as feasible (given the level of political enforceability) with the threshold of 1.5°C (with 66% probability) [26].

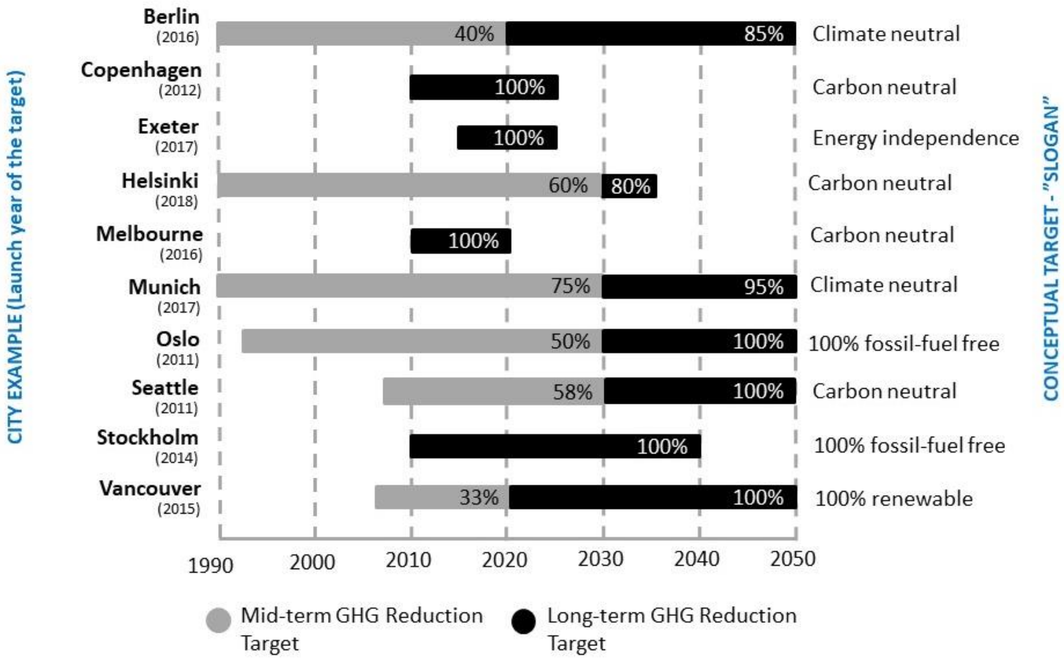

Figure 2. Examples of cities' conceptual long-term targets (adapted from [18] with new additions: Exeter, Munich and Helsinki).

At the same time, the usage of the word "climate" might be misinterpreted; it might be easily assumed that it also refers to air pollutants other than GHGs. Some have thus started replacing it with the term "GHG neutrality" [23]. Additionally, it is often used interchangeably with the term carbon neutrality; however, the last one is unclear as to whether "carbon" refers exclusively to carbon dioxide or other greenhouses gases as well.

Despite the existence of some definitions in literature, "net zero emission" or "neutrality" concepts still remain vague, with unclear system boundaries, as well as calculation and assessment rules; Variations in ways of thinking about these concepts can influence urban development. In this regard, operationalization is required, if they are to be adopted as a goal for the future development of cities [27]. The clarification points presented in Figure 3 are based on the present authors' observations and ideas and can be used as a first step towards improving transparency.

3.1. Type and scope of emissions

Type of emissions: Many neutrality targets merely relate to CO_2 and neglect other non-CO_2 gases [4]. The reason for this can often be attributed to the lack of reliable information on these GHGs. However, these cause up to 40 percent of global GHG effect and should therefore not be omitted from inventarisation, target-setting and mitigation strategies [4]. Indeed, most of existing GHG accounting and reporting standards cover the GHG gases specified by the Kyoto Protocol [15]. However, some cities adopt a middle-road approach, accounting only for carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) [13].

Scope of emissions: Cities typically estimate Scope 1 and Scope 2 emissions. However, some cities have begun to experiment with consumption-based inventories that extend into Scope 3, e.g. City of Seattle. Although Seattle does not include these emissions in its carbon neutral scenario analysis, it has included a consumption-based inventory in its plan, as well as related actions [28]. This is a good example of a double strategy for exploiting all possibilities for action. Hence the inclusion of a complementary target-setting package according to the "consumer-based" approach is recommended by the authors to obtain a real picture of energy consumption and GHG emission balance. This is also useful for bringing citizens and local stakeholders "on board" as end-users and encouraging them to assume responsibility, since in many cases the share of emissions caused directly by municipality is rather small. It is no coincidence that C40 Cities recently released a new study establishing consumption-based GHG inventories for its 79 member cities on the basis of PAS 2070 methodology [29] with the aim "to better understand the ability of cities to contribute to GHG emissions reduction activities beyond their city boundaries" [30]. This study specifically reveals that cities have a 60% increase on their carbon footprint, compared to the previous estimations for the same cities using the GPC's sector-based approach [30]. Without doubt, this undertaking implies that the time is ripe for utilizing additional accounting approaches in city-level target-setting as well as that the window of opportunity to influence consumption patterns is huge.

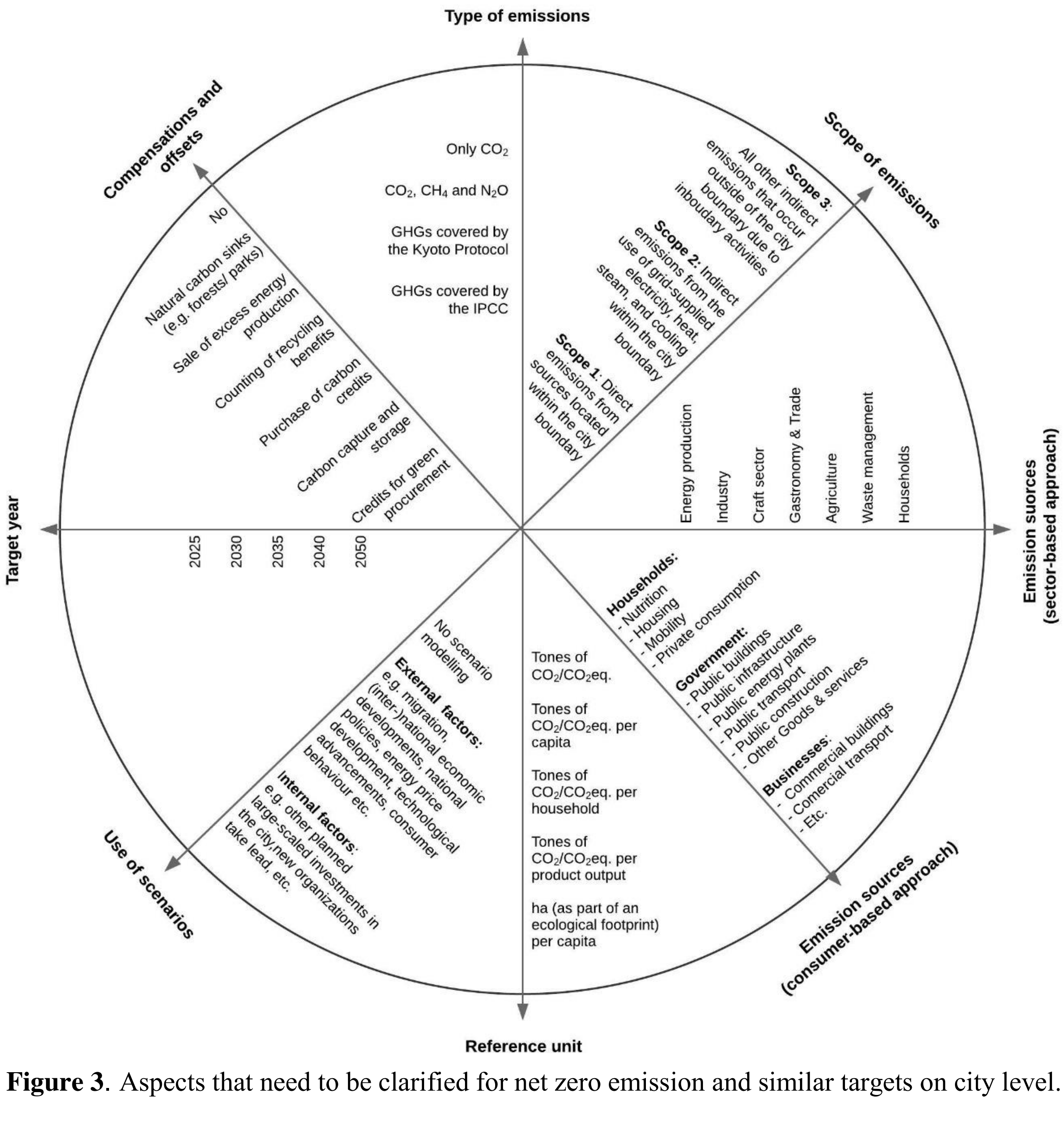

Figure 3. Aspects that need to be clarified for net zero emission and similar targets on city level.

3.2. Emissions sources

Emission targets can be set either for the entire suite of emission sources (activities in a city) represented and accounted in the GHG inventory or only for the ones over which the city governments have the greatest direct influence. While setting goals over all (or nearly all) emissions makes sense at national level (e.g. as part of the Intended Nationally Determined Contributions (INDCs) submitted under the Paris Agreement), this may be counter-productive for city-scale GHG inventories [31]. For example, some cities are dominated by emissions from large point sources, such as power plants and industrial facilities (usually serving demands far beyond the city boundary), over which they have little influence. It is recommended that cities initially exclude such emissions (only from the balance, not from the list of necessary actions – influencing industry is also essential for reducing impacts to local environment, in addition to GHGs) and instead follow a step-by-step approach, starting from the target of establishing a "GHG neutral" city administration. In addition to the decision of which sources to include in an inventory, the breakdown itself can also have an influence on the results. Figure 3 presents a breakdown both for sector-based and consumer-based approaches. The first breakdown follows the structure of macroeconomic sectors. The logic behind the second breakdown is to clearly distinguish between the different types of consumers (households, government and businesses) and the most common fields of need assigned to households, as well as end-uses assigned to other consumers, according to the currently available end-use classification frameworks. The latter is also largely compatible with [29].

3.3. Reference unit

The emission quantities can be expressed using different units and/or methods of normalization (e.g. per capita, per gross city product, etc.). For example, setting targets for per-capita emissions, in addition to overall emissions, ensures that expected population growth is being accounted for. In general, the indicator GHG emissions per capita and year is becoming central in the global debate and has already been adopted several cities as earlier described.

3.4. Temporal aspects

Use of scenarios: When planning is built in a long-term goal, understanding the baseline emissions scenario(s), also referred to as business-as-usual (BAU) emissions scenarios, is essential for better dealing with the uncertainties of the future. BAU represents the future emissions with the highest probability of occurrence in the absence of a mitigation target. Developing a baseline scenario typically requires a wide variety of inputs, such as data on critical GHG emission drivers, assumptions about how these drivers are expected to change, and information on policies that may cause these changes. On the other hand, a target scenario represents the cities' future GHG emissions based on the likely reduced emission levels caused by the planned actions (depending on whether action planning precedes or follows target-setting), and thus it shows the reduction pathway. The "distance" between a city's BAU and target scenario equals the emissions savings. There are many methods of scenario modelling that can be used [32] and various cities have extensive experience in using them, but this is not part of this paper. It is important though to distinguish "external" factors – i.e. factors capturing the uncertainties emerging from the outside world and not in the sphere of influence of the city authority, such demographic, economic and technological developments – from "internal" factors – i.e. factors that include future developments shaped by the decisions of city authority [33]. The development of scenarios as a process can also be used for another purpose: to support and stimulate larger scale discussions with non-experts and enlarge the circle of decision-making through workshops [27, 33].

Target year: Another question is how to decide upon the horizon over which the end target needs to take place. The time frame chosen influences the need for including interim targets. Setting intermittent targets as near-future milestones to compliment the longer time frames necessary for achieving overarching targets could bring several benefits [34]. This increases the particularity and practicality of the climate plan, as well as the sense of urgency, responsibility and political commitment, leading to the enhancement of the overall credibility of the "reduction path". Indeed, Figure 2 shows that most of the cities with targets beyond 2025 have also interim targets in place.

3.5. Compensations and Offsets

Several cities have adopted compensation and offsetting measures as an option for fulfilling their total carbon reduction targets. It is important to place restrictions on offsetting the unavoidable emissions in order to ensure that the focus is not shifted from overall emission reductions. This means that before anything else cities have to work on their own mitigation strategies, so as to reach the optimum level of emission reductions that can be achieved, and then take the offset possibilities as a way to balance the remaining emissions. Additionally, detailed guidance is required around the types of offset allowed, for example, in terms of whether offset actions occur onsite (e.g. production of a surplus of green energy, as in the case of Copenhagen planned to offset part of its CO_2 emissions through the provision of excess wind power to the electricity grid [35]) or offset credits are purchased from a third party (e.g. Melbourne included the purchase of carbon offsets in its 2020 plan [36]), and in the latter case, how credible the offset provider is [37]. Figure 3 shows different options for addressing a city's remaining emissions. The pros and cons of each option are explored in [28].

4. Conclusions and Recommendations

Despite the lack of a shared understanding of net zero concepts, several cities and developments around the world claim to be on the path to net zero GHG emissions, mostly focusing on a combination of efficiency and consistency strategies (improvement of energy efficiency and increased use of renewable energies). If the demand side is included, the addition of sufficiency strategies is indispensable. However, even under the condition that common understanding will be reached in the future, comparing the climate efforts of different cities around the world in terms of their "distance" to net zero emissions target would not be reasonable. It is an indisputable fact, that the starting position of each city with respect to mitigation and the way in which each one of them intends to achieve its claimed status often differ considerably [27]. The issues earlier described are not the only ones requiring attention. They bring out the need for further work in other related areas. The present authors identify implications and consequences in the following fields:

Data collection: Strong and comprehensive data that enable the tracking of changes over time is a prerequisite for any systematic work on monitoring, assessing and reducing GHG emissions. Most cities lack sources of such data. Especially in the context of the deregulation of energy markets, there is hardly any institution/body collecting all the energy consumption-related data. An additional problem is that this type of data is usually subject to data protection laws. This forces the city authorities and the experts commissioned by them to be dependent on the analysis of (partial) data from different sources. Under these conditions, besides their necessary involvement in the development and implementation phase of the action plan, industries and citizens should be also actively involved in the provision of the necessary data to ensure a more comprehensive accounting and assessment.

Reporting instruments: Cities can benefit from borrowing ideas and practices from big companies; one example is the instrument of sustainability reporting that can also be used by city authorities for the formulation of goals and the monitoring of the compliance with them.

Standardization: Currently, it is unlikely that there will be an international agreement on harmonized methods and procedures for the net zero GHG emissions approach in cities in the form of one international standard. It is rather likely that an even greater number of approaches will continue to be pursued in parallel. It is, however, important to first attempt to reach a more global consensus on a set of minimum information (including the system boundaries, the offsetting methods and limitations, etc.) to be reported in the future when municipal climate protection concepts are published. In the medium term, the development of a standard leaving adequate leeway for adaptation to the local situation, while supporting a transparent declaration of used methods and system boundaries and providing a basic typology of cities is possible. The profiles indicators according to ISO 37120 [38] already provide a good basis for the latter; the definition of cities' profiles for the purpose of fairer cross-city comparisons.

In this sense, this topic cannot yet be considered as completed and further investigation and discussion is needed.

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Visualisation of KPIs in zero emission neighbourhoods for improved stakeholder participation using Virtual Reality

Wiberg A H[1], Løvhaug S[2], Mathisen M[2], Tschoerner B[3], Resch E[1], Erdt M[3], Prasolova-Førland E[4]

[1] The Research Centre for Zero Emission Neighbourhoods in Smart Cities (ZEN), Department of Architecture and Technology, Faculty of Architecture and Design, Norwegian University of Science and Technology, Trondheim, Norway
[2] Department of Computer Science, Faculty of Information Technology and Electrical Engineering, Norwegian University of Science and Technology, Trondheim, Norway
[3] Fraunhofer Singapore, Nanyang Technical University, 50 Nanyang Avenue, Singapore 639798
[4] VR/AR lab (IMTELlab), Department of Education and Lifelong Learning, Faculty of Social and Educational Sciences Norwegian University of Science and Technology, Trondheim, Norway

aoife.houlihan.wiberg@ntnu.no

Abstract. This paper addresses the role of virtual reality in addressing the specific challenge of the increasing complexity and decreasing usability when dealing with the level of detail required to model a zero emission neighbourhood (ZEN).[1] In such neighbourhoods, there is a need to handle both 'top down' neighbourhood level data with 'bottom up' building and material level data. This can quickly become overwhelming particularly when dealing with non expert users such as planners, architects, researchers and citizens who play a key part in the design process of future ZENs. Visualisation is an invaluable means to communicate complex data in an interactive way that makes it easier for diverse stakeholders to engage in decision making early and throughout the design process. The main purpose of this work has been to make ZEN key performance indicators (KPIs) more easily comprehensible to a diverse set of stakeholders who need to be involved in the early design phase. The paper investigates how existing extended reality (XR) technologies, such as virtual reality, can be integrated with an existing dynamic LCA method in order to provide visualise feedback on KPIs in early phase design of sustainable neighbourhoods. This existing method provides a dynamic link between the REVIT Bim and the ZEB Tool using a Dynamo plugin.[2] The results presented in this paper demonstrate how virtual reality can help to improve stakeholder participation in the early design phase and more easily integrate science-based knowledge on GHG emissions and other KPIs into the further development of the user-centered architectural and urban ZEN toolbox for the design and planning, operation and monitoring of ZENs. [3]

1. Introduction

In the future, municipalities must handle a completely different level of complexity in society. In order to have well-functioning cities, cities must improve how they utilise their resources and how they engage with technologies in different ways. A smart city will use digital technologies to enhance performance and wellbeing, to reduce costs and resource consumption and to engage more effectively and actively with its citizens. In this context, the objective of this work is to investigate how visualisation methods, such as, Virtual reality (VR), can support the evaluation of zero emission neighborhood (ZEN) and zero emission building (ZEB) design concepts with respect to key performance indicators, such as, greenhouse gas emissions and other potential environmental impacts. [4, 5] The aim is to evaluate how virtual reality can help communicate, involve and improve participation from diverse stakeholders involved in the ZEN design process including politicians, municipality planners, design/planning practitioners, and citizens.

Current methods for visualizing semantic information are mostly limited to coloured map overlays, 2d and 3d-graphs or values spread across maps. The potential of using Immersive technologies, such as VR to enable users to explore and interact with real design projects is investigated in this paper, as well as, the extent to which it can be used for the planning of complex infrastructures and the visualisation of multiple key performance indicators (ZEN KPIs). This VR approach is particularly of interest to diverse experts and decision-makers in order to provides them with the means to explore results early in the design phase and on-site. Full details related to the research presented in this paper can be found in Løvhaug and Mathiesen. [6]

1.1. ZEN Definition, KPIs and pilot project

1.1.1. ZEN Definition and ZEN KPIs

The vision of the ZEN Research Centre, together with its industrial partners, is to create zero emission neighbourhood in smart cities (ZEN). [1] In the ZEN Research Centre, a neighbourhood is defined as a group of interconnected buildings with associated infrastructure, located within a confined geographical area. A ZEN aims to reduce its direct and indirect greenhouse gas (GHG) emissions towards zero over an analysis period typically of 60 years, in line with a chosen ZEN ambition level with respect to which life cycle modules, buildings, and infrastructure elements to include. The ZEN assessment criteria and key performance indicators are divided into seven categories (GHG emissions, energy, power/load, mobility, economy, and spatial qualities), and each of these categories is divided into several assessment criteria. [4] The assessment criteria are then divided into several key performance indicators (KPIs) which are listed in Appendix A.

1.1.2. ZEN Pilot projects

In the context of the ZEN Research Centre, pilot projects are geographically limited (primarily urban) areas in Norway and serve as innovation hubs where researchers, building professionals, property developers, municipalities, energy companies, building owners and users, test new solutions for the construction, operation, and use of neighbourhoods in order to reduce the greenhouse gas emissions to zero on a neighbourhood scale [4]. Various stakeholders will have different influences on a ZEN pilot area at different times during the development of the area. In this case, key stakeholders include Trondheim municipality and the project owner NTNU, as well as, other stakeholders. The pilot site at Nidavoll Skole [7] in Sluppen is located in the larger ZEN pilot project called The Knowledge Axis [8] and culminates in Sluppen, a mainly commercial area that is planned to be developed into a multi-functional neighbourhood.[9]

1.2. Virtual Reality

There exists a variety of techniques, tools and technologies for displaying data using diverse media. Examples includes 2D-based screens like traditional desktop applications, tablets or interactive multitouch solutions. On the other hand, there are more immersive tools which are covered by the term Extended Reality (XR), which is an umbrella term to refer to all real-to-virtual combined environments such as Augmented Reality (AR) and Virtual Reality (VR). While more traditional user interfaces like desktop applications which are more advantageous when displaying and navigating through large quantities of text-based data, whereas XR is more suited to creating an experience for the user. Solutions span from showing information on a tablet, to strapping the user into a haptic suit with a head mounted display. Due to the immersive effect of head-mounted displays, the user can interact with the data in a way that is limited in desktop-applications. For this project, it was decided to further explore the possibilities of visualizing data using VR. In recent years, the main focus for VR has been centred around the entertainment industry. This focus has driven the innovation in the field where different manufacturers are promising better and cheaper solutions, and has also made the technology available for consumers. There has been a large increase in technologies allowing for users to interact and alter a virtual environment, and technologies suited for immersive experiences.

Virtual Reality is a computer-generated experience which takes place in an virtual environment. Normally the user wears a head mounted display (HDM) with two individual images for both eyes, creating a depth perception. The HMD is tracked by either itself (inside-out) or sensors in the room (outside-in). This allows the application to mirror the position of the user in the real world, in the virtual world. The user can interact with the environment by using speech, hand-tracking, eye-tracking or input devices, where the most common is a form of controller which is tracked in all directions, mimicking the user's movements. VR technologies are potentially groundbreaking for visualising data and creating an experience for the user. It is now possible to not only showcase the data and environment on a 2D screen, but also put the user in the actual environment itself. Combined with different techniques of data visualisation, the overall aim is to leave an impression on the user, as found in a study from University of Maryland where their results showed that participants remembered on average 8.8% more of information presented in VR.[10] By using existing floor plans one has the ability to create a digital twin of the buildings. With this 3D-model one have the ability to re-create a realistic replication of the environment with connected information displayed on and around the 3D-model. In addition to the data visualisation, it is also possible to display the building in a realistic way before the building is even constructed. This use case can make it easier to communicate data and engage diverse stakeholders early in the design process. There are several VR products available, all in different price-ranges which can be defined in two sub-categories; low- and high-end.

The focus of this paper is on the results using high-end VR involving the development of the HTC Vive [11] for use in our application using the Unity 3D software[12] which works well with all known VR headsets and controllers supporting OpenVR. The reason for choosing the HTC Vive was also because of its availability and ease of use. As opposed to the low-end sub category, this kind of equipment is in general more expensive. While the application relying on the low-end equipment can be tried at home, the high-end solutions often needs to be made available for user at for example stands or promotional events. The technology needed to fulfill the requirements in the high-end sub category varies depending on the application. For less intensive tasks, it can suffice to use with a mid-range desktop computer, but for applications which demand more processing power, it is recommended to use a top of the line GPUs. VR head mounted devices (HMDs) have seen rapid development, which initially was mostly driven by the fast hardware iterations of the smartphone industry. The current wave of VR devices began with the Oculus Rift Kickstarter campaign in 2013 accumulating close to 2.5 US dollars in pledges.

Table 1 Development of of VR devices based on popular HMDs

Date	Description	Resolution per Eye	Horizontal View	Features
3.2013	Oculus Rift DK1	640x800	90	only 3 DoF tracking
7.2014	Oculus Rift DK2	960x1080	90	
4.2016	Oculus Rift CV1, HTC Vive	1080x1200	90	
10.2017	WMR Lineup	1440x1440	90	inside-out tracking
4.2018	HTC Vive Pro	1440x1600	90	
2.2019	Pimax 8k	3840x2160	170	

2. Method

2.1. Research Method

The Design Science Research [13] has been used in this research and focuses on three different cycles, as explained by Hevner [14]. This includes the *relevance* cycle, *rigor* cycle and *design* cycle. In short, the *relevance* cycle ensures that the result of the research fits into the intended usage area. The *rigor* cycle aims to ensure that the research is representative of the 'state-of-the-art' in the application domain. Finally, the *design* cycle facilitates a development process which consists of several iterations with rapid evaluation.

The prototype used in this research is the ZEN pilot project at Nidarvoll Skole [7] as the main design project, and gives the user the ability to view the pilot project from both a building- and neighbourhood perspective. The embodied carbon data is gathered from an Excel based tool called The ZEB Tool [15]. The pilot project is in a very early stage of design and since there is limited available data, the data used in the prototype is based on another school named Østensjø School in Oslo. There are also limitations regarding to the availability of a 3D model, however, by using existing building plans, an initial Revit model of the main building has been created. New models will be added to the system in the coming months. By using this project for the ZEN VR application, the results from retrofitting and new buildings with data from early phase design can be compared to data from different stages of design to visualise how different design or materials changes impacts the different KPIs in a design project.

2.2. Data Source and LCA Method

This works builds upon the work already developed by Houlihan Wiberg together with students to develop a visual LCA method, using a user interface in the form of a dashboard, connected to an integrated dynamic Revit 3D and the ZEB Tool [16, 17]. In this initial version of the developed VR software, the focus is on visualizing the KPIs related to carbon embodied in the production, transport, and replacements of building materials. The embodied carbon data from the ZEBTool [15] is stored together with data from other sources in a MySQL database which is specifically developed for the purpose of structuring and storing building LCA studies in a comparable and accessible format [18], so that the data can be used in applications such as the one presented in this paper. This solution allows easy online access and ensures that the user is always presented the most up to date information and that it is easy to add new information relevant for the application. Furthermore, the database has a set of additional building LCAs which are used to set reference values when benchmarking the results of the case study. In order to be able to run the application offline, the application has a local copy of the database which it used when there is no database connection.

2.3. User study and questionnaire

The VR application and its potential was evaluated through the use of semi-structured expert interviews and its usability, through a questionnaire. The participants of these two methods of data collection tes the application on the same terms, with a set of predefined tasks. These were conducted in order to answer the research questions. The strategy for obtaining informants used was primarily the snowball technique. To evaluate the user interface and ascertain the degree of usability when using the system, a questionnaire was designed. The questionnaire was designed after the principles of a Likert scale. The general methodology used when conducting the user study has been semi-structured expert interviews which allows one to get the chance to ask the informant specific questions, but it also allows for unexpected turns. There were three participants in each of the interviews including the informant and two of the authors of this paper which allowed for one to lead the interview and the other to take notes on essential parts of the interview. However, the main collection of data were audio recordings that were later were transcribed. A detailed description of the user study and questionnaire methodology may be found in Løvhaug and Mathiesen [6].

2.4. 3D Model – Unity Software - VR

For the visualisations to be as realistic as possible, the buildings are exported from the BIM software Revit [19]. The models are then converted Autodesk Maya [20] before importing them into the Unity 3D, because when Revit exports 3D modes, it does not use a naming convention resulting in some building elements end up being unnecessarily detailed, making the app run slow. The choice of using BIM models in the application ensures that the building models are directly linked to the work of the architects, and visualisations can therefore be part of an iterative design process.

3. **Results**

The preliminary results in this paper describe the application prototype, and the informal and rapid feedback from user testing in order to visualise ZEN KPIs and improve stakeholder participation early and throughout the design process. The results provide a way to visualise a selection of KPIs from the an actual ZEN pilot projects at different levels of detail. Non-expert users of the application can see how this neighbourhood is performing compared to other projects in the vicinity. It is also possible to walk around the neighbourhood, inspect individual buildings and identify which building components and materials are the highest driver of emissions. The application also has the flexibility to add new KPIs when more data becomes available for each pilot.

3.1. VR Application Overview

The Research Centre on Zero Emission Neighbourhoods in Smart Cities have defined a set of assessment criterias and key performance indicators which are used to track, evaluate and validate the progress of ZEN pilot areas. The developed prototype builds upon existing work conducted at the Fraunhofer Research Centre in Singapore, where several different VR and AR-applications have been developed, one of which is used to assist the Housing and Development Board in Singapore. [21] This application utilizes VR in a way that correlates with the vision of the end product of our research. The application aims to visualize data for the Nidarvoll site in light of a selection of these predefined criterias. In order to achieve different levels of detail, a three layered model with the following views which were developed in the VR application as shown in table below:

1. *Full view*
   This view displays all available projects in the Sluppen area. The map of the neighbourhood and surrounding area are are put on a table-surface and the user have the ability to get an overview of the whole area. Relevant KPIs for this view would be aggregated values from all buildings and other high level high level KPIs such as mobility, economy and energy efficiency.

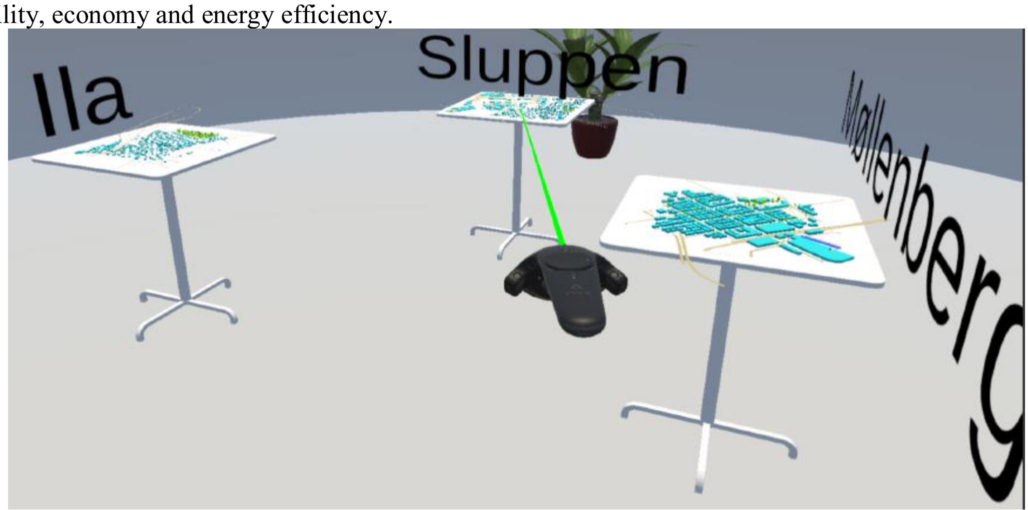

Figure 1. Full View of the Sluppen area Using VR

2. *ZEN-view*
   When selecting a specific pilot project in the full view the user gets transported down one layer, and is presented with the ZEN view. In this view the user stands in a small scale model of the environment and have a ability to teleport around and inspect each part of the neighbourhood. The user can, to begin with toggling between two different KPIs i.e. GHG emissions and energy consumption/generation. Emission values are presented as either a colorisation of the buildings or a column visualisation, both of which have a possibility to be further developed in the future. For comparing the score of the buildings in the neighbourhood, the user has two options: 1) evaluate the buildings total CO_2eq/m^2 compared to the total CO_2eq/m^2 for all buildings present in the pilot area. 2) Evaluate the buildings total CO_2eq/m^2 compared to the total CO_2eq/m^2 for all buildings that are present in the database. To put these numbers into context and to engage the user, it is possible to visualise the weight of the CO_2eq emissions in terms of vehicles most users are familiar with using images of airplanes and cars. In addition, it is possible to get an explanation as to what the emission equals in kilometers driven in cars and round world trips in airplanes. This is shown on the left in Figure 2. Energy is visualized as a bar which displays energy consumption versus energy production for each building. The user will also be able to see the sum of consumption and generation. In the next stage of development, when the energy KPI has actual data, the user would be able to get examples of feedback for energy usage.

Figure 2. Snapshot in ZEN View of the Sluppen area using VR to visualise emissions of buildings

3. *ZEB-view*
   If the user selects one specific building in the ZEN view, they teleport down to the ZEB-level (Building level). This view focuses on one particular building, and serves the purpose of communicating the KPI GHG-emissions for both each building part and every material in said building part. This view has two models; one 1:1 model where the user can teleport inside and experience/inspect the building. The other is a "dollhouse"-model where the user can inspect and interact with the building by clicking on building parts. The user is also presented with a menu for toggling between different building parts. The KPI score is visualised using colorisation similar to the ZEN-view. The user can choose two different approaches; the first compares the performance of each building part to the total emission of the building. The second approach weights the building mass as part of the equation and returns a score based on both the emission and building part mass compared to total building mass. If the user selects one specific part, they get presented with material information in tabular form for the selected element. In addition to the tabular form, the materials used will be visualised in actual size and weight so the user can put the quantity of materials into context. The intensity of the emission is visualized by using the same columns from ZEN-View. The purpose again is to give the user a more immersive experience and to put the numbers into context.

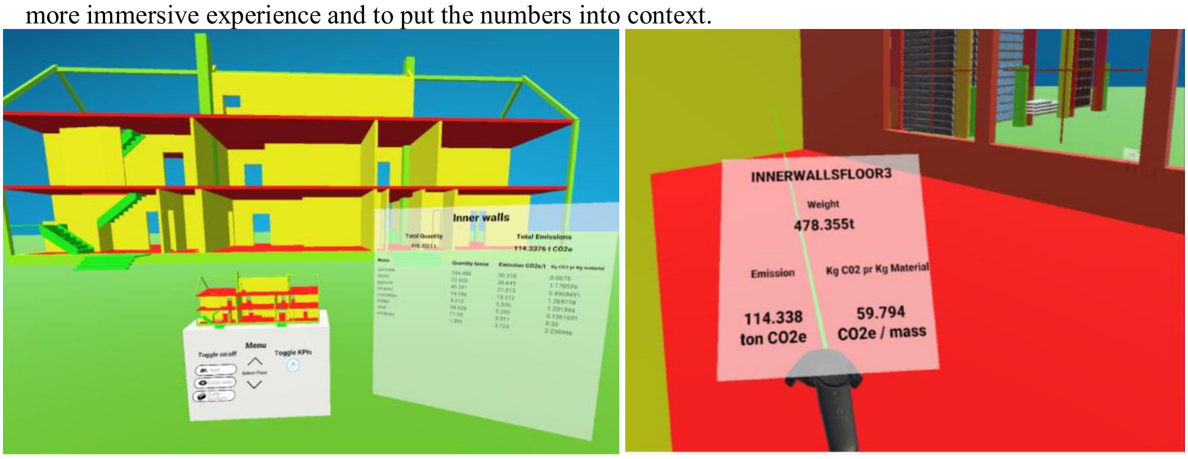

Figure 3. ZEB View of a building using VR to visualise emissions and by listing materials in tabular form

3.2. Results of user tests and questionnaires

After conducting some informal user-tests on subjects without prior knowledge regarding sustainable neighbourhood design, the results show that average citizens and other stakeholders do not find it easy to understand what the emission data means in relation to the neighbourhood context, and designers find it difficult to understand how to integrate this data into the design process. As a result, a design has been developed which focuses more on the immersive experience and visual display of data as a means to communicate complex KPI data. An example of this, is the visualisation of the amount of timber used in construction not only as a number, but also as as number of virtual logs stacked. Another example is, that the contribution of transport related emissions is indicated as a number of different vehicles and GHG emissions for travel distance and intensity of pollution is indicated in size and colour.

It was found that when working on the application, that by using high-end VR equipment, a more immersive experience is achieved which results in more engagement from the user and facilitates easier interaction and feedback with the ZEN KPIs. The results also show that users enjoy exploring the novelty of a virtual environment and because of this, it was decided to only implement a small portion of the pilot area, so the user would not get lost in the experience, but rather focus on interacting with the relevant information and specific KPIs for the area. It was also found that the *Unity 3D* software allows for quick prototyping and development for multiple platforms at once in addition to making a high quality result.

Another finding was that size matters. Some of the visualisation methods, first deemed unnecessary, ended up being the most important in making an impression on the user. By using only colour visualisation of the emission data, the user does not fully understand the significance of the emission results. However, it was found if different sizes of columns are used instead to communicate the significance of the level of resulting emissions from the building, it was found that the users more easily understood this data in this more visual context. One of the test-subjects stated when looking at a large, red column that she *"I would not like to live in that house"* due to the associated high emissions.

4. Conclusion and Discussion

The results of this paper show that this ZEN VR approach provides for a new and intuitive way of interacting with and viewing multiple KPIs simultaneously. This approach presents a new way of combining KPI data with BIM models early in the design process. By utilising visualisation methods which inspire and engage diverse stakeholders to explore the environment and learning by putting numbers into context, the ZEN vision of a sustainable neighbourhoods can more easily be communicated by diverse stakeholders. VR is a valuable tool to engage users with no prior knowledge of ZEN or KPIs, to put data into context and to more easily understand the meaning and size of the numbers presented. This VR approach improves communication with and between stakeholders and provides a means to overcome traditional interdisciplinary barriers. It was also found that high end equipment offers a better immersive experience by having better image quality, performance and input possibilities. This makes it easier to engage the user and keep their attention in the application while learning useful information, but with an increased cost and more cumbersome setup.

The research explored the utilization of virtual reality as a tool for engaging and interacting with emission data in new and immersive ways. A VR application, called ZENVR, was developed through several iterations by connecting an existing MYSQL database, containing life cycle assessments of 11 projects in Unity 3D. Furthermore, the application and its potential was evaluated through the use of semi-structured expert interviews and its usability through a survey. The participants of these two methods of data collection all tested the application on the same terms, with a set of predefined tasks. These were conducted in order to answer the objectives of this work which was to investigate how visualisation methods, such as, Virtual reality (VR), can support the evaluation of zero emission neighborhood (ZEN) design concepts with respect to key performance indicators, such as, greenhouse gas emissions and other potential environmental impacts.

The results of this study found that virtual reality is a good platform for communicating and visualising complex data including the KPIs in sustainable neighbourhoods, for not only researchers but also for the general public. ZENVR can be used as a data visualisation tool for presenting data in a understandable format by creating a presence inducing environment which subsequently may result in an emotional experience when interacting with the application. In ZENVR we have shown that these principles can be used to visualize the KPIs from ZEN. These visualisation methods are exemplified through greenhouse gas emissions related to the transport and use of materials, but the principles are transferable to numerical data in general.

In terms of which form of data visualisation are most beneficial for comprehending the KPIs for different user group, it was found that ZENVR allows for selecting between several forms of data visualisations. Expert interviews revealed that professionals preferred traditional visualisation approach i.e. columns, colors and numbers when looking at KPIs. It was further discovered that in order to make a lasting impression, which ultimately is the goal of ZENVR, one have to use visualisation methods which appeal to the human emotions. This can be achieved by anchoring the visualisations to human factors by using the principles mentioned earlier, for instance using sizes to make the user feel small or movement of objects for dramatic effects. The visualisation type which made the biggest impact on all users was when numbers were put into context by using relatable objects from everyday life.

In relation to how can VR be used to improve stakeholder participation in sustainable neighbourhood projects, the results show potential areas where ZENVR can be used to improve stakeholder participation include citizen engagement, promotion and the advertisement of ZENs, tool for interdisciplinary communication and collaboration between professionals. With its natural immersive properties, VR has proven to be a suitable platform to spark engagement among its users. Through a well designed VR environment, highlighting the beneficial parts of an environmental friendly neighbourhood, all subjects agreed that this has a huge potential to promote sustainable neighbourhoods. In addition, VR allows for displaying data in new perspectives making it understandable for different stakeholders, reducing the barriers of interdisciplinary communication and collaboration.

5. Further work

The application in its current state is experimental and should be viewed more as providing a foundation for further development. Further work should investigate how more KPIs can be included in the application and the associated effect on stakeholders. In addition, when the application is more complete and thorough, user-testing might reveal if the usability improvement suggestions from the latest iteration are indeed useful. From a technical point of view, some alterations and features which might benefit the application arose from conducting user tests and interviews. These mostly centred around the user interface and how it might be changed to better suit the user's needs and understanding. It would be advantageous to test the application with other virtual reality systems to test its compatibility and possible adaptations that may be necessary.

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Appendix A

Category	Assessment criteria	Key performance indicators (KPIs)
GHG emission	• Total GHG emissions • GHG emission reduction	• Total GHG emissions in tCO_{2eq}; tCO_{2eq}/m^2 heated floor area (BRA)/yr; $kgCO_{2eq}/m^2$ outdoor space (BAU)/yr; tCO_{2eq}/capita • % reduction compared to a base case
Energy	• Energy efficiency in buildings • Energy carriers	• Net energy need in kWh/m^2BRA/yr; Gross energy need in kWh/m^2 BRA/yr; Total energy need in kWh/m^2 BRA/yr • Energy use in kWh/yr; Energy generation in kWh/yr; Delivered energy in kWh/yr; Exported energy in kWh/yr; Self-consumption in %; Self-generation in %; Colour coded carpet plot in kWh/yr
Power/Load	• Power/load performance • Power/load Flexibility	• Net load yearly profile in kWh; Net load duration curve in kWh; Peak load in kWh; Peak export in kWh; Utilisation factor in % • Daily net load profile in kWh
Mobility	• Mode of transport • Access to public transport	• % share • Meters; Frequency
Economy	• Life cycle cost (LCC)	• NOK; NOK/m^2 heated floor area (BRA)/yr; NOK/m^2 outdoor space (BAU)/yr; NOK/capita
Spatial qualities	• Demographic needs and consultation plan • Delivery and proximity to amenities • Public Space	• Qualitative • No. of amenities; Meters (distance from buildings) • Qualitative

Table 2. ZEN assessment criteria and KPIs covered in ZEN definition guideline.[2]

Crafting local climate action plans: An action prioritisation framework using multi-criteria decision analysis

Balouktsi M[1]

[1] Centre for Real Estate, Karlsruhe Institute of Technology, Karlsruhe, Germany

maria.balouktsi@kit.edu

Abstract. The COP21 target to keep global warming to well below 2 (or 1.5) degrees Celsius cannot be met without massive transformation in cities. A major challenge on the road to nearly greenhouse gas (GHG) emissions-neutral cities is the successful development of a climate action plan (CAP) by the local authority, sometimes within the framework of its participation to different initiatives (e.g. the Global Covenant of Mayors). While the identification of the best actions for reaching their long-term GHG emission reduction target constitutes a common decision-making problem for local authorities, it is also an intricate one: conflicting and incommensurable aspects such as environmental, economic, social and technical issues, as well as conflicting stakeholder interests should be dealt with simultaneously when actions have to be programmed. Multi-Criteria Decision Analysis (MCDA) methods are well-known to cope with these complexities and have already been used for decades in several fields. However, they have not been systematically used within the context of local CAPs. The methodologies which are normally implemented to support the prioritisation of actions wholly or to a great extent rely on economic analyses and do not capture the potential co-impacts. In this context, this paper proposes a general participatory framework for guiding collaborative prioritisation of actions as a methodology to help local authorities with the development of more sustainable CAPs, while using MCDA. Finally, advantages, limitations and further steps in research regarding the proposed framework are discussed.

1. Introduction

Climate change is undoubtedly the global environmental risk currently receiving the most attention, and is, according to the Intergovernmental Panel on Climate Change (IPCC) [1] one of the most serious contemporary challenges to achieving a sustainable society. A collective response of nations to the urgency of tackling climate change is marked by the COP21 target to keep global warming to well below 2 (or 1.5) degrees Celsius compared to preindustrial levels. However, it is nowadays well-acknowledged that such ambitious global goals are predestined to fail if climate action is limited to national or regional levels [2]. Massive transformation in cities and the engagement of non-state actors in mitigation action are indispensable, since cities' residents are responsible for more than two-thirds of the global energy consumption and up to 70 percent of GHG emissions [3]. Certainly, the recognition of the vast potential of cities to mitigate climate change by both researchers [4] and policy makers [5], has led to an increasing number of local governments committing to climate and energy pledges and developing local climate action plans (CAPs), sometimes within the framework of their participation to different city networks. Examples of such networks are the EU Covenant of Mayors (CoM) and the Compact of Mayors, which were recently merged together to form the largest global coalition of cities and local governments of all sizes, the Global Covenant for Mayors for Climate and Energy (GCoM) [6]. Particularly in Europe, already more than 60 percent of its cities have some sort of local climate plan in place [7]. In France, Slovakia and the UK, the adoption of such local CAPs is even compulsory for municipalities [7].

Although these numbers are encouraging, not any type of climate plan is sufficient. Cities should not only eventually strive to limit their emissions as close to zero as possible (i.e. become climate neutral), but also do so in the most sustainable way possible. Climate action is not an issue to be considered in isolation; it is one of the sustainable development goals (SDGs) of UN Agenda 2030 (i.e. SDG13) and is significantly linked – positively or negatively – with achieving many of the other SDGs [8]. In this sense, for local authorities on the road to developing a successful CAP the decision-making problem of identifying and choosing the best actions for practical implementation among the plethora of the possible ones is a multi-criteria and intricate one: conflicting and incommensurable aspects such as environmental, economic, social and technical issues, as well as conflicting stakeholder interests should be addressed simultaneously. It is no coincidence that a 2017 survey by the EU CoM Office on their community's capacity-building needs and knowledge gaps for the design and implementation of Sustainable Energy and Climate Action Plans (SECAPs), revealed that the second strongest methodological need of EU cities is "defining and prioritising actions based on certain criteria" [9]. In other words, local authorities lack understanding for prioritizing mitigation (and adaptation) actions.

Multi-Criteria Decision Analysis (MCDA) methods are well-known to cope with the complexities inherent in participatory and transdisciplinary decision-making and have already been used for decades in several fields. However, the methodologies which normally support the prioritisation and eventual selection of actions as part of developing local CAPs are limited to analyses wholly or partly relying on economic metrics. Most CAPs do not suggest the systematic use of MCDA. Indeed, there is still a limited number of case studies where MCDA methods have been applied to address this specific problem. In this context, this paper proposes a general participatory framework for guiding collaborative prioritisation of actions as a methodology to help local authorities with the development of more sustainable CAPs, while using MCDA. The framework is primarily built on a scan of recent literature and developments and it has not yet been systematically tested on real projects.

2. MCDA: An alternative approach to traditional methods for prioritizing interventions

In general, in addition to traditional financial analysis, the most employed and widely accepted forms of analysis amongst governments to inform decision of whether a particular project or policy is worthwhile are cost effectiveness analysis (CEA) and cost benefit analysis (CBA) [10]. CEA is limited to identifying the most "cost-effective" action for achieving a single objective – in this case GHG emission reduction – and is therefore inappropriate for evaluating alternatives with co-impacts [11]. On the other hand, CBA can incorporate potential co-impacts by first assigning a monetary value to non-monetary aspects that need to be considered, such as environmental quality and health effects (in order to make all aspects comparable) and then comparing the aggregated costs and benefits of different alternatives expected to accrue along a specified duration [12]. However, for several social, environmental and technical aspects, monetization becomes controversial as limited examples of valuation techniques are available, or if available, significant uncertainties remain [13]. Several authors warn about converting all values into single metrics like monetary units [14].

In those cases, the use of alternative evaluation techniques, such as MCDA is advisable. MCDA enables the evaluation of the performance of an action or policy on multiple objectives/criteria and offers an alternative to the monetary valuation of environmental and social aspects when faced with the selection of actions. As pointed out by Ürge-Vorsatz et al. [13] MCDA has at least three strengths that go beyond what social CBA can offer and make it particularly suitable for climate-related decision-making. First, it provides a framework to handle together quantitative and qualitative information, therefore it can deal with incommensurability and it does not necessitate the use of any valuation technique to monetise non-monetary aspects [13, 15]. The fact that MCDA can include criteria which CBA cannot immediately makes it more suitable for strategic decision-making [16]. Second, it allows the inclusion of stakeholders' preferences into the decision-making process through the definition of weights for the criteria. Third, it frames decision-making within a structured process of social deliberation and dialogue between stakeholders, analysts and scientists [13, 17, 18]. In other words, MCDA allows the use of qualitative information, the incorporation of stakeholder perspectives through weighting, and promotes a more democratic decision-making in the search of a compromised solution.

However, MCDA is not as standardised as CBA, despite its wide application in academic research – also in fields related to climate action – and the publication of government guidelines for some countries to support public authorities in its effective conduction (e.g. see [10]). The lack of official guidelines leads to most officials being less familiar with MCDA techniques [10]. However, when informed, they view MCDA as a useful decision-support tool for complex decisions. A study where 21 Dutch transport officials (and therefore real decision makers (DMs)) were interviewed showed that: (1) they find the composite result of CBAs pretentious and therefore they use CBA in a non-decisive manner, and (2) they are interested in appraisal tools which clearly show the important tradeoffs of different policies [19]. Therefore, it is recommended to use MCDA as a tool to support the early stages of climate action planning for first narrowing down the wide number alternatives to the most promising ones from a multi-stakeholder perspective. Then, one can switch to CBA for more detailed analysis.

3. The framework

The systematic undertaking of MCDA to support the prioritisation of actions requires specific procedures, methods and tools to be available. This section provides a standardised and transparent decision procedure that integrates MCDA as a tool to help decision makers to the specific problem of climate action prioritisation and eventual selection (Figure 1). Roy [20] distinguished between four major stages of the decision procedure with regard to multi-criteria decision problems: definition of alternatives, definition of criteria (i.e. parameters characterising the decision problem), synthesis and modelling of the DMs' preferences, and solving the problem. The structure of the standardised procedure proposed in this paper expands Roy's major stages and was partly inspired by previous work in this field [21, 22]. The proposed procedure consists of three phases, namely: (a) problem structuring, which establishes the context within which the prioritisation takes place; (b) development of the MCDA model, which defines all the inputs required to run a multi-criteria evaluation according to the selected method; (c) the MCDA application including a sensitivity analysis. These steps are further subdivided into eleven further methodological steps requiring different methods/tools. Due to the limited space here, the paper focuses on steps V, VI, VIII, while Phase I is only briefly described (since it forms the basis).

3.1. Problem structuring

It is generally well-acknowledged that the participation of local stakeholders in energy and climate planning could improve not only the quality of the local CAPs due to the integration of local knowledge, but also their acceptance and effectiveness [23]. To identify stakeholders and assess them based on their power, interests, motives and attitude in relation to climate planning (as part of Step I, Figure 1) the instrument of stakeholder analysis has to be utilized. Such an analysis facilitates authorities to eventually bring the most salient stakeholders into the decision-making process. The literature proposes various methods for facilitating the process of stakeholder analysis [24]. Most papers argued that no method is better than the others and that a combination of existing methods likely produces the most useful results. The same applies to the engagement methods, where again a variety of possibilities are available [23], and the decision will depend on whether the purpose of participation is to inform, consult, cooperate, collaborate and/or empower. Regardless of the methods selected for the stakeholder analysis and their subsequent engagement, special attention should be paid to the two following aspects not enough highlighted in literature: (1) in addition to inviting powerful stakeholder groups as DMs in the process, representatives of vulnerable populations that will be most impacted by the plan must also be involved. This will help avoid situations of environmental, social and economic injustice; (2) in the creation of communication messages not only complex concepts should be simplified but also should be tailored to the mental model of each targeted stakeholder. Useful advice on how to more effectively communicate the controversial topic of climate change to non-technical public is available by Shome et al. [25].

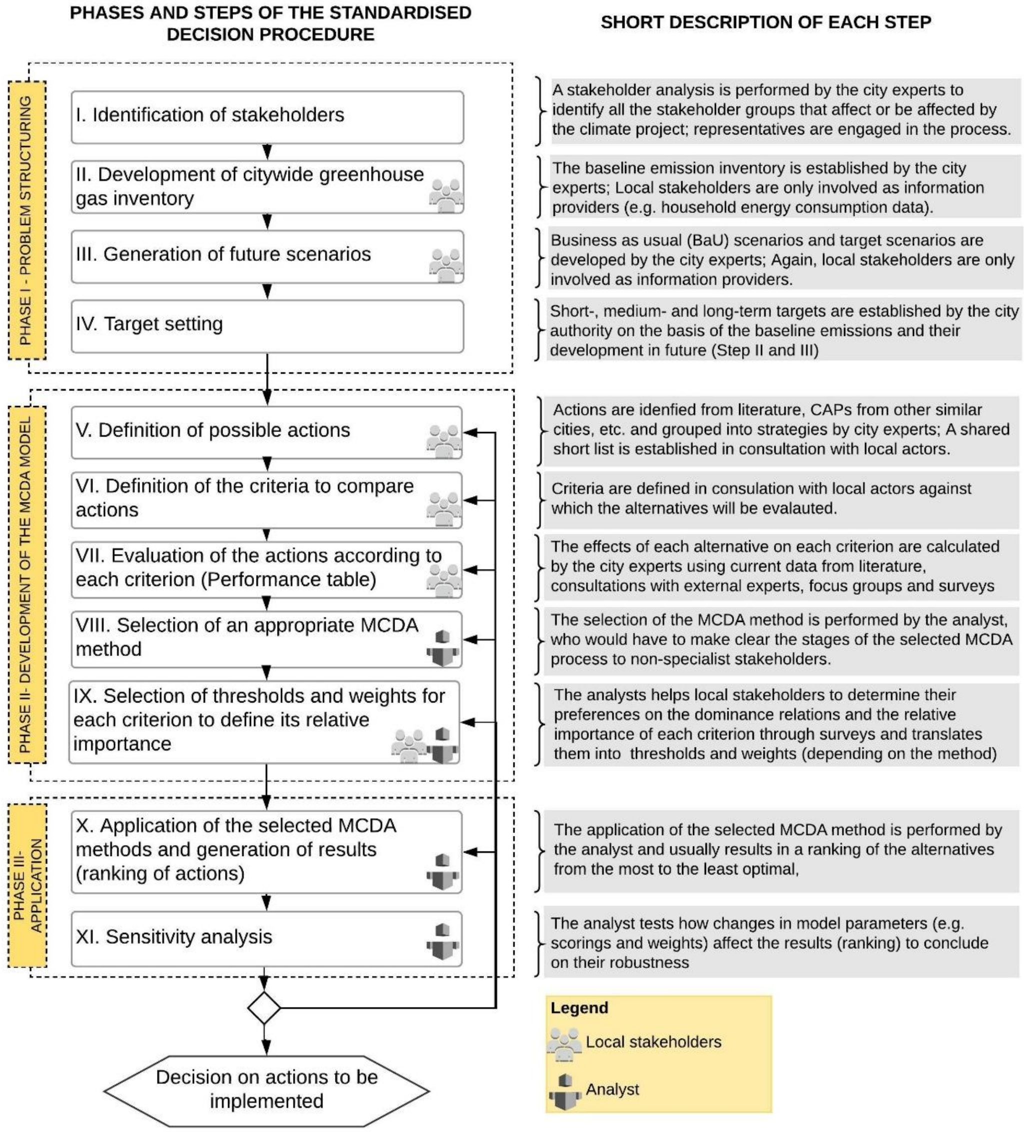

Figure 1. An action prioritisation framework for CAPs on the basis of typical MCDA procedures

The creation of a citywide GHG inventory (Step II, Figure 1) is mainly a technical task usually assigned to the related technical departments of municipality. A GHG inventory helps in determining the baseline emissions and identifying key emission sources and reduction opportunities [26]. In this step local stakeholders are involved as information providers and not as DMs. There are several inventorying methodologies in place that cities can apply [27]. The current trend is though towards the use of common reporting standards, such as the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC) to allow the comparability of climate progress. Regardless of the inventorying standard used, it is noteworthy that although the city authorities are responsible for the generation of the inventory, they are not exclusively responsible for all of the emissions reported; some sources can only be influenced on a national level (e.g. industry). After selecting the strategic areas of action, cities have to conduct scenario analysis (Step III) to identify possible future emission trends on the basis of different socio-economic growth and climate mitigation assumptions [26]. This serves the basis for setting short-, medium-, and long-term citywide emission reduction targets (Step IV). The local knowledge, the baseline emissions, and the different targets form the ground of all the steps that follow.

3.2. Definition of possible actions

Actions are the fundamental building block of CAPs [26]. In addition to the categorisation and examples of climate actions provided by the EU CoM [28], there is nowadays an abundance of sources (either in the form of reports, tools or databases) that provide similar generic listings and categorisations (e.g. see [27, 29, 30, 31]) and can form a basis for this step. Many of them only incorporate actions in critical sectors where cities have the greatest control (i.e. buildings, transportation and waste management). Of course, actions can also be cross-sectoral. In addition to these typical lists, cities can also learn from implementation experiences in other cities. However, each city has its own geographic and socio-economic context and an action proved to be effective in one city may not be in another. Although the usefulness of learning from already realized good practice initiatives has been acknowledged by the EU CoM through the provision of a related database [32], the only context specific factors provided to filter the provided real examples of (more than 6000) measures are the population and country.

A need for more contextualized comparisons (with the purpose of learning) among cities is better expressed in CURB tool – the recommended tool to use by the Compact of Mayors for the development CAPs [30]. This tool, through its "benchmarking module" allows comparison of cities with similar characteristics on the basis of three filters: (1) region; (2) socioeconomic development (measured on the basis of the Human Development Index (HDI) rating); (3) climate. The latter parameter is an especially strong driver of energy consumption and associated GHG emissions in buildings, since heating and cooling demand may vary widely across cities with different climates, even in the same region. Although this "module" primarily aims at comparison, cities in the process of developing a CAP can use it to identify similar cities with already some experience and learn from their successes or failures.

Another critical point for cities to consider in this step is that achieving ambitious targets means that cities should also consider the inclusion of testing of more innovative actions in their climate plans. They should therefore grasp the opportunity to move from an above typical (or good) practice to becoming a leading paradigm for cities of a similar type. In this sense, for populating the list of possible actions cities can also seek inspiration from initiatives, such as C40 and Carbon Neutral Cities Alliance (CNCA), which actively encourage the recognition of the boldest and most ambitious climate actions in cities not only though climate leadership awards [33] and innovation funds [34], but also through reporting on best practice (e.g. in the Cities100 report [35] or the CNCA game changers report [36]).

Finally, for this step, it is not only important to identify possible actions per stakeholder (with the main one being the local authority), but also to develop a typology of actions and group them under certain strategies. A good practice example of such a typology is the distinction between "major actions" (i.e. actions for which the direct GHG emissions reduction can be quantified) and "enabling actions" (i.e. indirect actions that enable, accelerate, or multiply the effect of the major actions – e.g. campaigns about climate change and better training for the workforce) employed by New York City [37].

3.3. Review of criteria used in MCDA models

Using multiple criteria to evaluate, prioritise and select actions to be included in local CAPs is not yet a common (or transparent) practice. In most action plans, although an impressive list of actions is included, no clear-cut reference to the use of some kind of criteria to help in the choice of actions can be found [38, 39]. Indeed, out of the seventeen CAPs of CNCA cities only two of them, the City of Toronto and New York City, present a distinct prioritization approach (see [40] and [37]). To identify a set of generic criteria against which DMs can evaluate the feasibility and impact of actions as part of an MCDA framework, the present author investigated selected literature sources, including the two above-mentioned local CAPs. Specifically, the survey included: (1) studies and guidance frameworks developed by major national, regional and international organisations, i.e. the German Federal Institutes BBSR and BBR [27], the United Nations [41] and the C40 cities [42]; (2) Three open access decision support tools for city-level climate action planning, i.e. the CLIMACT Prio Tool [43], the BEST Cities Tool [29] and the most recent CURB tool [30]; (3) individual researches [22].

The results of the literature survey are presented in Table 1. In the case of the EU CoM signatories one can argue that the proposed indicators by the CoM already used by local authorities to describe key actions as “Benchmarks of Excellence” can also be applied as criteria to solve the MCDA problem of action prioritisation [44]. In this regard, this has also been included as a source in Table 1 (see [28]). One can easily observe that, in addition to effectiveness (GHG emissions saving potential) the most common type of criteria found in the different sources are the ones of primarily economic nature (initial investment cost, annual running cost and generation of jobs). The ones that follow in popularity are the technical feasibility and the speed of implementation. When combined with “effectiveness” the first most recommended/used criteria (except for job generation) help in finding the most cost-effective actions, while the second ones help in identifying the key easy to implement short-term opportunities (i.e. “quick wins”). With the inclusion of quick wins in an action plan, municipalities can effectively demonstrate the added value produced by the plan and more easily engage people in contributing to the reductions until the longer-term benefits of the plan become apparent [16].

Table1. Parameters identified in selected literature sources that can act as criteria in an MCDA model.

	Criterion group	Criterion	[41]	[28]	[27]	[42]	[43]	[30]	[29]	[40]	[37]	[10]
Feasibility criteria (Efforts required)	Economic	Initial investment cost	✓	✓	o	-	✓	✓	✓	✓	✓	✓
		Annual running cost	✓	✓	o	-	✓	✓	-	✓	✓	✓
		Annual financial savings	-	✓	-	-	✓	✓	-	o	-	✓
		Payback duration/period	-	✓	-	-	-	✓	-	-	-	✓
		Return on investment (ROI)	-	✓	-	-	-	-	-	-	-	✓
		External funding programmes	-	-	-	-	-	-	-	-	✓	✓
	Regulatory	National regulation necessity	✓	-	✓	-	✓	-	-	-	-	-
	Technical	Level of technical difficulty	-	-	✓	-	✓	✓	-	-	✓	✓
		Possibility of pilot projects	-	-	✓	-	-	-	-	-	-	-
	Temporal	Speed of implementation	✓	-	✓	✓	-	-	✓	-	-	✓
	Social	Citizen acceptability	-	-	✓	-	✓	-	-	-	-	✓
		Stakeholder acceptability	-	-	✓	-	✓	-	-	-	-	-
		Social compatibility (mainstreaming potential)	-	-	-	-	✓	-	-	-	-	-
	Governance	Level of city power	-	-	-	✓	-	✓	✓	-	✓	-
Impact criteria	Climate-related	Effectiveness (GHG emissions saving potential)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Economic	Private investment mobilization potential	✓	-	-	-	o	-	✓	✓	✓	-
	Socio-economic	Generation of additional jobs	✓	✓	-	-	o	✓	✓	✓	✓	-
		Mobility	-	-	-	-	o	✓	-	✓	✓	-
		Affordable housing	o	-	-	-	o	-		✓	✓	-
		Energy poverty	o	-	-	-	o	-	✓	✓	✓	-
		Exemplarity/image	-	-	-	✓	o	-	-	-	✓	✓
	Enviro-economic	Deferred infrastructure	-	-	-	-	o	✓	-	✓	✓	-
		Renewable energy produced	-	✓	-	-	o	✓	-	✓	-	-
	Environ-mental impacts	Adaptability to climate change	✓	-	-	-	o	-	-	✓	✓	o
		Energy resource use	✓	✓	-	-	o	✓	-	o	✓	o
		Other resource use (e.g. water, material, land)	-	-	-	-	o	-	✓	o	o	o
		Biodiversity conservation	✓	-	-	-	o	✓	-	-	✓	o
	Socio-environ-mental	Health: Air quality	o	-	-	-	o	✓	✓	✓	✓	-
		Health: Waste management	o	-	-	-	o	✓	-	-	✓	-
		Preserve cultural heritage	✓	-	-	-	o	-	-	-	o	o
	Social	Comfort	-	-	-	-	o	✓	✓	-	✓	-
		Noise pollution	-	-	-	-	o	-	-	✓	✓	-
		Aesthetic quality	-	-	-	-	o	-	-	-	✓	o
		Social mobilisation potential	✓	-	-	-	o	-	✓	-	✓	✓

Note 1: “✓” indicates that the parameter is explicitly mentioned; “o” indicates that it may form part of a broader category
Note 2: In some sources the cost(s) and revenue(s) (financial feasibility) are examined as part of marginal abatement curves (cost-effectiveness), e.g. [40]

However, for achieving ambitious 2030 and 2050 targets cities will need to ensure that they move beyond low cost and quick win opportunities and also pursue more investment intensive ones that take longer to play out but will be critical in achieving the required decarbonisation (such as urban densification and land-use planning) [45]. The business case for including such actions can be made by looking at their co-benefits. Actions delivering multiple benefits at once not only can be considered as cost-efficient, but they also increase the likelihood of their success by engaging more diverse communities of interest (also as investors) and demonstrating compelling added value for them [46]. These are the so-called “win-win” actions. Table 1 shows that although an increasing interest in the inclusion of co-benefits is observed, the inclusion of a larger list of sustainability indicators to account for positive side effects of actions as criteria in a MCDA model is still not the norm. In addition to that, an action may also be associated with unintended adverse consequences (co-harms). Most guides, however, solely use expressions such as “co-benefits” or “multiple benefits” introducing a positivity bias towards the impacts. For actions to be “no-regret”, they should not only be cost-effective and involve co-benefits but also be free of hard negative side effects with other objectives. For these and many other reasons, municipalities must seek comprehensive coverage of potential co-benefits and co-harms in their prioritization process to avoid counterintuitive results [46].

A problem that can arise in the case of including the numerous sustainability aspects as individual criteria in the MCDA model is that its complexity increases and therefore the interpretability of its results decreases. Some researchers agree that an average person can handle a maximum of nine criteria because of the general limitations of abstract thinking [47, 48]. When the number of the criteria is more than nine, the aggregation of criteria into groups is generally recommended. Several attempts to develop an ordinal scoring method for quantifying the qualitative mapping the positive and negative interactions between SDGs and their targets have been observed in the literature (e.g. see Nilsson et al. [49] for a sophisticated seven-point scoring method). This way of thinking can be easily transferred to the analysis of synergies and trade-offs between specific climate actions and other objectives. This is evident in the New York City’s plan where a five-scale qualitative system is employed, ranging from “major risk” (score 1) to “major benefit” (score 5) [37].

In regard to other underrepresented criteria in the various sources, it becomes clear that only a few MCDA models include social feasibility criteria. In general, social feasibility is concerned with gaining people’s acceptance regarding the actions to be programmed. In participatory frameworks where anyway representatives of stakeholders are included in the overall process, measuring their “acceptance” and include it as a criterion in the MCDA becomes easy. However, for a broader public acceptance the process of asking a considerable sample of local residents of the willingness to accept certain solutions may be impractical and time consuming. The present author suggest that the criterion of social compatibility is applied in any case, which can indirectly provide information on public acceptability [16]. Social compatibility captures the extent to which a solution is compatible with people’s current frame of mind and does not challenge their values and habits. Solutions with low social compatibility are usually met with a low degree of acceptability. For example, car sharing requires a significant shift in people’s mindset and travel habits. This was also revealed in an EU-wide survey [50], which found that only a minority of the respondents were interested in a car-sharing service, and even fewer considered this service as an actual alternative to car ownership. Information on social compatibility can be fairly easily retrieved from a discussion with the main stakeholder groups, literature sources and common sense.

Finally, it is also significant that cities take into account their “level of power” (i.e. control). Again, this criterion is not as highlighted as expected in the different guides. This factor can be included in a local CAP either as a criterion in the overall action prioritization exercise or it can form the starting point for a first shortlisting of actions, which are later evaluated and prioritized against all the rest criteria. To assist the first case, C40 provides a scoring framework broken down into four main categories, each with a score from 0-3 [42]: (1) Own/operate; (2) Set/Enforce Policies and Regulation; (3) Control Budget; (4) Set Vision. A similar framework is also employed by the BEST Cities Tool [29].

All these considerations are taken into account in the generic criteria tree presented in [16]. This tree may be used by city leaders as a starting point in order to facilitate the implementation of this step and/or may form the heart of a potential future standardization of the prioritization procedure in the context of climate action planning. Whatever the criteria tree used from literature (or a future standard) is, it should only be seen as a foundation to start this step; its acceptance by all involved DMs is crucial and criteria might be added and/or dropped depending on the specific objectives of the different DMs and the CAP.

3.4. Selection of an appropriate MCDA method

Selecting a suitable MCDA method (Step VIII) is a multi-criteria problem in itself. Each method has its weaknesses and strengths (e.g. for a comparison see [17]) and there is no consensus about which methods are more appropriate in a particular context. A comprehensive review of studies comparing the application of selected MCDA models in the same case study to investigate whether the resulting rankings and the derived recommendations vary depending on the method shows that no definitive answer can be given [51]. In some cases, different methods led to the same best alternatives and in others the rankings changed significantly. Under these circumstances, to increase the robustness of the results, several authors recommend to use different methods in parallel [52, 53]. Usually the analyst decides which method(s) to use based on discussions with the DMs and his own competencies. The proposed framework does not aim to recommend a specific method. What can only be advised is to consider the use of methods that do not allow a high degree of compensation, and therefore support the strong sustainability concept [54]. Although it is argued that many of the compensatory MCDA techniques, such as the weighted sum model, use simpler algorithms, are easier to communicate, and potentially have less problems in gaining acceptance from stakeholders [17], any mathematical complexity can be handled if user friendly softwares are available. Several researchers [16, 17, 55] point out that the availability of software support to implement an MCDA method, manage the information and visualise the results in a clear, dynamic manner can provide considerable additional value for the user, and therefore can also be an important reason for choosing one method over the other. Indeed, the availability of such tools is growing – even the ones allowing the parallel use of different methods (e.g. Diviz [56]).

4. Conclusions and next steps

Whereas the technologies and expertise are in place for cities to reach climate neutrality, the challenge to change their emissions trajectory while meeting multiple competing priorities is still tremendous. It has become evident by surveys that local authorities lack understanding and methodological bases with respect to the definition and prioritisation of actions based on certain criteria. The present paper attempted to translate the decision process with respect to action prioritisation into a standardised or formal procedure which integrates MCDA technique to enhance the bindingness of the overall exchange between stakeholders. Due to limitations, the paper focused on particular steps in the process and attempt to shed light on the latest sources and developments that could support them. It is recognised that quantifying stakeholder's preferences and a great number of criteria may be a laborious and time-consuming process. For this reason, city governments, when faced with limited resources, should make effective use of all ready-at-hand existing tools to support this task. Next steps in research that could help improving and accelerating the implementation of such a framework in the context of next generation local CAPs are: (1) the creation of a common database of best practice of climate actions in cities allowing the application of "filters" – so that to enable local authorities to focus on cities with similar geographic and socioeconomic context – to facilitate and accelerate the definition of actions. It is recommended that this becomes part of the future activities of GCoM to promote shared learning; (2) the development of "co-impacts" tools assisting their integration into the prioritization of actions; (3) Group decision-making software tools especially designed for the task of action planning that guide the municipalities throughout the entire action prioritization process, from the stakeholder analysis (Step I) to the sensitivity analysis (Step XI) and streamlines the communication process between stakeholders.

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A systematic review of the international assessment systems for urban sustainability

Pedro J[1], Reis A[1], Duarte Pinheiro M[2], Silva C[1]

[1] IN+Center for Innovation, Technology and Policy Research, Instituto Superior Técnico – Universidade de Lisboa, Avenida Rovisco Pais 1, 1049-001, Lisbon, Portugal
[2] Department of Civil Engineering, Architecture and Georesources, Instituto Superior Técnico – Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001, Lisbon, Portugal

joana.m.pedro@tecnico.ulisboa.pt

Abstract. Planning and managing the rapidly growing cities in a manner that delivers a balanced solution for their environmental, social and economic long-term development constitutes one of the grand challenges of societies. In the urban planning field, several sustainability assessment systems emerged to guide the planning process towards these goals. After two decades of existence, there is a need to further analyze the lessons learned from the application of these systems and discuss the pathways towards more sustainable societies. This paper provides a literature review of the most widely used urban sustainability assessment systems: BREEAM Communities, LEED Neighborhoods, CASBEE Urban Development, Green Star Communities, and DGNB Urban Districts. Here, we analyzed 124 publications on the topic published between 2015-2018, using the selected assessment systems as keywords. This study revealed that there is a need for context customization of global targets into local actionable measures; involvement of regulatory bodies to ensure the successful application of such systems; and, consideration of socioeconomic factors as the assessment is still very focused on the environmental impact. This study provides insights for practitioners and researchers on the existing systems to assess urban sustainability and pathways for future research.

1 Introduction

The share of the global population that lives in cities has been growing and is projected to rise to 68% by 2050 [1]. While cities are hubs of development, they also pose increased stress in the demand for scarce resources and environmental concerns, which affects the economic and social balance of urban areas. These concerns rise the need for systems that can enable sustainable planning for managing the rapid growth of cities in a long-term perspective [2], [3].

As a response to these concerns, the construction industry has been making efforts to integrate sustainability principles into projects planning and practices by developing sustainability assessment systems like BREEAM (UK, 1990), LEED (USA, 1998), CASBEE (Japan, 2001), GREEN STAR (Australia, 2002) or DGNB (Germany, 2008), used and recognized internationally [4], [5]. These systems provide a set of indicators to evaluate the sustainability performance of a building, which can help the project owner to manage the impacts of their construction project [6]. Although the number of indicators and metrics may differ, they all define a set of criteria to assess a construction project based on their environmental, social and economic dimensions [6][7][8][9]. In the last decade, these systems have also new versions for neighborhood sustainability assessment (NSA), such as BREEAM Communities, LEED Neighborhoods, CASBEE Urban Development, DGNB Urban Districts. At the neighborhood scale, buildings become a component of an urban system, interrelated with the other components, such as public transport, and services. At this scale, it is also possible to explore to its fullest the synergies among buildings and its surroundings, for instance, by making use of district energy solutions and taking advantage of economies of scale. However, it also introduces complexity in the evaluation process, with a higher number of stakeholders involved, and the increased number of indicators [4], [5], [10], [11]. Moreover, there are still few certified neighborhood projects compared to the building scale. For instance, sustainable assessment systems, such as BREEAM passed already the 400.000 building certificates [12], but only summed 50 neighborhood projects by 2018 [13], followed by LEED system with over 100.000 certified buildings and only 188 neighborhood projects [14].

Previous research has largely discussed the metrics for evaluating sustainability at the building scale, for which more mature assessment systems exist for a longer time, but relatively few studies have focused on the urban scale [15]. Happio [16] was one of the first studies to provide a critical review of the main categories used by three of the most well-known NSA systems (BREEAM-Communities, LEED-Neighborhood development, and CASBEE-urban development) and highlighted the potential problems of using these systems outside its region of the origin. In this line, Sharifi & Murayama [8], [17] conducted an in-depth analysis of seven NSA systems, introducing a framework for the examination of NSA systems, and discussing some of their common limitations. Regarding the categories used to measure sustainability, Komeily & Srinivasan [18] criticized the systems for underperforming in the social, economic, and institutional aspects of sustainability. Tam et al. [19] contributed with an extended review of the NSA systems, evaluating 20 international systems and comparing their different approaches on urban sustainability, similarities, and limitations. While previous review studies contain implicit or explicit knowledge of the NSA limitations and research gaps, no prior study, to the best of our knowledge, has applied a systematic review approach to identify the main shortcoming of the existing systems for assessing urban areas.

In this study, we selected five of the most widely spread NSA systems for an in-deep analysis: LEED Neighborhood Development, BREEAM Communities, DGNB Urban Districts, CASBEE Urban Development, GREENSTAR Communities [20] [19]. These five systems were chosen because they are well developed and known internationally, have the highest number of certified projects, have publicly available manuals, and include scoring as part of their process. Here, we browsed the existing publications on the topic based on the name of each system as a keyword. The analysis is limited to the publications between 2015-2018 in-peered review articles in the urban planning field, which resulted in the identification of 124 publications. Afterward, we made an in deep-analysis of the gaps and limitations of these systems for future improvement. This framework can be a starting point for researchers to formulate new assessment systems or improving the existing ones.

This paper is structured as follows. Section 2 describes the analytical framework used for identifying the gaps in the literature. Section 3 presents and discusses the results of the gap analysis. Finally, Section 4 summarizes the main conclusions of this analysis and identifies future research avenues.

2 Methodology

This study started with a comparison of each system based on the statistics and content analysis from their technical manuals. This process focused on the analysis of their similarities and differences in terms of timeline, spatial spread, categories, and certification. Even though each NSA system aims at measuring and attaining sustainability in urban areas by providing a set of criteria and weights, the organization of these criteria tends to be different, making it difficult to compare the systems. To overcome this challenge, we rearranged the issues and indicators of the NSA systems in a common framework, grouping the criteria under the three main sustainability dimensions: environmental, social and economic. We proceeded with the review of the published scientific literature concerning the NSA systems to identify the gaps most frequently mentioned. This review followed the Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [21] [22] [23]. We started with a search in Web of Science and Scopus of the following by keywords: “Neighborhood Sustainability Assessment”; “LEED neighborhoods” or “LEED-ND”; “BREEAM communities” or “BREEAM-CM”; “CASBEE urban development” or “CASBEE-UD”; “DGNB urban districts” or “DGNB-UD”, and “Green Star Communities” or “Green Star-CM”. With this approach, we identified 821 records, of which 275 duplicated were removed. Then, we restricted the data to peer-reviewed articles written in English and published between 2015-2018, and to literature that focused on the urban scale rather than buildings. This resulted in the selection of relevant 124 articles for further systematic review and identification of the most frequent gaps of the NSA tools.

3 Results and discussion

3.1 Comparison of the NSA systems.

This section presents the comparison of the analyzed NSA systems regarding their timeline, spatial spread, categories and scoring (summarized in Figure 1, Figure 2, Table 1).

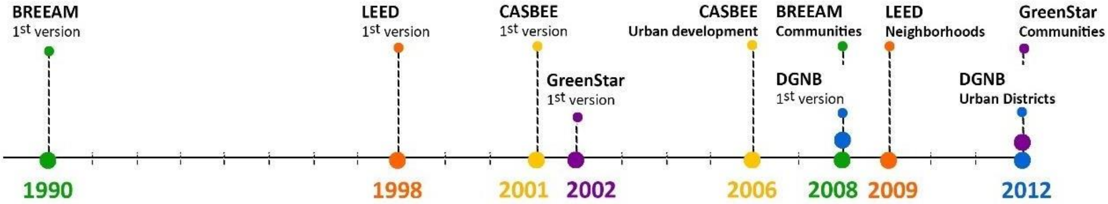

Figure 1 - NSA systems timeline

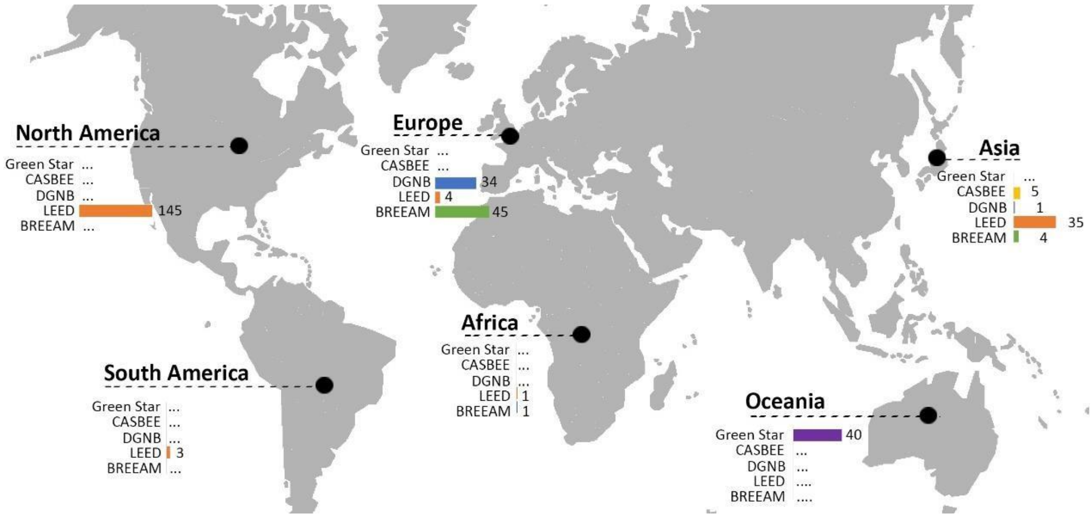

Figure 2 - NSA systems around the world (number of certified projects by the system in 2018)

BREEAM was the first developed system. Its first version for the building scale was launched by the UK Building Research Establishment in 1990, and BREEAM Communities (BREEAM-CM) version for urban planning was released in 2012 [24]. BREEAM-CM provides a set of criteria to evaluate sustainability distributed within five main categories: governance, social & economic wellbeing, resources, land use and ecology, and transport and movement. It also provides bonus credits for innovative features. Distributed under these categories, there are 40 criteria, subjects to scoring, of which 12 are mandatory. By fulfilling the criteria, projects earn points that determine its certification level: Pass (30 points), Good (45 points), Very Good (55 points), Excellent (70 points) and Outstanding (80 points) [24]. In 2018, there were 50 BREEAM-CM certified projects, 45 in Europe and 5 in Asia [25].

LEED was launched by the U.S. Green Building Council in 1987, and LEED Neighborhoods (LEED-ND) version was released in 2014 [26]. LEED-ND evaluates sustainability performance at the urban scale by addressing three main categories: smart location and linkage, neighborhood pattern and design, and green infrastructure and buildings. It also accounts for two extra categories: innovation; and regional priority. Distributed under these categories, there are 40 credits subjects to scoring and 12 prerequisites that must be respected but do not count for scoring. By fulfilling credits, projects earn points that determine its certification level: Certified (40 points), Silver (50 points), Gold (60 points) and Platinum (80 points) [26]. In 2018, there were 188 certified LEED-ND projects, 145 are in North America, 35 in Asia, 4 in Europe, 3 in South America, and 1 in Africa [27].

CASBEE was launched by the Japan Sustainable Building Consortium (JSBC) in 2001, and CASBEE Urban Districts (CASBEE-UD) was released in 2006 [28]. It considers the improvement of three main urban dimensions: environment, society, and economy. The evaluation attributes a score to each of these dimensions based on two factors: built environment quality (Q) and built environmental load (LR), the assessment scale for Q and LR ranges from 1 to 5. Then, these two factors are used to calculate the final score for Built Environment Efficiency (BEE). For CASBEE-UD there are no mandatory requirements. The calculated score projects determine its certification level: Poor (BEE 0.5), Fairly Poor (BEE 0.5-1), Good (BEE 1-1.5), Very good (BEE 1.5-3), and Excellent (BEE 3) [28]. In 2018, there were 5 CASBEE-UD projects, all of them in Asia [29].

DGNB was first developed for the building scale in 2008, and DGNB Urban Districts (DGNB-UD) was released in 2012 [30]. DGNB-UD includes the five main categories of assessment: environmental quality, economic quality, sociocultural and functional quality, technical quality, and process quality. Distributed under these categories, there are 30 criteria subjects to scoring. By fulfilling credits, projects earn points that determine its certification level: Silver (55 points), Gold (65 points), Platinum (80 points) [30]. In 2018, there were 34 certified DGNB-UD projects, all in Germany [31].

Green Star was launched by the Green Building Council of Australia (GBCA) in 2002, and Green Star -Communities (Green Star-CM) was released in 2012 [32]. The evaluation process comprises the collection of credits for four main categories: governance, livability, economic prosperity, and environment. It also provides bonus credits for innovative features. Distributed under these categories, there are 32 credits subjects to scoring. By fulfilling credits, projects earn points that determine its certification level: 4Star (45 points), 5Star (60 points), the 6Star (75 points). In 2018, there were 40 certified Green Star-CM projects, all in Australia [33].

Overall, although the number of indicators and metrics may differ between systems they all define a set of criteria to assess a construction project based on their environmental, social and economic dimension, as summarily presented in Table 1. This analysis shows that BREEAM-CM, LEED-ND, and DGNB-UD present a higher number of criteria and weight related to access to services, but attribute a much lower number of criteria and weights to cultural heritage and life cycle costs. In fact, BREEAM-CM, LEED-ND systems address only indirectly life cycle costs by incorporating it in the energy's evaluation measures and reuse of materials. In CASBEE-UD the weights are more evenly distributed, attributing slyly higher importance to waste, land use, participation, and governance, but there is no specific category for life cycle costs. Finally, GREEN STAR-CM also attributes higher importance to participation and governance, but less importance to cultural heritage. Overall, the NSA tools have more criteria and attribute more weight to the environmental and social dimensions of the evaluation, rather than the economic factors.

Table 1 - NSA tools: criteria and weight comparison

		BREEAM-CM	LEED-ND	DGNB-UD	CASBEE-UD	G.STAR-CM
Environmental criteria	Energy	energy strategy*; transport carbon emissions (Wst: 7%)	minimum building energy performance*; solar orientation; optimize building energy; renewable energy; district heating and cooling; infrastructure energy efficiency (Wst: 9%)	energy infrastructure; LCA -emissions (Wst: 9%)	possibility demand/supply …; adaptability and expandability (Wst: 6%)	greenhouse gas strategy; peak electricity demand (Wst: 8%)
	Water	water strategy*; water pollution; rainwater harvesting (Wst: 5%)	indoor water use reduction*; outdoor water use reduction; wastewater management (Wst: 5%)	water cycle (Wst: 3%)	water resource – waterworks; sewerage (Wst: 6%)	integrated water cycle (Wst: 7%)
	Waste	low impact materials; resource efficiency; existing buildings*; sustainable buildings (Wst: 12%)	construction activity pollution prev.*; solid waste management; building reuse; certified green building*; recycled and reused infrastructure (Wst: 8%)	lca-resource cons; resilience and adaptability; resource management (Wst: 10%)	resources recycling-construction; operation; environmentally considerate buildings (Wst: 17%)	materials; waste management; sustainable buildings (Wst: 11%)
	Land use	ecology strategy*; enhancement of ecological value; green infrastructure; land use*; landscape (Wst: 12%)	smart location*; imperiled species*; wetland & water body conservation*; agricultural land conservation*; site design for habitat or wetland*; restoration of habitat or wetlands; long-term conservation management; minimized site disturbance (Wst: 4%)	biodiversity; land use; smart infrastructure; land use efficiency (Wst: 15%)	greenery - ground greening; building top greening; biodiversity – preservation; regeneration & creation; consistency with upper level; planning; land use (Wst: 17%)	sustainable sites*; ecological value (Wst: 4%)
	Well-being	noise pollution*; light pollution (Wst: 3%)	light pollution reduction (Wst: 1%)	thermal comfort open spaces; open space; noise, exhaust and light emissions (Wst: 10%)	View; inhabitant population; staying population (Wst: 8%)	healthy and active living*; light pollution (Wst: 6%)
	Climate adapt	adapting to climate change; flood risk assessment*; flood risk management; microclimate (Wst: 8%)	rainwater management; floodplain avoidance*; steep slope protection; brownfield remediation; heat island red (Wst: 8%)	urban climate; environmental risks; groundwater and soil protection (Wst: 7%)	basic disaster prevention; disaster response ability; traffic safety; crime prevent (Wst: 11%)	adaptation and resilience; safe places*; heat island effect (Wst: 7%)

Social criteria	Access to services	access to public transport; public transport facilities; transport assessment*; cycling network; cycling facilities; local parking; demographic needs*; delivery of services, facilities; public realm; utilities; inclusive design; safe and appealing streets (Wst: 26%)	preferred locations; access to quality transit; transit facilities; transportation demand management; bicycle facilities; reduced parking footprint; compact development*; connected and open community*; mixed-use neighbor.; access to civic & public space; access to recreation facilities; neighbor. schools; walkable streets; local food production; visibility and universal design; tree-lined & shaded streets (Wst: 51%)	motorized transportation; pedestrian and cyclists; robust social and functional mix; social & commercial industry; barrier-free design (Wst: 21%)	convenience; health and welfare, education; development of traffic facilities; traffic - logistics management (Wst: 11%)	sustainable transport & movement; walkable access to amenities; access to fresh food; digital infrastructure (Wst: 9%)
	Heritage	local vernacular (Wst: 1%)	historic resource preservation (Wst: 2%)	urban design (Wst: 3%)	history and culture (Wst: 3%)	culture, heritage and identity (Wst: 3%)
	Participation	consultation plan*; consul. & engagement*; design review; training and skills; community management of facilities (Wst: 15%)	community outreach and involvement (Wst: 2%)	integrated design; consultation; project management); governance; monitoring (Wst: 10%)	compliance; area management; information service performance; information system - block management (Wst: 17%)	green star accredited professional; design review; engagement; corporate responsibility; sustainability awareness; community participation & governance; environmental management; community development* (Wst: 28%)
Economic	Economic prosperity	Economic impact*; Housing provision (Wst: 12%)	Housing and jobs proximity; Housing types and affordability (Wst: 10%)	Local economic impact; Value stability (Wst: 6%)	Economic development - revitalization activity (Wst: 6%)	Community investment; Affordability; Employment& economic resilience; Education & skills (Wst: 13%)
	Life cycle	Not found any exclusively dedicated criteria, although costs calculation is included in the energy-related criteria (Wst: 0%)	Not found any exclusively dedicated criteria, although costs calculation is included in building reuse and energy criteria (Wst: 0%)	Life cycle cost; partially included in resilience and adaptability (Wst: 6%)	(Wst: 0%)	Return on investment; Incentive programs (Wst: 4%)

* = includes mandatory requirements, wst = weight subtotal

3.2 *Identified shortcomings*

This section presents the most frequently identified limitations of NSA systems (in Table 2) that can be used to discuss the possible pathways for improvement of these systems.

Table 2 - NSA systems: results from the gap analysis

Gaps identified	% of Papers
G1 Lack of consensus on sustainability definition and concepts	10%
G2 Overlapping and incoherent distribution of criteria and weighting	18%
G3 Need for widening the scope by including evaluation criteria on socioeconomic conditions, mobility and walkability, disaster resilience and climate change, cultural factors	26%
G4 Little flexibility for local adaptation, particularly for developing countries	28%
G5 Need to adapt the assessment systems for urban regeneration projects	11%
G6 Regulatory bodies involvement and participation	18%
G7 Need for widening the scale of assessment	9%
G8 Integration of the NSA with computer-based models	6%

*total number of papers analyzed: 124

G1 - Lack of consensus on sustainability definition and concepts. Results from the literature review show that sustainability is not a fixed term yet [34], [19]. One of the first definitions of sustainable development was set by the Brundtland Commission 1997 [35], that emphasized that sustainable development is only achievable through the integration and acknowledgment of economic, environmental, and social concerns throughout the decision-making process. These concerns became the main pillars for most of the NSA systems, which investigate practical ways of measuring and achieving the sustainable development of urban areas [19], [34], [36] [37] [38]. As argued by Boyle [7], although NSA systems address the concept of urban sustainability by providing a practical pathway to measure it based on a set of indicators, they often group and use different metrics and weights to each sustainability issue. In this sense, further consensus on the concepts and definition is necessary to make them globally applicable and understood.

G2 - Overlapping and incoherent distribution of criteria and weighting. Because of the lack of consensus on the definition of sustainability, these systems often face the problem of completeness, and overlapping criteria [39]. Reith [39] further highlights that the lack of a consensual definition and clear metrics makes it difficult to measure the sustainable performance of a project and makes the comparison of the different rating systems ambiguous, as it is not possible to make a direct correlation between categories or translation between their oversell scores. For instance, a high score achieved by a project in the BREEAM-CM does not immediately translate into LEED-ND high performance, which raises the question about what exactly do they measure ("Do green neighborhood ratings cover sustainability?"). Wallhagen [40] argues that the use of interchangeable criteria can create a bias in the analysis because if the sustainability aspects are exchangeable, a project can become certified without being sustainable. Also, Komeily [18] and Kaur [22] argue that there is a need for a more coherent distribution of the criteria and categories. Ali-Toudert [15] argues that these systems have often overlapping criteria, and often ignore interactions between the criteria, which may lead to the overestimation or underestimation of sustainability compliance.

G3 - Need for widening the scope. Although the efforts of NSA systems to provide a holistic approach towards sustainability, the literature review revealed that most of these systems lack completeness in terms of content and criteria. Authors such as Wu [41], [42] notice that these systems emphases on the ecological and environmental aspects, ignoring the economic and social aspects of sustainability. Gouda [43] and Riggs [44] discuss the criteria used to evaluate the mobility modes and point out the need for a more expansive view of walkability based on both quantitative and qualitative factors. Sally Naij [45] and Diaz-Sarachaga [46] notice the need to include evaluation criteria for climate change adaptation and disaster resilience. Kaur [22] highlights that the evaluation often attributes more importance to certain aspects like infrastructure and resource management rather than cultural, business and innovation.

G4 - Little flexibility for local adaptation. Most of the NSA systems are developed within a certain country but are often used in contexts other than their origin. This opens the debate on the viability of using global standards and the pertinence of their use in actual local conditions [47] [48]. In this context, Gouda [49] further highlights that NSA systems are often related to standards, codes, guidelines highly dependent on the country of origin, which is contradictory to their characterization as independent or international. Kaur [22] argues the need to assure local requirements and site-specific aspects which may differ within cities and regions. Authors such as Dawodu [50] Diaz-Sarachaga [51] also point out that most of the existing NSA systems come from developed countries, particularly North America and Europe. Yet the developing countries such as African cities, are the ones expected to have the highest expansion rates over the next years. Therefore, the expansion of the existing systems or development of new ones for developing countries is a major challenge to be addressed.

G5 - The need to adapt the assessment systems for urban regeneration projects. The NSA systems are mostly designed to evaluate and guide the development of new urban areas, however, authors such as Zheng [52] and Boyle [7] highlight the need to adapt and use these systems to the context of previously build urban environments and their role in achieving global sustainability. Further, on this topic, Cappai [53] explores the reuse of brownfields to meet urban densification and sustainable development requirements. Appendino [54] stresses the need to develop a set of indicators to assess the role that heritage could play in urban sustainable development.

G6 - Regulatory bodies involvement and participation. The results from the literature review show that a key factor for the successful adoption of green communities is government involvement and social participation. To this point, Boyle [7] argues sustainable urban regeneration must be grounded in principles of urban governance, participatory action and an understanding of market dynamics. Therefore, it is necessary for a new iteration of the NSA systems centered on institutional mechanisms to engage citizens and support local action. In fact, Morris [55] conducted a survey on Green Star-CM and concluded that the main factor frequently appointed in the interviews for implementing this system was the requirement for government involvement and funding. Göçmen [56] and Oliver [57] discusses how planning at the local government level play a fundamental role to play in advancing local and regional sustainability. Encinas [58] argues that the improvement of the obligatory minimum standards may push forward the current voluntary standards by establishing a more demanding baseline that incentivizes competitiveness in the market.

Gap 7 - Need for widening the scale of assessment. While the first sustainability assessment systems and studies focused on the evaluation of single buildings, a growing number of studies are shifting towards larger scales by widening the evaluation to the neighborhoods and cities. To this point, Verovsek [59] stresses that at the neighborhood scale buildings become modules of a system that also considers spaces in-between buildings, public spaces, and infrastructures, the holistic and the community aspect. Addressing sustainability at larger scales opens new opportunities for improved efficiency and better management of local resources, but also opens new challenges because of the increased complexity and interconnectivity. Skaar [60], Aghamolaei [61] and Koutra [62] discuss the importance and difficulties of passing from Zero Emission Buildings to Zero Emission Neighborhoods. Wu [42] discusses how the traditional focus on the green building can transit to green communities by comparing LEED versions for buildings and neighborhoods. Additionally, Pedro [63] addresses the opportunities and challenges of scaling up LEED-ND from the neighborhood towards the city scale. Koutra [62] reviews existing systems and how they address the challenges of sustainability at the building, neighborhood and city level.

G 8 - integration of the NSA with computer-based models. NSA systems are typically expert-based rather than computer-based models, although a few recent studies suggest the integration of both. In this sense, Kuster [64] proposes a near real-time environmental assessment approach for the district level, that combines the expert consultation with ICTs and artificial intelligence to ensure an improved temporal and local adaptability of actual neighborhood sustainability assessments. Oregi [65] further discusses the use of ICT systems in sustainable urban planning projects and the advantages of integrating them in the early stage phase, providing a way of visualizing the sustainability performance scores and means to communicate with stakeholders about the sustainable performance, right from the start of the project. Cheshmehzangi [66] suggests integrating environmental performance analysis for urban design with Computational Fluid Dynamics (CFD) to achieve urban sustainability. Pedro [63] argues that combining sustainability assessment with a computer-based model such as geographic information system (GIS) enables assessing large datasets in reduced processing time. Chen [67] proposes incorporating sustainability assessment into architectural design software such as REVIT to facilitate the integration of sustainability concepts in the normal workflow of architectural professionals.

4 Conclusion

This paper provides a systematic literature review on five of the most widely used urban sustainability assessment systems (BREEAM Communities, LEED Neighborhoods, CASBEE Urban Development, Green Star Communities, and DGNB Urban Districts). Therefore, we analyzed 124 publications on the topic published between 2015-2018 and identified the following eight shortcomings: 1) lack of consensus on sustainability definition and concepts; 2) overlapping and incoherent distribution of criteria and weighting; 3) need to widen the scope by considering, for instance, more socio-economic factors; 4) little flexibility to local adaptation; 5) need to adapt assessment systems for urban regeneration projects; 6) call for regulatory bodies participation and involvement; 7) need to widen the assessment scale; 8) quest for integration with computer-based models. Despite providing a systematic review of recent literature, this study is limited to journal articles found by the selected databases between 2015-2018, within the urban planning field. Therefore, future work can consider expanding the time range and a more detailed analysis of each of these gaps considering hypothesis for improvement. Overall, these findings can be a starting point for researchers and practitioners to formulate new assessment systems or adapt the existing ones, thereby promoting the continued development of this field.

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Optimization-based planning of local energy systems - bridging the research-practice gap

Andrew Bollinger L, Marquant J, Sulzer M

Empa – Swiss Federal Laboratories for Materials Science and Technology, Urban Energy Systems Laboratory, Überlandstrasse 129, 8600 Dübendorf, Switzerland

andrew.bollinger@empa.ch

Abstract. Optimization-based planning of local energy systems – though increasingly mature from a methodological perspective – is not commonly applied in practice. This paper synthesizes learnings from 4 case studies – focused on 4 different sites – in which optimization-based methodologies have been applied to the planning of local energy systems. The aim is to generate insights to facilitate the more effective application of optimization-based methodologies to local energy systems planning in practice. The results indicate that an intensively iterative methodology is critical not only as a basis for adapting the analysis based on stakeholder input, but also to facilitate learning on the part of stakeholders with regard to the value and limitations of the approach and the results. With regard to optimization methodologies, in particular temporal decomposition methodologies are identified as critical to preserving computational tractability in the optimization of complex technical systems, especially those featuring networks and those with many energy carriers or technology options. It is suggested that the methodological tailoring of an optimization model to a specific case and the calculation/visualization of key indicators can be largely automated, which could significantly accelerate future studies and reduce the knowledge required for their execution.

1. Introduction

Optimization-based planning of local energy systems refers to the use of computational optimization methodologies to facilitate the planning of decentralized energy systems for neighborhoods, campuses, urban quarters/districts and municipalities. In particular over the past decade, significant research has been dedicated to the development of optimization-based methodologies to facilitate local energy system planning. The added value of these methodologies is their ability to enable a more comprehensive and holistic perspective in the design of local energy systems. This research domain is generally characterized by the application of linear or mixed-integer linear programming approaches, sometimes in combination of genetic algorithms or other meta-heuristic approaches, and a focus on energy systems featuring multiple energy carriers and multiple conversion/storage technologies.

Optimization-based planning of local energy systems – though increasingly mature from a methodological perspective – is not commonly applied in practice. While numerous examples of the application of this approach to practical cases can be found in literature [1-7], the focus is generally on methodological demonstration/validation. Systematic integration of this approach into local energy systems planning processes is lacking. If the potential of optimization-based local energy systems planning is to be realized, it is critical to understand the reasons for this lacking, and how the research-practice gap can be more effectively bridged.

This paper synthesizes learnings from 4 case studies – focused on 4 different sites – in which optimization-based methodologies have been applied to the planning of local energy systems. Each of the case studies was carried out in close collaboration with one or more industry partners with a strong interest in using the results of the study for the planning of the respective site's energy system. The aim of this paper is to generate insights to facilitate the more effective application of optimization-based methodologies to local energy systems planning in practice.

In the next section, the approach of optimization-based local energy systems planning is clarified, and important methodological developments explained. Each of the 4 case studies is then briefly described, after which key learnings are extracted and elaborated.

2. Optimization-based planning of local energy systems

Optimization-based planning of local energy systems encompasses a range of methodologies, which may be combined or adapted depending on nature of the problem. Most commonly, the problem is formulated as one of cost minimization [2,4,8-10], with costs most often (though not always) expressed as the system's life-cycle costs (investment costs + maintenance costs + energy/fuel costs + decommissioning costs). Most often, the problem is formulated as a linear or mixed-integer linear programme. Variables commonly include the input and output energies of conversion and storage technologies per timestep and the capacities of these technologies. Mixed-integer formulations are necessary for cases in which binary variables are required to represent the installation of the specific components or their operation within a given timeframe. Less commonly programming approaches are combined with meta-heuristic approaches – in particular genetic algorithms – in the context of a bi-level approach as a basis for enabling the solution of more complex problems [11,12]. Multi-objective optimization – the simultaneous optimization with respect to multiple objectives – is most often enabled through the use of an epsilon (ϵ)-constraint method [13], in which a pareto front of optimal solutions is built up by optimizing with respect to costs and constraining a second variable to sequentially higher or lower values.

This basic optimization problem may be augmented or adapted in different ways depending on the requirements of the study and the complexity of the problem to be solved. Research in recent years has led to the development of various methodologies which may be applied in combination with the basic approach described above. This includes, for instance:

- **Thermal and electrical network optimization methodologies**, which extend the basic approach from a single-node to a linked multi-node problem. This enables the identification, e.g. of optimal structures and capacities of thermal networks between buildings [9, 14,15]
- **Spatial clustering methodologies**, which reduce the complexity of multi-node problem formulations by clustering nodes so as to decrease the number of problem variables. Different algorithmic clustering methodologies have been developed, including density-based clustering (most common), load-based clustering and combined clustering [16,17]
- **Temporal decomposition methodologies**, which reduce the complexity of the basic optimization problem by reducing the number of timesteps and thus the number of problem variables. Whereas the basic optimization problem is characterized by a set of sequential timesteps – most commonly hourly over the time horizon of one year – temporal decomposition methodologies either select a subset of "representative" timesteps for capturing the most critical features over the entire year (e.g. typical days methodology), or divide the optimization problem into smaller chunks (e.g. rolling horizon methodology) [18,19]
- **Multi-stage optimization methodologies**, which entail optimizing not just a "snapshot" system design, but rather the sequence of technology investments to be made over a defined period of time. This is essential for cases in which multiple planning phases are foreseen, or in which the composition (e.g. number/type of buildings) of a site is expected to change over time [20,21].
- **Stochastic and robust optimization methodologies**, which enable the explicit representation of parameter uncertainties into the optimization problem, either with associated probabilities (stochastic optimization) or windows of feasible values (robust optimization) [22-24].

Each of these methodologies may essentially be viewed as modular add-ons to the basic optimization problem outlined above. It is possible, and sometimes even necessary, to apply multiple of these methodologies in combination in order to arrive at a formulation of the optimization problem which both sufficiently accurately represents the real-world problem and is capable of being solved within a reasonable amount of time. A particular challenge, however, is that each methodology requires a (to some degree) fundamentally different formulation of the optimization problem (i.e. different sets, parameters, variables and constraints). Insofar as the application of optimization-based approaches to local energy systems planning in practice requires identifying solutions on a short timeframe, the manual development of a tailored problem formulation based on the specific needs of a given case is prohibitive. Within this context, an important motivation for the research team behind the case studies described below was to understand which specific methodologies are necessary for addressing different types of real-world cases and if/how the associated formulation of the optimization problem could be automated to enable rapid but tailored assessment of each case.

3. Case studies

In this section, the 4 case studies are introduced and briefly described. Each case study was carried out in close collaboration with an industry partner, and focused on a specific physical site (see Table 1). However, to a greater or lesser degree, each case study was a broader collaborative initiative involving multiple stakeholders including for instance the building-/land-owners, general planners, local utilities and municipalities. The case studies addressed sites of different sizes. The first two dealt with building agglomerations of 10-15 buildings. The second two case studies dealt with building agglomerations on the scale of hundreds of buildings. All case studies dealt with sites located in Switzerland. The second case study dealt with a greenfield site, whereas the others were focused on sites with an existing and, importantly, evolving building stock. The different scales and characteristics of each case study, as well as the different categories of stakeholders involved, meant that each case came with a specific set of questions and methodological requirements. The case study descriptions below are presented in anonymized form at the request of the involved partners.

Case study	Main industry partner	Size of site (buildings)	Type of site
1	Municipal authority	10-20	Existing
2	Local utility	10-20	Greenfield
3	Local utility	600	Existing
4	Engineering consultancy	1000+	Existing

Table 1: Key features of the case studies.

The analysis for each case study was carried out using a common software tool – the *Ehub Tool* – developed by the researchers prior to the start of the case studies. In the course of carrying out the case studies, the tool was further developed to accommodate the specific requirements of each case and the specific knowledge needs of the respective industry partners. In addition to contributing to the development of an energy plan for each site, a goal of the researchers was to adapt and extend the software base of the Ehub Tool to meet the requirements of real-world problems such that the Tool could be more efficiently applied to similar cases in the future. A third goal of the researchers was to develop a replicable methodology for applying the Tool to local energy systems planning in practice. Prior to the start of the case studies, the research team defined a preliminary version of such a methodology. This methodology provided a common overarching sequence of steps to be carried out – or at least considered – in each of the projects, although it was understood that this methodology would inevitably vary to some degree across the case studies. Indeed, better understanding the necessary deviations from this methodology was a central goal of the research team. The following basic steps defined the methodology:

1. **Requirements definition & problem specification**: Define the scope and objectives of the study, the assumptions to be made and the key performance criteria.
2. **Data collection & processing:** Compile and prepare the necessary input data for the study, including e.g.: estimated building energy demands (hourly profiles for heat, electricity, cooling, steam, etc.), technical & cost specifications of supply technologies (e.g. efficiencies, lifetimes, installation costs, operation costs), on-site renewable energy potentials (e.g. solar, groundwater)
3. **Adaptation Ehub Tool:** As necessary, adapt or extend the Ehub Tool based on the specifications of the problem, by adding custom constraints, objectives or evaluation criteria.
4. **Case implementation & execution:** Implement the problem specification in the input files of the Ehub Tool. Run the tool.
5. **Results analysis & interpretation:** Assess the results to identify the optimal technical configurations under different conditions and the performance of each in terms of the specified evaluation criteria. Key outputs of the tool include the optimal sizing and locations of conversion, storage and thermal network components to be installed, the respective optimal operational schedules of each, and the resulting life-cycle costs and CO_2 emissions of the system.
6. **Iteration:** Iterate to evaluate alternative scenarios or test sensitivities to boundary conditions.

3.1. Case study 1 - Strategic energy planning for a mixed-use urban neighborhood

The first case study focused on the development of a strategic energy plan for an existing mixed-use urban neighborhood. The primary energy users on the site are currently industrial operations with large demand for high-temperature process heat (85-170 degrees C). Significant uncertainty exists regarding the long-term development of the site and thus the future quantity and type of energy demands, in particular after 2030. After 2030, it is possible that industrial operations may cease at the site, being replaced for instance by greater intensity of residential or commercial use. A set of 15 scenarios for the future development of the site in terms of floor area and building tenants were defined. The site is furthermore characterized by the existence of several historically protected buildings, which limits possibilities for energy-focused building retrofitting. It is also characterized by an existing groundwater well which may serve as a low-temperature thermal source for heating and cooling. In the short-term, it will be necessary to replace or renovate parts of the site's current energy system. The industry partner would prefer to make these short-term decisions in line with a longer-term strategy for the future development of the site's energy system. The task of the research partner was – given the inherent uncertainties in the future development of the site – to facilitate the identification of an energy strategy in line with the stakeholders' priorities.

3.2. Case study 2 - Early-stage energy planning for a greenfield commercial campus

The second case study focused on the development of an early-stage energy plan for a greenfield commercial campus. The future tenants of the site and precise configuration of buildings was uncertain, though it was possible to bound this uncertainty in the form of a handful of scenarios for the future tenants and energy demands of the site. Unlike the first case study in which a high-level, long-term energy plan was sought, here the stakeholders sought to identify a specific technological energy system configuration for the site. Key criteria for evaluating potential configurations were life-cycle costs, carbon dioxide emissions and energy autonomy. Of particular interest were technology configurations based around a thermal network. The optimal topology and temperature levels for this network, as well as the optimal set of buildings to be connected to the network, was an open question to be addressed by the analysis. Additionally to be addressed by the analysis was the optimal mix of production and storage technologies to install at each parcel within the site, and the optimal location of an energy center. Next to more conventional technologies, the potential roles of rooftop and facade PV technologies and seasonal ground heat storage were of particular interest.

3.3. Case study 3 - Strategic energy planning for an urban district

The third case study dealt with the development of a strategic energy plan for an urban district of ca. 600 buildings. The site in question is a mixed-use site with significant industry presence. Already now and even more so in the future, the site is undergoing a transition towards greater intensity of commercial and residential use. This shift is expected to result not only in changing energy demand patterns – in particular, increased future cooling demand by commercial buildings is foreseen – but also greater demand for sustainably produced energy. The goal of the industry partner was to determine which technological energy supply options may be best suited to meet these demands, and to what degree it is technically and economically feasible to achieve an energy supply based largely on renewable resources. The site already features a thermal network which provides heating to a fraction of the buildings in the district. An important question was the degree to which, and in which areas, it might be desirable to extend this network, and potentially complement it with a groundwater-fed cooling network.

3.4. Case study 4 - Energy master planning for an Alpine municipality

In 2008, the first energy master plan for the municipality in question was developed. Ten years later, the municipality requested an update of its energy master plan, which was to review the last 10 years while also giving an updated outlook for 2035 and 2050. The 2018 master plan sets new targets for the municipality based on the Swiss Energy Strategy 2050. The goal of the study was to understand how different combinations of energy technologies could best contribute to meeting the new targets. Of particular interest in this case was the potential of an energy system based around the provision of groundwater-based heating and cooling distributed via an anergy (low-temperature, <20°C) thermal network. In addition to groundwater, the potential contributions of various hourly-/seasonally-varying renewable energy resources such as local hydroelectricity and solar energy were a particular focus of the study. A critical question was how to bridge the winter shortfall in renewable energy availability.

4. Synthesized learnings

In this section, key learnings from the four case studies are synthesized. The actual results of the case studies are not presented – rather we focus here on methodological learnings which may inform future studies applying optimization-based approaches to the planning of local energy systems in practice. Three categories of learnings are presented here:

1. Learnings with regard to *project methodology*, i.e. the overarching procedure followed to achieve the stated goals of the study.
2. Learnings with regard to *optimization methodologies*, i.e. which optimization methodologies were of relevance.
3. Learnings with regard to *key indicators and results presentation*, i.e. which indicators were relevant to the involved stakeholders and to which forms of presentation did they best respond.

4.1. Project methodology

In section 3 above, the basic sequence of steps foreseen to be used in each of the case studies was presented. This basic methodology proved to be relatively robust across the case studies, with the major differences across cases seen in the duration and manner of execution of the individual steps rather than the structure of the methodology itself. Two specific patterns are worth noting.

Firstly, the data collection and processing phase was generally found to take considerably longer than foreseen, and was itself subject to multiple iterations. Two categories of data were most effort intensive: building energy demand data and technology cost data. For each of the case studies, building- or parcel-scale energy demands at hourly resolution were required. In all cases a combination of building simulation, standards-based assumptions, public building databases and monitored data was used to obtain suitable demand profiles. A particular challenge – the scale of which was not foreseen in advance – was the presence of missing and erroneous values in building databases and monitored data. This challenge was particularly onerous in case studies 3 and 4 due to the large number of buildings and the inconsistency of the databases used. In both cases, considerable manual effort was required to identify anomalous data points and replace them with justifiable estimates. A second challenge was the estimation of time resolved demands for industrial buildings. The energy intensity and temporal distribution of industrial energy demands are very specific to the processes involved, which are often not precisely known in such studies. Monitored data was therefore especially critical to estimating the energy demands of industrial buildings – sometimes workarounds using available data were necessary. For instance, in case study 1, highly resolved electricity demand data could be used as a basis for estimating the refrigeration demand of the industrial buildings. A specific challenge with regard to technology data was to estimate the capital costs of technologies in a comparable manner. These costs may be highly local, and reliable databases covering the full range of possible technologies do not exist. Moreover, different data sources may rely on different assumptions, meaning that the costs of two technologies may not be comparable if the data is drawn from two different sources. Most of the case studies here included several dozen different conversion and storage technologies, more than was anticipated. For each technology, multiple data sources had to be compared and necessary assumptions had to be verified with the involved stakeholders.

Secondly, for most case studies, the overarching methodology was more iterative than anticipated. Each iteration turned up unexpected results which had to be verified, and adjustments made. For instance, in case study 2, it was observed after one iteration that an external district heating network connection – the costs of which had been roughly approximated – was being used exclusively to cover heat demand peaks rather than provide for the heat base load. This was deemed an unrealistic modelling artifact and adjustments were made to the technology definitions in the subsequent iteration. It was also observed that multiple iterations are necessary not only as a basis for refining the results, but also as a basis for helping stakeholders to grasp the approach, the inherent assumptions underlying it, and the value and limitations of the results. These iterations therefore served the secondary purpose of a learning process for the stakeholders. In most of the case studies, 4 to 6 iterations were eventually necessary to arrive at a set of results acceptable and understandable to the stakeholders. In most of the cases, the possibility and benefit for further iterations beyond the conclusion of the original project was foreseen, in particular focused on the development of detailed concepts for specific subsystems, such as district heating networks or seasonal storage, which could be addressed at only a relatively high level in the holistic analysis.

4.2. Optimization methodologies

As evident in the descriptions above, the requirements of each case study differed, due to the varying knowledge needs of the involved stakeholders. This resulted in different sets of demands on the optimization methodologies used. As illustrated in Table 2, two of the case studies required multi-node problem formulations due to the need for optimizing the topology and dimensioning of a thermal network. In both cases, a temporal decomposition approach was required to preserve computational tractability of the optimization problem. Due to the large size of the site, case study 3 also required clustering in the spatial dimension to reduce the problem size. In case study 2, temporal decomposition was complicated by the need to represent seasonal storage technologies, requiring a solution tailored specifically to that case. Case study 1 – uniquely amongst the case studies – required a multi-stage problem formulation in order to accommodate phased changes in the spatial development of the site. Although a single node problem, the need for a multi-stage formulation in case study 1 and the large number of technologies being represented (due to many different energy carriers), significantly increased the complexity of the optimization problem, again requiring the use of temporal decomposition. None of the case studies used stochastic or robust optimization methodologies. Rather it was generally preferred by the stakeholders to address uncertainties through the use of scenarios and sensitivity analyses, as this provided a transparent basis for assessing the effects of different sources of uncertainty.

Methodology	Case study			
	1	2	3	4
Network optimization		thermal	thermal	
Spatial clustering			density-based	
Temporal decomposition	typical days	typical days	typical days	
Multi-stage optimization	3-stage			
Uncertainty handling	scenarios	scenarios		scenarios

Table 2: Overview of the methodological extensions used in each of the case studies.

Although the different case studies were subject to different methodological requirements, it was possible to carry them out using a common code base. In particular, it was possible to implement each of the methodologies into the Ehub Tool such that they could be active or inactive depending on the requirements of the problem at hand. This allowed for the formulation of the optimization problem to be automatically structured based on the problem definition as expressed in the Tool's input files, which are prepared individually for each case. However, it was noticed that each case came with certain characteristics that required the implementation of a limited set of parameters and constraints tailored specifically to that case. Based on the authors' experiences in these case studies, this is unavoidable, and suggests that there are limits to the development of a standardized "one-size-fits-all" software code base for optimization-based local energy systems planning.

4.3. Key indicators and results presentation

Based on the preferences and feedback of the stakeholders, a specific set of key performance indicators was calculated based on the results of each case. Five categories of indicators were relevant in one or more of the case studies: economic, sustainability, resource use, system design, system operation and energy autonomy. As indicated in Table 3, certain indicators were requested by the stakeholders in all case studies, including life-cycle costs, CO2 emissions and the optimal supply system configuration. Groundwater energy use and electricity grid interaction patterns were also required in 3 of the 4 case studies. In 2 of the 4 case studies, the stakeholders requested that all indicator values be compared with those of a "reference" scenario – a scenario based around the use of a conventional (in both cases natural gas-based) system configuration for the site. Comparison to the reference scenario served as an indication to the stakeholders of the potential benefits of developing a "non-conventional" energy supply system for the site. This was critical to enabling the industry partners to justify the results to other stakeholders and decision makers not directly involved in the project.

A challenge for the research team, especially in case studies 1 and 2, was the large number scenarios calculated. In all cases, multiple pareto fronts composed of 4-8 "optimal" solutions – a cost-minimizing solution, as CO2-minimizing solution and several in-between solutions – were calculated. In case study 2, such a pareto front was calculated for each of 45 different scenarios. This produced 180 "optimal" solutions for which each indicator was calculated. Identifying and communicating key patterns within this large body of results data were key challenges in this case. This was accomplished through the use of color-coded comparison matrices, which condensed a large amount of information into a single visualization, facilitating the identification and communication of important patterns. Detailed results for selected solutions were additionally provided to enable greater depth of understanding.

Category	Indicator	Case study			
		1	2	3	4
Economic	Life-cycle costs (per kWh or per m2)	■	■	■	■
	Cost breakdown (CAPEX, OPEX)		■	■	
	Overnight costs (per technology)		■		
Sustainability	CO2 emissions (per m2)	■	■	■	■
	CO2 avoidance costs	■			
Resource use	Primary energy use		■	■	
	Groundwater use patterns	■		■	■
System design	Optimal supply system configuration (optimal set & dimensioning of technologies)	■	■	■	■
	Optimal thermal network structure		■	■	
System operation	Storage utilization patterns		■	■	
	Renewables-based production			■	■
	Electricity grid interaction pattnerns		■	■	■
Energy autonomy	Hours of autonomous operation		■		

Table 3: Overview of the key indicators calculated for each case study.

5. Conclusions

The aim of this paper has been to generate insights to facilitate the effective application of optimization-based methodologies to local energy systems planning in practice. Key learnings from 4 different case studies were presented, each carried out in close collaboration with industry partners and focused on a specific physical site. The following learnings have been emphasized:

- It is possible to apply a *common overarching methodology* to case studies with different requirements and in the presence of different knowledge needs.
- An *intensively iterative methodology* for optimization-based local energy systems planning projects is critical not only as a basis for adapting the analysis based on stakeholder input and developing detailed concepts for specific subsystems, but also to facilitate learning on the part of stakeholders with regard to the value and limitations of the approach and the results.
- The presence of *anomalous, inconsistent and incomplete data resources* – especially with regard to building energy demands and technology costs – requires significant manual effort.
- *Temporal decomposition methodologies* are a critical enabler to preserving computational tractability in the optimization of complex technical systems, especially those featuring networks and those with many energy carriers or technology options.
- Both the methodological tailoring of a model to a specific case – i.e. the selection and adaptation of methodological extensions suited to solving the problem at hand – and the calculation of key indicators (see Table 3) can be *largely automated* using basic object-oriented software approaches.

In general, it was observed that at least 4 categories of knowledge are necessary for carrying out case studies similar to those presented in this paper: (1) on-the-ground knowledge and data concerning the site in question, (2) engineering knowledge regarding feasible technological solutions, (3) knowledge of optimization methodologies, and (4) software development knowledge. In the experience of the authors based on the case studies described in this paper, the 3rd and 4th categories of knowledge can be effectively solidified in a generally applicable – within certain limitations – software tool. To a certain degree, the 2nd category of knowledge can be solidified within a consistent and complete technology database linked with such a tool.

Taken together, the findings of this paper suggest that a combination of software tools and consistent/complete technology and building databases could significantly accelerate future studies and reduce the knowledge required for their execution. Effectively implemented, such a resource has the potential to facilitate the uptake of optimization-based local energy systems planning approaches in practice.

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Integration of multiple methodologies to evaluate effects of Nature Based Solutions on urban climate mitigation and adaptation

López A[1], Mabe L, Cantergiani C[1]

[1] Tecnalia Research & Innovation, Astondo Bidea, Edificio 700, Derio, 48160

arantza.lopez@tecnalia.com

Abstract. Nature Based Solutions contribute both to mitigate and to adapt the cities to the impacts caused by climate change at urban level. Several methods and tools exist for assessing each strategy. However, none of them allow to cover the whole steps included from analyzing climate trends that could affect the cities, to NBS effectiveness. This paper reviews and classifies existing methods according to the relevant steps of climate resilience and NBS effectiveness, and a combination of various of those methods is presented in a practical case study. Bottom-up city energy, economic and environmental modelling have been performed to understand mitigation effects of NBS implementation at building and neighborhood level. Urban hydrodynamics and fluid dynamics have been modelled too, allowing the estimation of the adaptation effectiveness of the NBS scenarios in flooding and temperatures reduction respectively. Moreover, city vulnerability and urban risks, considering IPCC scenarios regarding climate trends, have been assessed to understand the areas of the city more vulnerable to the impact of climate change. Results show that strategies and climate hazards has been worked in a split way and there is a need to connect better mitigation and adaptation information to facilitate the municipalities taking robust decisions regarding the NBS implementation.

1. Introduction

Urbanization is widely acknowledged to be on an upward trend with 66% of the global population expected to be living in cities by 2050 [1]. Projections of climate change show increasing frequency and severity of extreme weather events, such as heatwaves. Such events, coupled with the UHI are likely to amplify the challenges facing this urban growth [2].

In this context, the European Union considers between their four main goals in this topic, the need of developing climate change adaptation and mitigation strategies. In order to promote this goal, for the current budget period 2014-2020, the European Commission has proposed that at least 20% of the budget (Multiannual Financial Framework) should contribute to climate change objectives, helping to ensure substantial support for adaptation and mitigation action in the Member States [3].

Following this, in March 2014, the European Commission launched the Mayors Adapt initiative on urban adaptation. It merged in 2015 with the Covenant of Mayors, combining urban adaptation and mitigation into an integrated approach. Today, the EU Covenant of Mayors for Climate & Energy brings together thousands of local governments voluntarily committed to implementing EU climate and energy objectives [3]. The trend driven by the Covenant of Mayors for Climate and Energy (CoM) is to include both climate and mitigation aspects [4]. This is also aligned with IPCC approach which considers that Adaptation and mitigation are complementary strategies for reducing and managing the risks of climate change [2].

In this global context of mounting challenges (e.g., climate change) and human activities (e.g., rapid urbanization), this Special Issue of Environmental Research attemps to lay the theoretical and applicative foundations of the Nature based solutions (NBS) concept by focusing on the most recent innovative strategies and scientific advances for building resilient landscapes and cities [5]. NBS are living solutions inspired, continuously supported by and using nature, designed to address various societal challenges in a resource-efficient and adaptable manner and to provide simultaneously economic, social and environmental benefits [6]. Having recognized NBS as one of the most comprehensive approaches for developing resilient landscapes and cities, governments and scientific communities are currently faced with the challenge of moving from general pronouncements to practical applications [5].

This paper presents the analysis of the existing methods and tools for assessing NBS effectiveness to mitigate and/or adapt the urban environments to climate change. Considering the trends driven by the most relevant entities about considering both mitigation and adaptation contributions, special focus has been put to identify methods that allow considering both strategies with the idea of providing an integrated approach.

2. Procedure followed

The procedure followed to understand the potentialities of the methods and tools to provide robust information regarding NBS effectiveness to climate change mitigation and adaptation has been done in 4 main steps:

- Step 1: Climate resilience methodology. Definition of all the features that a climate resilient methodology must cover.
- Step 2: Methods selection and characterization. Identification of all the methods and tools that can cover at least one part of the previously defined features.
- Step 3: Methods classification. Classification of the methods according to the relevant steps of climate resilience and NBS effectiveness that they cover.
- Step 4: Case study. Analyze in a practical case study a combination of various of those methods

2.1. Step 1: Climate resilience methodology.

The ambition of the climate resilience methodology as is understand in this paper, was the identification and organization of all the potential issues of interest in the context of climate change and NBS fields. Following objectives were defined for the methodology:

- It must allow understanding how the climate trends can affect the cities.
- It must consider how to assess the climate hazards that could affect the cities.
- It must allow assessing mitigation and/or adaptation strategies.
- It must include how to assess the effectiveness of the NBS to improve city resilience.

These objectives guided a completed state of the art revision which was supported in the identification and analysis of more than 80 references [7]. These references include more than 60 scientific articles identified thanks to key words such as climate resilience, mitigation, adaptation, Nature based solutions, urban climate trends, urban heat island effect, etc. Related projects and networks were identified and analyzed too, providing a detailed view of the of the state of the art.

From the literature review, information was extract in order to stablish the basis the methodology development. This information attends to the climate issues, scale (region, city, district, object), target of the measures (adaptation, mitigation, resilience), type of NBS considered, indicators used, actuation areas, etc.

The literature review had as a result the collection of all the features of interest that a methodology that allows assessing from climate trends to NBS effectiveness must cover:

1) Climate trends: air temperature, Rainfall/precipitation, air quality
2) Climate threats/impacts/hazards: Colder winters and warmer summers, Urban heat Island effect (UHI), runoff, air pollution, water quality, wind field.
3) Strategies: Mitigation and adaptation
4) Indicators to assess urban vulnerability and risks: Building cooling and/or heating energy demand reduction, global warming potential reduction, primary energy demand reduction, runoff reduction, carbon sequestration, external air temperature reduction.
5) Nature based solutions: parks and gardens, structures associated to urban networks, structures characterized by food and resources production, natural and semi-natural water bodies and hydrographic networks, constructed wetlands and built structures for water management, green roofs, urban planning strategies, works on soil, vertical structures (green walls and façades), direct human interventions.

2.2. Step 2: Methods selection and characterization.

This step consisted on the identification of all the methods and tools that can cover at least one part of the previously defined features of the methodology. After the identification, the methods have been characterized according to the mentioned features.

2.3. Step 3: Methods classification.

The classification of identified methods and tools according to their suitability for the urban climate resilience and NBS methodology application has been done by using the RACER method. RACER is an evaluation framework design by the European Commission to assess the value of scientific tools for use in policy making [8, 9, 10]. RACER stands for Relevant, Accepted, Credible, Easy and Robust:

- Relevant – e.g. closely linked to the objectives to be reached.
- Accepted – e.g. by staff and stakeholders.
- Credible for non-experts, unambiguous and easy to interpret.
- Easy to monitor – e.g. data collection should be possible at low cost.
- Robust – e.g. against manipulation.

This generic approach has been adapted to the objectives of the method classification:

- **Assessing urban climate issues**: methods that take into account issues related to climate, (such as temperatures, rainfall, air quality) are considered relevant for the purpose of the methodology.
- **Consideration of different scales**: methods that cover object, neighbourhood and city scales

are needed in order to fully characterize the NBS effectiveness over the climate resilience of the city.

- **Analysing all the stages**: from identification of threats to the analysis of NBS effectiveness. Methods that allow assessing the whole process are presented as suitable for the purpose of the methodology. However, according to the specific characteristics that this methodology wants to fulfil, it was considered challenging finding a method that could assess the whole process.
- **Assessing NBS**: as Nature Based Solutions are the focus of the project, methods that consider several NBS are included as relevant.
- **Feasibility to apply the method**: data, tools and information availability for the application of the methods by the municipalities, it was considered interesting too.

These dimensions have been considered as the main criteria to appraise the climate resilience of the cities and NBS.

2.4. Step 4: Case study. Donosti/San Sebastian city (north of Spain)

A real case study has been defined and the most promising methods according to the RACER, to the classification and to the issues of interest for the municipality, have been selected to understand the integration options of them.

It is important to note that after identifying all the potential interesting methods regarding the climate change and NBS fields, several expectations have been defined to be answered by the method (or methods in plural):

- understanding current situation (climate threats currently affecting the municipality),
- identifying potential future impacts due to the climate change if there is no intervention (BAU),
- building NBS scenarios to try to minimize the potential impacts,
- assessing the scenarios and
- selecting the most suitable NBS solutions according to their effectiveness

Following this approach, the case study of has been defined and performed and integration options have been studied:

- Envi-met has been used to understand the effectiveness of the NBS to adapt the neighbourhood to the expected temperatures increase.
- CityCAT, on the other hand, has been used to understand the NBS effectiveness to run-off reduction.
- ENERKAD has been used to understand the mitigation effects of the NBS in the energy demand of the buildings.
- NEST has been used to understand the NBS effectiveness to reduce the climate impacts at the neighbourhood scale.

3. Results

3.1. Methods characterization: Climate resilient features covered by analysed methods.

Full list of considered methods is given in chapter 3.2. In total, 21 methods have been studied and characterized. Results from the methods characterization is given in table 1.

Table 1. Climate resilient features covered by analyzed methods

Climate resilient feature	Climate resilient (sub)feature	Number of methods
Strategy	Mitigation	8
	Adaptation	14
	Mitigation & Adaptation	5
Climate trends	Air temperature	11
	Rainfall / precipitation	11
	Air quality	9
Climate threats/impacts	Colder winters, warmer summers	12
	Urban Heat Island	12
	Runoff	12
	Air pollution	13
	Water quality	8
	Wind field	10
Indicators	Building cooling and heating energy demand reduction	9
	Global warming potential reduction	6
	Primary energy demand reduction	7
	Runoff reduction	11
	Carbon sequestration	5
	External air temperature reduction	10
Scale	Object	15
	District	17
	City	17
	Up to the city	15
Nature Based Solutions	Parks and gardens	15
	Structures associated to urban networks	15
	Structures characterized by food and resources production	13
	Natural and semi-natural water bodies and hydrographic networks	13
	Constructed wetlands and built structures for water management	14
	Green roofs	17
	Urban planning strategies	12
	Works on soil	13
	Vertical structures (Green walls and facades)	15
	Direct human interventions	12

3.2. Methods classification according to their suitability to assess from climate trends to NBS effectiveness.

Table 2 summarizes the results obtained from the RACER assessment applied to selected methods together with the number of features of the methodology that they consider.

Table 2. Methods classification according to their suitability to assess from climate trends to NBS effectiveness

Method	RACER position	Methodology features covered (tot 32)
Envi-MET	1	21
Library of Adaptation Option	2	25
Design Builder	3	9
EPA Storm Water Management Model (SWMM)	4	18
Enerkad	5	13
Green Pass	6	23
HAVURI	7	26
NEST	8	14
CITY-CAT	9	18
Soil and Water Assessment Tool (SWAT)	10	19
Climate-ADAPT web platform	11	7
Rayman	12	8
Fault tree analysis (FTA)	13	21
SIRVA	14	26
Simile	15	22
URB-CLIM	16	19
EPESUS	17	22
Enviro-HIRLAM	18	9
PLINIVS models	19	6
IVAVIA	20	27
IPCC projections	#NA	7

TEB, i-tree eko and Solweig methods have been identified as potential methods of interest and will be included in next steps of the work done in this field.

3.3. CityCAT, ENVI-met, ENERKAD and NEST methods applied to a real case study.

CityCAT method allows to calculate quantitatively the effectiveness of any type of Nature Based Solution regarding runoff reduction, at any scale. CityCAT allows the visualization of the results given as a reduction of a high of the sheet of water and as runoff reduction in centimetres. Although, the model requires a very time consuming cartography pre-processing, once this work is done, the simulation of different scenarios with different NBS configurations or different meteorological conditions, is very easy to perform. Moreover, ENVI-met model, needs very similar inputs to the ones required for CityCAT. Therefore, the information can be shared for both models.

ENVI-met method allows to calculate quantitatively the effectiveness of any type of Nature Based Solution regarding temperature reduction, at neighbourhood scale. Meteorological information representative of the study site matches with the information demanded by CityCAT. According to ENVI-met results, the effectiveness of NBS temperature reduction varies depending on the selected moment of the day and according to the solar radiation. Unfortunately, there is a lack of consensus on how is the better way of measuring the thermal effectiveness of adaptation measures. The scientific community is working on standardising thermal effectiveness related process that is, the way of measure the thermal variable and the metrics to express the effectiveness.

Enerkad allows studying the NBS effectiveness to reduce the energy demand of the buildings. In this sense, the implementation of NBS it is considered a mitigation strategy. This is because the aim is to reduce the consumption of energy and, as a consequence, to minimize the environmental impacts due to energy consumption. Enerkad can be also linked with ENVI-met, but strong efforts are needed to obtain the whole hourly temperatures of a year with this approach, other urban climate tools like UWG would be more adapted1 as it directly provides local climate temperature in a district in function of a temperature from close rural meteo station, depending on the district land use. It also can be use with weather projection to add the local NBS effect. Regarding the NBS, it must be note that Enerkad is focused on buildings and, as a consequence, only NBS that can be implemented in buildings, such as green roofs and green façades, are going to have remarkable effects on the results.

NEST tool has been selected for the case study in order to understand the NBS effectiveness to reduce the climate impacts at the neighbourhood scale. In this sense, the implementation of NBS it is considered a mitigation and adaptation strategies because it allows the assessment of the impacts of:
(1) Vegetation on GWP and runoff reduction
(2) Permeable pavements and green roofs on runoff reduction

Runoff reduction is given in NEST in terms of absorbed water (green spaces and mineralised areas with low permeability) and unabsorbed water in m3/year. This kind of results differs from the ones provided by CityCAT (runoff reduction in cm). Therefore, depending on the objective of the study, one or the other could be more suitable.

Enerkad results can also be translated to GWP reduction due to NBS implementation. Nevertheless, the scale at which Enerkad and NEST work is different. A bottom up approach can be applied to compare the results of both methods but and, again, depending on the aim of the study could be more suitable selecting one of them.

4. Conclusions

Nature Based Solutions contribute both to mitigate and to adapt the cities to the impacts caused by climate change at urban level. Several methods and tools exist for assessing each strategy. However, none of them allow to cover the whole steps included from analysing climate trends that could affect the cities, to understand the NBS effectiveness to mitigate and/or to adapt the cities.

Results show that strategies and climate hazards has been worked in a split way. Some methods are focused in a specific climate feature, and do not provide information about other potential benefits of implementing NBS. Analysing the same NBS scenarios with different methodologies, reflects other advantages associated to NBS implementation. Data needed for the methods and the treatment of it was similar in some cases. Nevertheless, is not possible to put together the results obtained with each method and the different approaches do not allow the comparison between results. Therefore, there is a need to connect better mitigation and adaptation information to facilitate the municipalities taking robust decisions regarding the NBS implementation. This conclusion can be also transfer to the specific field of adaptation.

[1] http://urbanmicroclimate.scripts.mit.edu/uwg.php

This paper presents just the starting point of the work to be done in this field. Conducting a full study, from understanding climate trends, to identify urban vulnerabilities and risks, to analyse nature based solutions effectiveness to minimize the effects of climate, is something that the municipalities are already demanding. Scientific community must answer to this demand in a robust way and must help the municipalities in the decision making processes regarding the most suitable NBS to be implemented. As a result, the introduction of NBS in the cities will be supported too and the climate change effects will be minimized.

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Fostering the implementation of green solutions through a Living Lab approach – experiences from the LiLa4Green project

Tötzer T[1], Hagen K[2], Meinharter E[3], Millinger D[4], Ratheiser M[5], Formanek S[6], Gasienica-Wawrytko B[2], Brossmann J [3], Matejka V [3], Gepp W [5]

[1] AIT Austrian Institute of Technology GmbH, Giefinggasse 6, 1210 Vienna, Austria
[2] Technical University of Vienna, Erzherzog Johann Platz 1, 1040 Vienna, Austria
[3] PlanSinn Planung & Kommunikation GmbH, Wiedner Hauptstraße 54/12, 1040 Vienna, Austria
[4] GREX IT services Gmbh, Eglseegasse 10, 1120 Vienna, Austria
[5] Weatherpark GmbH, Gardegasse 3/3, 1070 Vienna, Austria
[6] GRÜNSTATTGRAU Forschungs- und Innovations-GmbH, Favoritenstraße 50, 1040 Wien/Vienna, Austria

tanja.toetzer@ait.ac.at

Abstract. For dealing with participatory aspects in urban planning, the method of Living Labs (LL) currently turns out to be a most popular and promising approach. In our project LiLa4Green we apply such a Living Lab in the City of Vienna for implementing green solutions in densely built settlement areas characterised by heterogenous ownership and building structures, few public open space and green areas and the dominance of car traffic. In the first year, the potential analysis of the status-quo situation was completed, and the Living Lab had been established. First lessons from the now successfully running LL process can be drawn. The analysis and the initiated process revealed deficits, but also clear potentials for the implementation of green measures which could significantly improve the current situation. So far, the Living Lab process made clear that the people are generally affected and therefore interested in the topic of heat stress and greening the city, but it does not seem to have top priority for them. Although many people could be addressed and involved in discussions, only a small group of people were willing to take part in the first workshop. Confronted with such challenges the strategy for the next stage was to bring the LL process closer to the people's everyday life context and to extend the participatory methods. Innovative ICT-solutions which help to intuitively visualize and understand green solutions and their effects were tested, as well as a co-decision process for the realization of a first intervention was offered. The higher participation rate in the second green lab indicates that this is a promising approach which will be continued in the further LL process.

1. Introduction

In order to sustain the livability of a historically grown city such as Vienna, adaptation measures to climate change must already be considered and implemented today to proactively counteract negative developments in the future. Climate models predict a clear upward trend of heat waves and tropical nights [1] which will affect an increasing number of people in future decades, not only in Vienna, but worldwide as urbanization as well as climate change is expected to continue through the 21st century [2] [3].

Consequently, many cities start to strategically plan and adapt the urban environment to the changing framework conditions. The building structure (height, orientation, density, facades/roof color, texture, etc.) plays an essential role for the urban microclimate. Equally decisive are type, shape and extent of the greening as well as a corresponding rainwater management [4] [5] [6].

The Urban Heat Island (UHI) effects in cities are intensified by solar radiation which is absorbed by buildings during the day and emitted during the night in form of sensible heat as well as by anthropogenic heat emissions, which are among others produced by traffic, households and industry and increasingly through air conditioning systems [7]. Due to this, the air temperature in the city and in the countryside can differ by 1 to 3 degrees in annual average during the day and up to 12 degrees during the night [8]. Buildings and green influence each other via light reflection, shadow, radiation, etc. A comprehensive implementation of green-blue infrastructure measures represents a possibility to significantly reduce the extent of UHI [9] [10]. Although strategies for counteracting the UHI in the city of Vienna already exist (e.g. UHI STRAT [9]), the realization of green-blue infrastructure measures is challenging as it addresses various urban issues (green&open space, traffic&pipeline infrastructure, water&sewage infrastructure, etc.) and stakeholders.

The Smart Cities demonstration project "LiLa4Green"[1] presented in this paper aims to support the realization of green-blue infrastructure projects (urban green and urban water areas) in densely built areas of the City of Vienna. It is carried out by an interdisciplinary project consortium consisting of the Austrian Institute of Technology, Technical University of Vienna, Weatherpark, PlanSinn, the green innovation laboratory GRÜNSTATTGRAU and GREX IT. In order to realize measures that not only consider climate-resilient aspects, but also social aspects such as quality of life, health, safety and usability, a Living Lab is set up that involves citizens, stakeholders and decision makers in the implementation process (co-creation). The Living Lab aims to raise the awareness for the positive effects of green-blue infrastructure measures as well as strives for increasing the acceptance and willingness to implement and invest. LiLa4Green started in March 2018 and has now run for one year. First findings on the potentials for greening densely built urban areas and the added value of applying a Living Lab approach are presented in the following.

2. Need for greening the City of Vienna?

Vienna is, like many other European cities, particularly affected by the impacts of climate change. Analysis of climate data clearly demonstrates the already pressing need for action as regional impacts of the global climate change for the city of Vienna are already apparent. Increasing temperature during the summer months is the most significant impact in terms of visibility in meteorological data and negative consequences for the inhabitants.

2.1. Heat waves and tropical nights in Vienna on the rise

For the climate analysis conducted within LiLa4Green hourly data of air temperature for the time period from 1984 to 2017 were purchased from the national weather service ZAMG (Zentralanstalt für Meteorologie und Geodynamik) for the climate station "Wien Innere Stadt" and "Wien Hohe Warte". The climatic analysis focused on two parameters that clearly show how quickly the character of summers in Vienna has changed during the last 30 years: the frequency of so called “Kysely-days” (i.e. heat wave days) and of hot nights with minimum temperatures above 20°C (“tropical nights”). A day is defined as a heat wave day, if there are three or more consecutive days with 30°C maximum temperature or more. The mean number of heat wave days per year in the city center of Vienna was 8.4 in 1984 and increased to 18.9 in 2017. The temperature data show a clear upward trend over the whole period, with maximum values reaching more than 30 days per year in the second half of the period (after the year 2000). The number of hot nights also rose significantly over the last 30 years. In 2018 there were 41 “tropical

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[1] LiLa4Green is funded by the Climate and Energy Fund and implemented under the "SMART CITIES - FIT for SET" program.

nights”, which is the highest number ever recorded in the city center. The mean value over the whole period was 13,8 tropical nights per year.

Especially the longer lasting heat waves and tropical nights pose an additional stress to the body and lessen the quality of life. Respiratory and cardiovascular diseases, impacts on mental health and, as a consequence, reduced work performance and productivity are just some of the proven implications of heat waves [11]. Particularly affected are elderly and sick people as well as children.

The temporal development of these and other parameters clearly show that the intensity and duration of hot periods during the summer months are rising dramatically. As a consequence, the city and its inhabitants have to adapt to new characteristics of summer, including extreme events becoming more frequent. Facing such changes, greening and proper rainwater management can have an essentially positive influence on the microclimate in densely built city structures. Green within the city not only creates a valuable recreational space while reducing CO_2, it also reduces the noise and pollutant exposure, decreases the radiation temperature through shadowing and cools down the adjacent air due to the evaporation of plants. Thus, vegetation should not only be limited to parks and dedicated green areas but integrated into the entire urban fabric for realizing its full micro climatically positive potential.

2.2. Microclimatic situation in the test area “Quellenstraße Ost”

The LiLa4Green test area “Quellenstraße Ost” illustrates the dilemma that is fairly common in densely built urban areas: the amount of green, unsealed areas is quite high with 33 %. However, the densest area - the Wilhelminian style block development area “Kreta” existing of 6 blocks crossed by 3 streets - shows no greening at all and is characterized by sealed surface and stationary traffic. Predominantly in such areas, green infrastructure measures are of utmost importance for the city´s climate and social cohesion.

The microclimatic analyses reflect the dense urban structure. During hot summer days the air temperature and the human comfort measure “PET” (Physiological Equivalent Temperature) rise in the mainly north-south and east-west orientated street canyons. While the distribution of the air temperature is quite even, the PET values vary strongly. Around noon the maximum values in the north-south-street canyons rise up to 50 degrees, which means that people experience strong heat stress in these areas. Minimum values are around 26 degrees, which is felt as slightly warm by humans. Areas with these moderate values are shady spots along north- or east-facades or under trees. The high values can be explained by a lack of vegetation and shade and the corresponding high radiation input, both short wave radiation from the sun and long wave radiation (i.e. sensible heat) from the blacktop and the building facades. During heat waves air temperature stays high also in the night.

Putting this characterization in context with the climate of the whole city, the test area “Quellenstraße Ost” can be described as a residential area with high bioclimatic stress. The area is vulnerable with respect to densification. Common recommendations for such areas are ameliorating the fresh air supply, increasing the green infrastructure and unsealing the ground.

3. Greening Potentials

In addition to the (micro-)climatic analysis, the potentials for implementing green-blue infrastructure measures within the test area have been analyzed. The aim was to highlight links to existing green networks and to general strategies of Vienna and to point out areas of especially high need for action. The analysis included the open space structure in regard to its private, semi-public and public character and especially the characterization of the streetscape concerning e.g. existing greening, division and public usability, parking situation and the quality of stay.

With respect to urban climate and social aspects the Wilhelminian style block development area “Kreta” has been identified as the area with the highest need for taking measures. Apart from that this area is surrounded by current urban development that will change the context and role of this city area in the near future. With the opening of two new bridges and a new connection to public transport in the north it will form an important link between the future development site and the currently temporary used area of the Kempelenpark and to the recreational area of Laaer Berg in the south-east. The potential map (see **Figure 1**) illustrates the important superordinate (green arrows) and internal district connections (orange arrows), adequate streetscape sections for restructuring (violet areas) and the location for especially important areas for quality of stay e.g. in front of educational buildings (dark violet hatch).

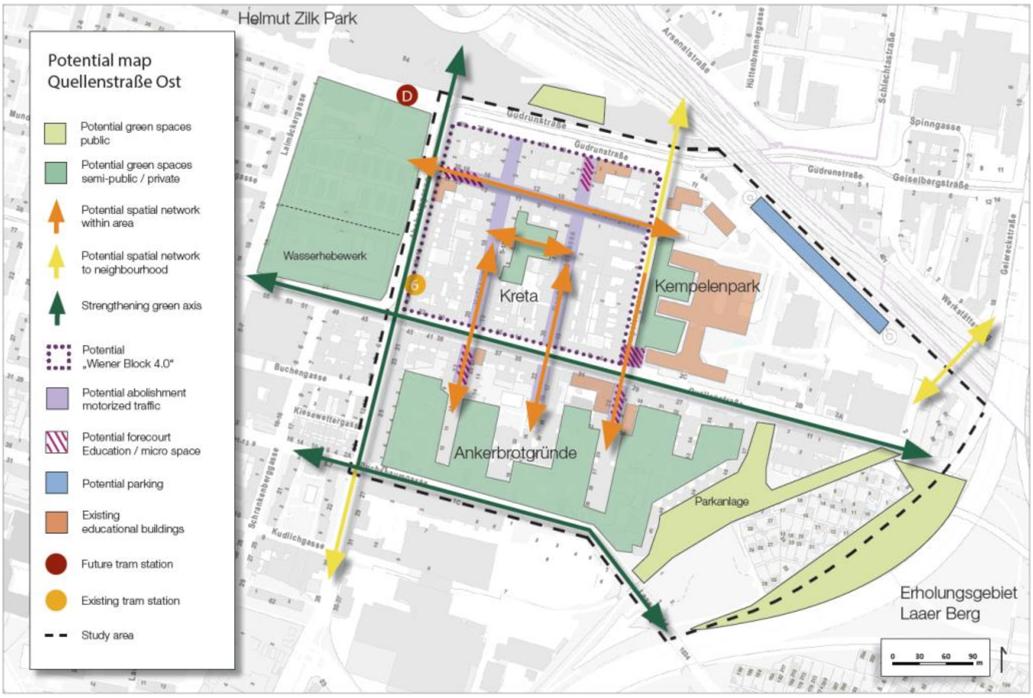

Figure 1. Potentials for improving the green space in the test area Quellenstraße Ost in the 10th district of Vienna.

4. The Living Lab in LiLa4Green

Parallel to the scientific analysis of the potentials, a participatory process in form of a Living Lab has been started. There is no unique definition of Living Labs (LLs), but commonly cited characteristics of Living Labs are openness, realism, empowerment, spontaneity, sustainability and value [12] [13] [14] [15]. One of the key criteria of urban LLs is the geographical embeddedness [16]. Urban LLs represent ecosystems of open 'urban' or 'civic' innovation and are situated in a real urban context where the process in focus is taking place. In our Living Lab for more urban green ("LiLa" for Green) we discussed its meaning in the specific project context and formulated the following definition: Our LL aims to find solutions to urban issues such as the effects of climate change, resilience and sustainability and focusses on citizens and stakeholders as core elements of an urban LL from a holistic view (ecological, economic, social, technical, spatial).

During this LL process it is examined how a smart user participation can be organized and designed in order to raise awareness within the public regarding mitigation and adaption measures to climate change. By combining innovative methods of social science with the latest digital technology an ideal dissemination of information with regard to the diverse functionalities of green and free spaces is to be facilitated. Therefore, also new methods of assessment (e.g. crowdsourcing) and visualization (Augmented Reality) will be tested. These new forms of smart user participation and the visual depiction of measures and their effects aim to ensure a broad acceptance within the public for green-blue infrastructure. The Living Lab in Lila4Green is constituted by a range of different activities that open the research project to stakeholders and citizens.

The LiLa4Green-LL started with a design process including a screening of suitable participatory methods and strategies and a workshop during which the research team collectively developed a shared practical understanding of our LL, clarifying the context, goals, key questions and initial design of the LL-process. The first step of the Living Lab was taken by hosting a "Start-Workshop". Within this meeting we gathered knowledge, constraints and needs together with relevant stakeholders (representatives of municipal agencies and local institutions) and collected information on spatial and social potentials within the project area. Furthermore, it was discussed what the participating stakeholders can "give and take" to/from LiLa4Green, emphasizing the importance of mutual benefits. The participating stakeholders made their commitment to take part in the upcoming process including the "Green-Workshops" and to support the project with their knowledge.

Figure 2. On-the-street activation for participation in the Living Lab.

Figure 3. Mapping of hot spots and cool spots in the case study area Quellenstraße Ost.

The corner stones of the LL are four major events called "Green Workshop". These will take place roughly every 6 months, bringing together the research team, stakeholders and citizens. Leading up to our first "Green Workshop" in October 2018, we conducted several on-the-street "activation" activities: we visited the project district with our cargo bike, built up a temporary space for conversations using pictures, signs with questions and a deck-chair (see **Figure 2**) and approached people walking by. To initiate conversations we used small, game-like activities like a "bean-poll" about people's perception of heat waves or a mapping of hot and cool spots in the area (see **Figure 3**). These conversations aimed at mobilizing people for the "Green Workshop" and to gain a better understanding of the area and its inhabitants.

The first "Green Workshop" (see **Figure 4**) was designed to kick off the LL-process and focused on sharing information, building mutual understanding and establishing social connections. At the beginning of the event all participants were asked to answer a brief survey about their perception of urban heat and potential solutions. At the end of the project, this survey will be repeated in order to detect changes in their perception. We then conducted a few simple exercises to allow people to get to know each other briefly. The first half of the workshop was set up as a "Knowledge Bazar", with the research team offering information to stakeholders and citizens about the topic of urban heat effects and sharing first insights from the so far conducted research. Posters, a memory set and a flyer have been prepared as playful and easily understandable starting point for the discussions. In the second half of the workshop we conducted a "World Café" and swapped tasks: now the stakeholders and

Figure 4. Participants of the first "Green Workshop" in October 2018.

citizens offered their local knowledge and ideas about the spatial and social environment of the project as well as ideas for potential solutions.

In May 2019, the second “Green Workshop” took place. As the first workshop revealed the desire of the citizens for action, the research team decided for a first intervention on-site by designing and implementing a green parklet in the streets. In the design studio project “Green up - Cool down” at the Landscape Department of the Technical University of Vienna students developed seven different design concepts for parklets which were presented at the second green workshop (see **Figure 5)**. After the presentations and a timeslot for discussions, all workshop participants formed a jury and voted for their preferred parklet design by awarding points to their favourite concept. In this way a co-decision process was established defining which design will effectively be implemented by the students in summer 2019. Further, local initiatives such as the Materialnomaden (re-use of building material), the local carpentry, kindergardens and the Stadtraum Kempelenpark are involved in consultation, maintenance and supporting the acceptance of and identification with the parklet.

Figure 5. Different design concepts for parklets presented in the jury process of the second “Green Workshop”.

In the second part of the workshop, a first application of a smart interaction tool was set up and tested with the workshop participants (see **Figure 6**). The chosen tool was a lightweight Augmented Reality (AR) tool that visualizes a greening project as it will look like after its realization. Users can view the AR model of the greening project superimposed on the real physical location on their smartphone. To lower the barrier to use, no installation and registration is required. Users can express their opinions about the project, and the tool stores user opinions and interactions in an existing civic participation tool (www.smarticipate.eu). In the sense of co-creation, the users where asked for feedback on applicability, user-friendliness and added value of the tool. Generally, the tool was well received and attracted a lot of interest. A quick survey revealed that it helps people to imaging how greening measures could look like. For some of the participants, the handling of the tool was still too complicated, which was a valuable input and will be incorporated in the further development of the tool.

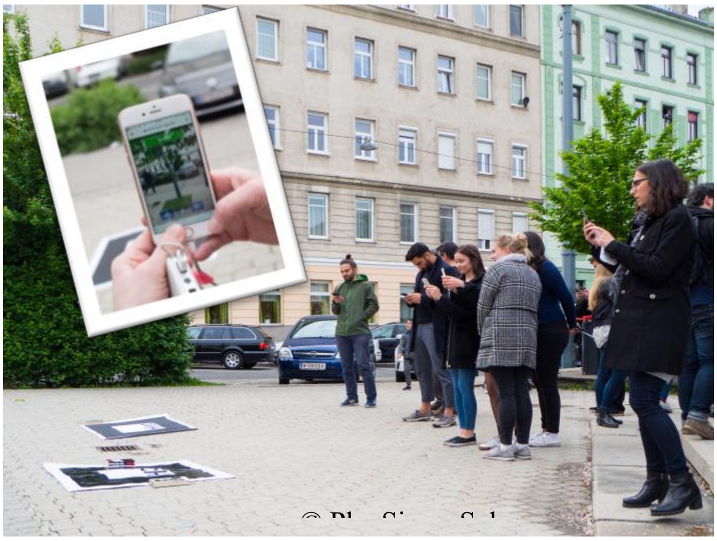

Figure 6. Participants of the second “Green Workshop” testing the AR application in the street.

5. Discussion and lessons learned

Four major insights from the LL process in LiLa4Green could be gathered so far:

1) **Continuity, co-decision-making and setting concrete actions** is essential for successful participation. During the mobilization process in the streets many people could be encountered who were interested in the subject. Yet it was hard to gain their commitment for joining the "Green Workshop". While they verbally supported the idea of greening their neighborhood, their interest did not translate into willingness/ability to participate in the "Green Workshop". Participants of the first "Green Workshop" were mainly acquired through tapping into local networks. The willingness to participate appeared to be much higher in the second "Green Workshop". One reason was that the LL process was already well established and continuously promoted through various channels. A second reason was the real opportunity given to the citizens to decide and co-create, which attracted additional participants. The participants in the LL had the chance to discuss the design solutions and be part of the decision which design will be implemented on-site. Through close collaboration with the residents the willingness to adopt – that means care for – the built design object in front of their building could be enhanced and enabled an emotional binding to "their" green island. The green parklet will work as a pilot project for later implementation activities of LiLa4Green and will help to foster the awareness and acceptance for such green-blue infrastructure measures in the close neighbourhood.
2) Participation needs a **professional accompanying process**. As a key component of LLs is experimentation and co-creation, the process has to be kept flexible. Nevertheless or exactly for that reason, such a process needs a guiding structure and profession management. In LiLa4Green, one partner is exclusively responsible for the LL process, which requires knowledge and resources. The first "Green Workshop" aimed at establishing a core group for the LL-process, including locals, decision makers, regional agents and scientists for gaining a better understanding on the context of microclimate, green and urban spatial planning. A shared idea of this Living Lab was developed. Between the workshops info-mails kept the participants updated and networking activities took place. The results and aims verbalized by the citizens in the first workshop were taken up and built the base for the second workshop. This approach appeared to be successful as the members of the core group also participated in the second "Green Workshop". This highlights the importance of aligning the "what, why and how" of participatory research activities carefully. Besides, a professional process management guarantees, that the results of these activities will be transferred into the documentation of the LL as a complementing source of learning. In that way lessons learned in the LL process is gathered and will not be lost.
3) It is crucial to create a **low-threshold level** for participating in a Living Lab process. The second green workshop proved that the participation process benefited from further on-the-street-activities, as well as from the mobilizing effect of local participants and stakeholders. Furthermore, the offering of co-creation (ICT-solution testing) and co-deciding (jury for the parklet) integrated into the workshop set-up built a pull-factor for the participants. As a result, 55 people showed up for the second "Green Workshop". The design offered a combination of low threshold activities and options to more deeply discuss and create solutions together.
4) For mobilizing and obtaining the local knowledge of the heterogeneous population in the test area **different approaches and sources** are needed. So far, the LL process made clear that it is rather difficult to reach all those residents that normally do not participate in a planning process. It requires perseverance, networking and visible activities for attracting attention. Thus, raising awareness for green-blue infrastructure projects and increasing stakeholder acceptance demands a wide range of communication and interaction measures. In Living Labs, face-to-face communication, supported by information material, is the dominant channel for information exchange and interaction. The low threshold activities on the street are a valuable methodology for gaining insights into people's perceptions and collecting local knowledge. However, this form of event requires potential stakeholders to actually come to a specific location at a specific time. The project team discussed and evaluated alternative ideas for intelligent information and interaction and decided to embed the

information dissemination and interactions in the physical space of concern in order to be closer to the everyday´s life and daily routes of people. As it is very time-consuming to be on site and directly address people, the project team decided for additionally applying a “smart” way of user participation and integrated a smart interaction tool by using Augmented Reality, which was well received by the participants of the second workshop.

6. Conclusions

Two well known facts could be verified for the City of Vienna by analyzing meteorological measurements and applying microclimatic simulations: first the frequency of urban heat waves and tropical nights are dramatically rising, and second densely populated areas are particularly affected by climate change. However, it could also be demonstrated that even in most densely built urban structures potentials for new green infrastructures can be found. Particularly the streetscapes as well as facades and rooftops offer a variety of possibilities for greening measures. However, for realizing those potentials, existing legal, technical and administrative barriers have to be overcome. Though the streetscapes are mainly public in character, they are currently dominated by the moving and stationary traffic. Moreover, a range of built-in installations under the sidewalks as well as, particularly in existing building structures, heterogeneous property relations often hinder the implementation of greening measures. In this regard, be it buildings or streetscapes as potential settings for measures, it is essential to bring decision makers and citizens on board. Without the integration of users within the process, the realization of urban green networks in built-in structures is not expedient and might not prove long lasting.

Therefore, the first step on the way to a greener city that is less affected by heat is to raise awareness of the manifold functionalities of green infrastructure in the city especially with regard to the streetscape. Secondly, solutions have to be developed, implemented and monitored together with local stakeholders that fit the specific framework conditions.

To this effect, a Living Lab proved to be a very appropriate approach to support the overall process and to combine classical participation methods as well as new, smart ICT-tools in an experimentally way. The process thereby facilitated the inclusion of a broad range of users (residents, users of buildings, architects and planners, housing subsidies, neighbours/social environment and politics and administration, etc.) with new and smart methods of participation to enhance the possibilities for the realization of green city infrastructures also in existing urban structures. So far, the experiences made during the Living Lab proved that it does not only serve as exhibition space for various measures to adapt to climate change, but also poses a networking opportunity. For the project LiLa4Green the Living Lab includes competence networking, dissemination and citizen cooperation in the form of integration of future users into new and old technologies and projects. Interaction with public stakeholders and involving local residents in open innovation processes (co-creation) leads to shortened iteration processes of technology developments and applications with a high level of acceptance. The Living Lab helps to bring information face2face to people and to gain acceptance for technologies and solutions.

The ongoing LL process already showed positive effects regarding the visibility of the issue (UHI, greening the city) within the area and the networking between single activities and actors. The biggest challenge appeared to be to reach those citizens who are not yet interested in the topic and to motivate them to participate in an organized workshop. It got clear, that it is crucial to meet the people on the level of their needs and in their everyday life context – “in the street”. It is a long-term process, continuity is needed, various efforts for mobilization have to be made, new ICT-tools are helpful for reaching additional population groups directly on the street and action in form of physical interventions designed in a co-creative way are essential. All these crucial components have been considered and applied in LiLa4Green. So far, the Living Lab established proved to be successful and will be continued in the next two years.

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The Potential of Greenable Area in the Urban Building Stock

Stangl R[1], Minixhofer P[1], Hoerbinger S[1], Kermer L[1]

[1]Institute of Soil Bioengineering and Landscape Construction, University of Natural Resources and Life Science, Vienna, Austria

rosemarie.stangl@boku.ac.at

Abstract. In the context of establishing green infrastructure in cities, urban retrofit has presumably larger area potential than ground-based green. To support the large-scale advancement of urban green, the assessment of greenable potential plots in the building stock, both on horizontal and on vertical scale, provides first indispensable indications for decision-making. However, reliable and solid data to the state of the buildings is currently not available. The research study Urbane GmbA explored a new methodological approach, based on publicly available geo-data, and applied it at two study sites in high-density urban quarters in Vienna. The combination of a GIS-based analysis with digital and on-site photos allowed for the creation of a Level of Detail 2 (LOD2) 3D-model and subsequently the estimation of the green retrofit potential of roofs and facades. Comprehensive maps with the data of the 2D building footprints provide valuable information for planners, including building characteristics and greenable area potential. The approach proved to provide more comprehensive information including building characteristics fundamental to the planning and decision-making process. The achieved results are merged with an evaluation matrix generated for attributing available facade and roof greening systems. This allows for more focused decision support for the retrofit of the building stock towards more sustainable and resilient district development.

1. Introduction

The quantitative increase in urban green areas is no longer the sole vision of environmentally conscious minorities. In 2015, the Paris Climate Agreement put the necessity for actions to confine the effects of climate change on the political agenda of national authorities. Many countries reacted with national climate protection and adaptation strategies.

Natural solutions have to become an integral alternatives or additions to grey infrastructure for the regional development [1]. With its research and innovation policies on Green Infrastructure and Nature-Based Solutions the EU strives for innovations based on natural and nature-inspired solutions to bring sustainability and resilience into the cities [2]. In Vienna, the city's Urban Heat Island Strategy (UHI-STRAT) aims to expand Green Infrastructure as an effective measurement against the effects of urban heat islands and proposes a variety of technical and strategic measures for planners, architects and administrators [3]. City planning and development will have to increasingly deal with the renovation of long-lasting architectural heritage and the results of an excessive building culture where so much undeveloped and natural land was lost to building projects. The restructuring of urban areas to incorporate more vegetation in horizontal and vertical orientation has a higher potential for success if the existing building stock is considered in addition to the construction of new (green) buildings. The potential of vertical areas is believed to be especially high. MA 22 estimates a potential net area of 12,000 ha facades, which can be used for the installation of green walls. This is well over a third of the total net area. In comparison, the potential net area for green roofs is only 1,800 ha [4].

The assessment of the potential of greenable area is the basis for the conception and planning of vertical and horizontal green on small and large scale. Reliable basic data is of the utmost importance to increase urban green infrastructure in the building stock (in streets, urban quarters and on district level). At the moment, the necessary data is only available in a very restricted way as the currently available instruments and various fragmented approaches, in part isolated solutions, reach their limit with their practical application. For example, the Viennese Gründachpotenzialkataster (cadastre of potential green roof area), based on the survey of roof inclination via airborne laser-can images, shows only a very small potential for green roofs. Important technical (e.g. statics) and legal parameters (e.g. preservation order, protection areas) were not included in the assessment or analysed. An adequate adaptation of the current cadastre would be necessary, but will be not released due to the economic expenditure for the individual users.

To fill this void, a new methodological approach was developed and applied at two study sites in the frame of the research project Urbane GmbA. The created maps provide comprehensive information for the planner regarding building characteristics and potentially greenable area.

2. Methodology

2.1. Description of the study sites

The study was conducted in two districts of distinct characteristics. The study site Neulerchenfelderstraße is situated in the 16th district of Vienna. It includes the street and its adjoining building stock. The site is characterised by a versatile building structure. Historical buildings alternate with modern ones along the street. The ground floor zone is strongly influenced by the retail trade, while the upper floor zone is mainly used as living space. In the public open space, there are barely public green areas. The adjacent sidewalks are often very narrow, which can represent an obstacle for the implementation of ground based green facade retrofits. The study site Innerfavoriten – Kretaviertel is situated in the 10th district of Vienna. Most of the buildings are from the years after 1945. The site is characterised by large blocks of flats and individual smaller historical buildings. Many of the large residential buildings are community buildings. Both, the ground floor zone and the upper zone are mainly used as living space.

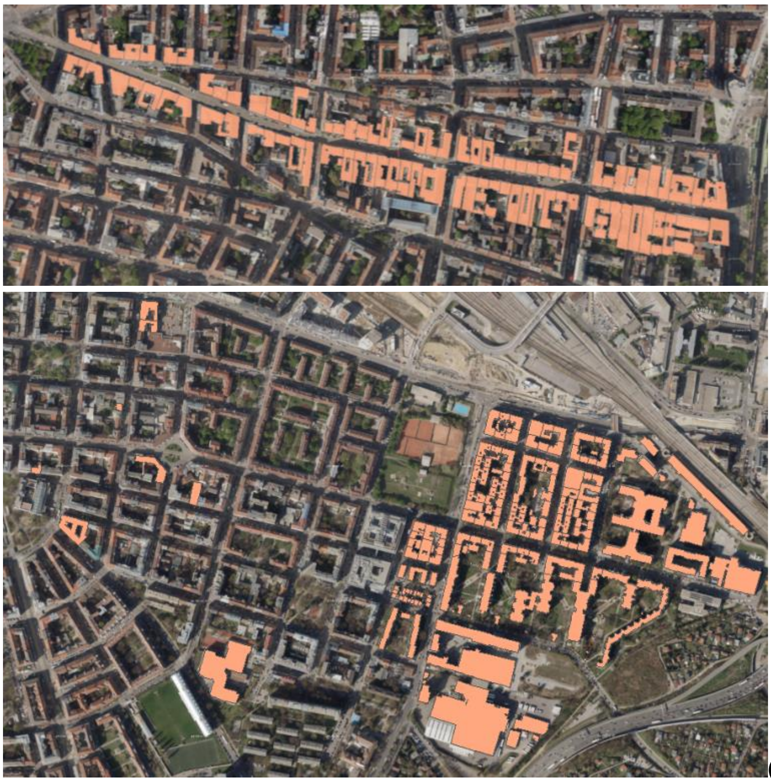

Figure 1: Study areas (A) Innerfavoriten – Kretaviertel and (B) Neulerchenfelderstraße

2.2. GIS-based system analysis

GIS-based analysis was performed and combined with analyses of photos, taken of each building in the study areas. On the basis of a Level of Detail 2 (LOD2) 3D-model the slope and exposure of the roof surfaces were calculated and the green roof retrofit potential was estimated. In combination with the photo analyses, the net-area facade retrofit potential was assessed. In order to describe the ground connection of the facades, the surrounding land cover was attributed by means of vicinity analysis. Subsequently, all data was transformed to 2D building footprints in order to make them easy to integrate in existing geo-date bases of the city of Vienna.

2.2.1. GIS-based survey of the green facade retrofit potentials.

The surrounding land use can provide first indications of the feasibility of green facade retrofit potentials. The relation of the facade areas to the adjacent land use was calculated by means of neighbourhood analyses in ArcGIS. For this purpose, the facades of the 3D-model (LOD2) were first separated from the other wall elements. The next step was to reclassify the land use map and assign the respective attribute to the facades. In total, seven categories were formed (see Table 1). The categories were selected to allow an initial assessment of the external effect as well as the feasibility of the potential greening methods. The pavement width is a very important parameter for the feasibility of pot and soil based vertical greening systems. To form the first two categories, "pavement width < 2.2 m" and "pavement width ≥ 2.2 m", areas that were disclosed as "pavement" in the FMZK (Flächen-Mehrzweck-Karte; map of the multi-purposes of areas) were analysed on basis of their width. The category "pedestrian zone" includes potentially greenable facades with a very high external effect. Facades in the category "green area" have a high potential for soil based systems as a direct contact to the soil can be established without any measures to re-open sealed surfaces. On the contrary, areas in the category "private parking and traffic areas" are connected to sealed surfaces and measurements and soil based measurements are not possible without de-sealing measurements. Additionally, the implementation of greening projects can be complicated by the current use as a parking space or traffic area. Facades in the category “consolidated area” will also lack of initial soil contact, which means the areas need pre-treatments in terms of allowing permeability. An additional attribute, namely “no soil contact – flat roof”, classifies all facades which adjoin to a flat roof. This means the potential lies with pot based systems. After the classification, the gross area of the various types of facades was calculated for each building within the project area.

Table 1: List and description of all categories for the survey of facades based on soil contact

Categories for the survey of facades	**Description**
Pavement width ≥ 2.2 m	Facades connected to pavements with a minimal width above 2.2 m
Pavement width < 2.2 m	Facades connected to pavements with a minimal width below 2.2 m
Pedestrian zone	Facades connected to traffic areas classified as pedestrian
Consolidated area	Facades connected to consolidated and sealed surfaces
Private parking and traffic areas	Facades connected to traffic areas on private property (e.g. entry ways, parking areas)
Green area	Facades connected to green areas (all green areas and additional unsealed surfaces)
No soil contact – flat roof	Facades with no soil contact, which direct contact to a flat roof

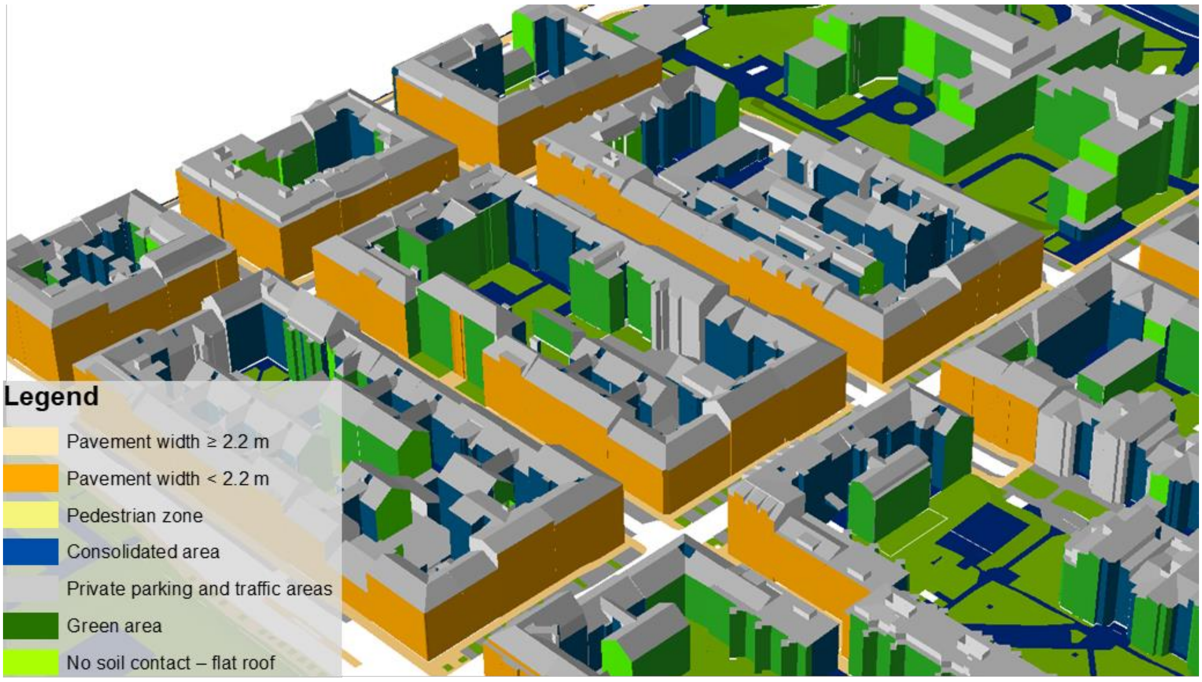

Figure 2: Facades in the study area Innerfavoriten – Kretaviertel classified by the surrounding soil use

2.2.2. GIS-based survey of the green roof retrofit potentials.

The Guideline on Green Roofs in Vienna (2009) notes that the roof slope is a significant factor of the usefulness and profitability for the installation of a green roof . The category limits are based on the recommendations of the Guideline for Green Roofs [5] and the Gründachpotenzialkataster [4] and modified within the project. The direction of the roof is an important parameter to describe plant habitats. Therefore, the direction of the roofs was calculated and integrated in the classification (see Fig. 3). A new category for very steep roof areas (15.1°-45°) in exposed sites (135°-225°) was created to gather these areas as they will have a very low potential for the installation of green roofs. As an additional information, the roof cladding was assessed based on visual interpretation of aerial images.

Table 2: Classification of the roof areas to assess the potentially greenable plots and a description of the categories.

Classification of the roof areas		
Slope	**Exposition**	**Description**
0° - 5°	0° – 360°	In this category, roofs can be equipped with extensive and intensive green roofs with relatively low effort [4].
5.1° - 15°	0° – 360°	Possibility for extensive green roofs [5].
15°.1 – 45°	0° – 134.9° and 225.1° – 360°	Slopes above 15° require a special shear barrier to prevent slippage of the structure. Extensive green roofs can be installed at roofs up to an inclination of 45° [5].
15°.1 – 45°	135° – 225°	Roof areas with a southeast to southwest exposition (135 - 225 degrees), which are strongly to very strongly inclined. These roof areas are classified as "exposed". The installment of green roofs is very difficult.
> 45°	0° – 360°	Green roofs are usually not possible anymore [5].

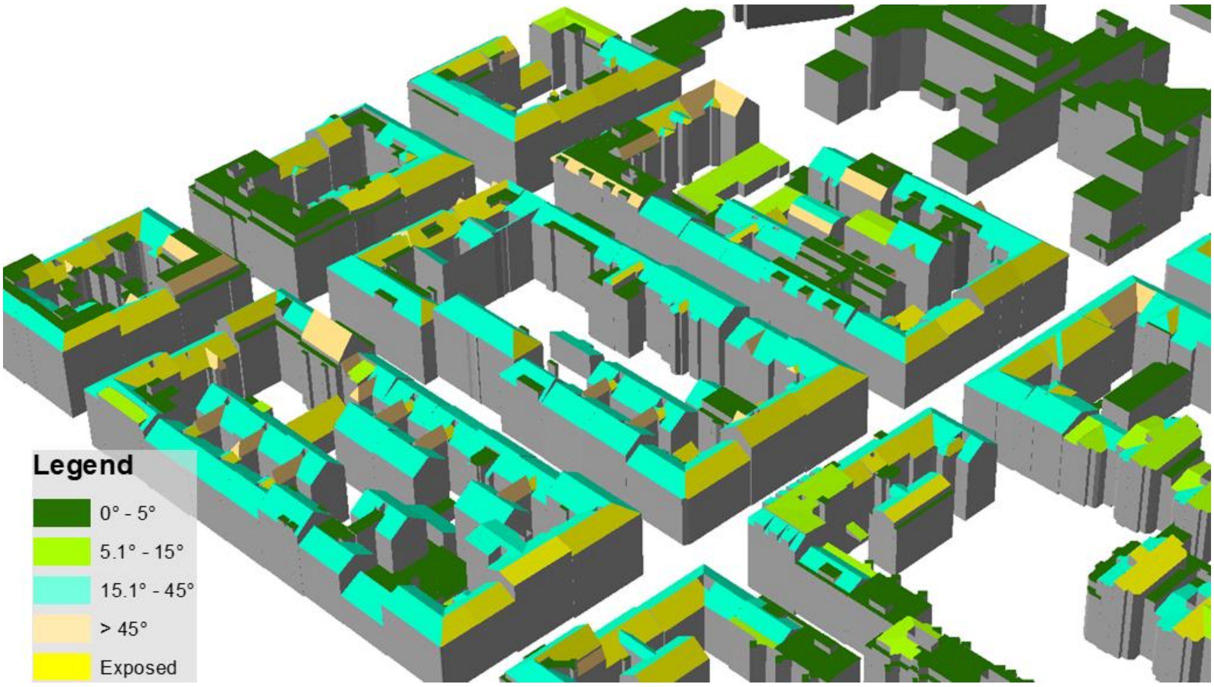

Figure 3: Slope and exposition as a basis for the assessment of the potentially greenable plots

2.2.3. Image based analysis of the buildings in the project area and intersection with the GIS analysis

The geo-data and the results of the GIS-based analysis were verified by an on-site inspection. Images of the external facades were the basis for further collection of the relevant data. The facades were sub-classified in ground floor and upper floor zone. All structural elements, that could possibly influence the decision for or against a green façade installation, were recorded. This includes balconies, stucco, logos, frescos, billboards, display cases and garage entrances. Subsequently, the total area of the structural elements was estimated in 25% intervals. Additionally, Google-Maps 3D complemented the survey, especially for inner courtyards, where in most cases access is difficult. Highly structured facades with a high cover ratio of structural elements have a lower potential for greenable area. Facades with a cover ratio ≥ 75% get the attribute "structured, covered facade".

Facades with a historically representative character will most likely have special requirements for the implementation of green walls. The assessment was subjective and did not include legal boundaries.

The number of windows was assessed to calculate the window area in comparison to the total facade area. The windows were categorised in regard to their building period and multiplied with a factor to obtain the total window area. The estimated window area was then subtracted from the gross facade area of the 3D model. Subsequently, the results were intersected with the building outlines and presented cartographically. Buildings under preservation order were excluded from the potential analysis.

3. Results

The greenable area potential was calculated for both project areas. Table 3 and 4 give an overview of the total potential area in the project areas broken down to the defined categories. Categories with a generally higher potential are colored in green. Differences are obvious when comparing the two study areas. The study area Neulerchenfelderstraße is smaller, with less buildings (89 against 134), and the building development structure varies from Innerfavoriten - Kretaviertel. There, a few freestanding buildings are in contrast with the closed perimeter block development in Neulerchenfelderstraße.

The ground floor zone in the study area Neulerchenfelderstraße has a lower potential than the upper floor zone. This can be a result of the intensive use of the ground floor zone. These facades often end in a very narrow pavement, which is a barrier for the installation of soil based systems. The sum of the potentially greenable area for inner courtyards is notably higher. Facades within the category "no soil contact – flat roof" have a high potential for pot-based systems. Both project areas present frequent green oriented facades. This means the potential for the application of soil based systems is high. Both study areas have big, flat and only slightly inclined roof areas. Gravel roofs are very interesting for the installation of green roofs as after the relatively easy exchange of the gravel, most often no alternations to the building statics and roof waterproofing are necessary to adjust for the green roof structure. Flat or slightly inclined roofs with gravel are the preferred roof areas for retrofitting green roofs. It was not applicable to include other structural building requirements to the analysis such as roof seal, insulation, brim height or accessibility in this survey.

Table 3: Potential of the greenable area in the study area Neulerchenfelderstraße

Project area Neulerchenfelderstraße		
	Category	**Greenable potential area [ha]**
Facade area	**Total area – facades**	**6.44**
	Pavement width ≥ 2.2 m	0.92
	Pavement width < 2.2 m	0.70
	Pedestrian zone	0.12
	Consolidated area	2.69
	Private parking and traffic areas	0.61
	Green area	0.87
	No soil contact – flat roof	0.53
Roof area	**Total area – roof**	**3.75**
	0° to 5°	1.50
	5° to 15°	0.42
	15° to 45°, no south exposition	1.74
	0° to 15°, gravel roof	0.09

Table 4: Potential of the greenable area in the study area Innerfavoriten – Kretaviertel

Project area Innerfavoriten - Kretaviertel		
	Category	**Greenable potential area [ha]**
Facad e	**Total area – facades**	**17.74**
	Pavement width ≥ 2.2 m	4.85
	Pavement width < 2.2 m	0.07
	Pedestrian zone	5.58

Project area Innerfavoriten - Kretaviertel		
	Category	**Greenable potential area [ha]**
	Consolidated area	1.37
	Private parking and traffic areas	4.65
	Green area	1.22
Roof area	No soil contact – flat roof	**10.19**
	Total area – roof	4.2
	0° to 5°	1.16
	5° to 15°	3.91
	15° to 45°, no south exposition	0.92

4. Conclusion

There is a need for supporting instruments to facilitate a more detailed survey of the potentially greenable area in the urban building stock on the neighborhood level. The study explored open source data for greening potential assessment and synthesised available applications. The presented approach is based on publicly available geo-data and was designed to enable the assessment of area potential for greening buildings on a larger scale. The results signify an advanced estimation of roof and façade based greening area potential and do not represent absolute values. They allow for more solid information on area potentials than provided in hitherto available instruments.

The numerous publicly available geo-data was a sound basis for the development of a GIS-based method. General information on the buildings (e.g. building outlines, location) is extensively available for the entire urban area of Vienna. The LOD2 3D model was used to calculate the gross façade area. In high resolution, the FMZK offers a lot of information on the surrounding land use of the buildings.

The presented approach allows for the creation of first indication maps, offering valuable information for planners and decision makers. However, it does not cover all necessary information on building requirements. The building characteristics were not or not extensively available as, e.g. referring to the building period of individual objects and their use, or are not provided in the required resolution.

The vertical greenable area potential is not yet recorded for the city of Vienna. Specific information on geo-data basis is lacking. In overall terms, a considerable need for geo-data is apparent to carry out an exact survey of the façade greening potential. The tested scheme needs further advancement since information on the structure, static condition and façade features is currently missing. The future integration of energy performance data and costs would be an additional asset for evaluation application on district level. An enhanced cadastre could further serve local authorities as decision support for green infrastructure development prioritisation and for financial support programs.

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Mapping of innovative governance models to overcome barriers for nature based urban regeneration

Egusquiza A[1], Cortese M[2], Perfido D[2]

[1]Building Technologies, Tecnalia, 48146 Derio (Spain)
[2] R2M Solution s.r.l. – Via F.lli Cuzio 42, 27100 Pavia (Italy)

aitziber.egusquiza@tecnalia.com

Abstract. The implementation of urban Nature Based Solutions (NBS) projects is deeply determined by the novelty of the concept. Its innovation is both an opportunity and a challenge: as a new concept, it generates uncertainty due to lack of technical and operational preparedness, but it also allows to deploy innovative approaches, new ways to address old problems and more inclusive practices. Nature4Cities project has systematically conceptualized the barriers and drivers on NBS projects implementation by a review of the state of the art. To see how these barriers can be overcome by governance strategies, different urban and environmental governance models have been mapped and characterized to assess their suitability for different NBS projects. Five clusters have been identified where models are grouped according to the involved actors, their position in the spectrum from high to low government involvement and their level of participation. This theorical model has been applied to real cases to check the incidence of the different clusters. Results show that urban and environmental governance is a map where the different models coexist in different degrees regarding some key axes such as level of innovation, polycentric vs. monocentric, involved sectors, level of participation and scale. Collaborative, multisector, polycentric and adaptive governance models address significant number of previously identified cross-domain barriers showing their suitability. The work presented in this paper can be the basis to define new institutional and governance arrangements that will foster multi-stakeholder involvement, citizens' engagement, leveraging both public and private funding of NBS in cities

1. Introduction

Nature Based Solutions (NBS) are defined by the EU as "*solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions"* [1]. They can enhance sustainable urbanisation, restore degraded ecosystems, support climate change adaptation and mitigation and develop strategies for improvement of risk management and resilience [2]. But, NBS is a new complex concept that is not totally clear for practitioners. The concept is frequently confused with other concepts such as biomimicry, sustainable development or green infrastructure. This loose definition of the concept and its novelty could be and opportunity for more flexible and inclusive dialogue and innovation [3], but also a challenge due to the diversity of required knowledge, stakeholders to be involved and challenges to be addressed [4]. Some authors believe that NBS concept includes the concept of integrative governance and participatory approaches to co-design, co-creation and co-management [5] and this could be one of the key differences that distinguish the concept from more traditional and top-down conservation approaches [6]. Governance could be an ambiguous concept also and there is not an agreed and clearly defined governance theory [7]. In this paper we will use the term “governance” to refer to collective action arrangements designed to achieve the implementation of NBS projects, and government to refer to the formal organisations of the “public sector” as in [8]. In Nature4Cities (N4C) project the different urban and environmental governance models have been mapped and characterized in order to assess their suitability for different NBS projects. An Implementation Model Data Base for an extensive range of Nature-Based Solutions has been developed as open-source with the purpose of illustrating the single characteristics, the concerned NBS and the governance, financial and business aspects related to each Implementation Model (IM) identified. The process allowed gathering a large amount of information, which facilitates the systematization of the implementation modalities through which single NBS can be applied in specific urban contexts.

2. Methodology

For the literature survey a snowball approach has been followed. In a first step some primary documents have been identified [4][9][10] taking into account the research outputs that have been generated for similar research project [3][11][12]. These documents guided the posterior literature review to specific fields and issues. The literature review has been complemented by the results of several interviews, on-line surveys and workshops were conducted targeting experts, urban planners and municipality workers. Finally, the results have been verified comparing them with the experiences of the partner cities participating in N4C project. After developing the theorical model, a database with different real cases was built in order to link the predetermined theoretical models with best practices and to study the incidence of them in practice.

3. Barriers and drivers

NBS-oriented urban planning can be considered a process of socio-ecological change. These processes are part of very complex systems with incomplete understanding and profound uncertainties [13] in need of interdisciplinary research [4], social engagement and feasible financing schemes. The literature shows that the main type of barriers for their implementation are the knowledge, governance and economic ones.

3.1. Barriers of NBS implementation (Process Inhibitors)

The identified barriers in the knowledge, governance and economic domains are highly linked to the novelty and complexity of the approach, since that amplifies some of the traditional barriers of urban planning. In addition to the lack of knowledge and evidence generation, integrated solutions, such as NBS, highlight the limited coordination among different actors with divergence of interests, competences and powers, especially in the public sector when different departments are required (urban planning, buildings licensing, infrastructures, water and waste management), all having their own targets, regulatory frameworks and budgetary constraints. Several reasons linked with this complexity and novelty can affect also the cost-effectiveness perception of NBS, such as technology maturity (subsidies to support technology maturing periods proved to be unsuccessful) and market uptake (some new products may be economically competitive only if commercialized at a significant scale). The following table shows the summary of the barriers and the correspondent literature sources (main and secondary).

Table 1. Identified barriers for NBS oriented planning (M=Main literature source, S=Secondary literature source)

CATEGORY		DESCRIPTION	SOURCE		CODE
			M	S	
Knowledge barriers					
Uncertainty	Operational unknown	Due to the newness of the approach there is a lack of protocols for design, implementation and maintenance for NBS projects.	[9]		BK1
	Performance unknown	Lack of evidence regarding the quantitative benefits of NBS, especially from policy makers and citizens’ perspective. Designers may encounter		[14] [15]	BK2

		difficulties in implementing NBS when compared to traditional solutions, since they are more familiar with the later from technical and legal compliance.		[16]	
Accessibility to information	Information overload	Municipalities are already overloaded with knowledge making new concepts and approaches as NBS more difficult to reach.			BK3
	Unusable presentation of results	Presentation of scientific results in formats that are incomprehensible or not accessible to urban hinders the knowledge transfer between science, policy and planning.		[17]	BK4
Technical inadequacy	Lack of ready-to-apply scientific results, concepts and technologies	The lack of ready-to-use technologies, scientific results and concepts and simple and overarching theoretical framework makes the implementation and communication of NBS difficult even if a certain policy receptiveness exists. People in charge of design, implementation regulation and permit granting of NBS would need specialized training.		[17] [18] [19] [20]	BK5
Governance barriers					
Disconnection between short-term actions and long-term goals	Short-term action and decision-making cycles	Usual short-term decision-making and action cycles within municipalities do not match with the whole life cycle of NBS projects (planning, implementation, maintenance processes and sustainable financing)			BG1
	Establishment of long-term responsibilities	Responsibilities for the maintenance could remain unspecified and actors who will be implied in the maintenance are not implied in the decision and design leading to difficulties not previously foreseen.	[9]		BG2
	Gentrification	The willingness of improve life and urban quality with NBS projects in a short term could lead to risk of gentrification in a long term.			BG3
Institutional barriers	Lack of coordination	Lack of coordination between traditional departments traps knowledge in "*sectorial silos*" hampering e implementation of NBS which usually requires transdisciplinary coordination		[18] [20] [21]	BG4
	Lack of flexibility of decision-making structures	The decision-making structure of municipalities where the different departments have clearly defined responsibilities could not be suitable for multilevel, multiscale and multi-thematic projects as NBS.	[9] [10]		BG5
	Bureaucracy and unsupportive legal frameworks	Lack of knowledge due to the novelty of NBS as concept. Excessive legal rigidity, bureaucracy and lack of specific regulation (e.g. difficult agreements in multi-property dwellings).		[17]	BG6
Complexity of governance structure	Goal misalignment	Different goals of stakeholders within partnership arrangements could hinder collaboration.			BG7
	Apathy	A high number of stakeholders could generate inertia and apathy.			BG8
	Role ambiguity	A high number of involved stakeholders can cancel out some process enablers related with collaboration through unclear responsibilities	[10]		BG9
Participation and awareness	Perception	The perception of nature as source of problems and the fear due to uncertainty can hinder the participation of the citizens			BG10
	Lack of participation	Top down processes with no real citizen participation makes the NBS more difficult to accept by the citizens.			BG11
Economic barriers					
Perception of the benefits	Under appreciation of benefits	Benefits of NBS are perceived as mostly public and 'soft' and not directly related with economic growth-oriented issues as creating jobs and attracting investments.			BE1
	Short term vision	Lack of insight that investment now will prevent costs later. Economic benefits are long term			BE2
	Vandalism	Robbery or destructive actions, especially during early stages, could prevent the viability of NBS.			BE3
Budget constraints	NBS not a priority	City budgets for green development and the maintenance of green spaces often face severe budget constraints, while staff and related expertise is decreasing.	[9]	[17] [22] [23] [24]	BE4
	Lack of funding knowledge	Financing mechanisms are available, but they are complicated to apply for requiring additional administrative staff and time resources and, more importantly, require co- financing			BE5
Risk perception		Lack of incentives and motivation to attract private investment			BE6

3.2. Drivers of NBS implementation (Process Enablers)

Parallelly, in literature can be found drivers and process enablers related to the knowledge, governance and economic barriers that take advantage of the co-benefits of the NBS approach. In the following table these drivers are summarised.

Table 2. Identification of drivers for NBS oriented planning (M=Main literature source, S=Secondary literature source)

CATEGORY		DESCRIPTION	Literature		CODE
			M	S	
Knowledge drivers					
Generation of evidence	**Lesson learnt in implemented projects**	Successfully implemented projects generate useful evidence regarding the benefits that can be used by other projects. Lessons learned from less successful projects are proved to be instrumental for an effective integration of NBS in urban planning.	[9] [11] [25] [26]		DK1
	Research on benefits	Generation of quantified information and knowledge regarding benefits (direct and indirect)			DK2
	Research on cost effectiveness	Research on cost effectiveness of implementing NBS might help to justify new investments and to promote long-term funding or public-private arrangements.			DK3
Collaboration	**Networks**	Demonstration projects create collaborative networks and communities of practice that cross institutional boundaries and are drivers for legitimizing practices and approaches		[27] [28]	DK4
	Co-creation	Solutions to be developed could be based in collaboration between designers, citizens and companies in the early stages			DK5
Information accessibility and sharing	**Knowledge platforms**	Knowledge platforms focused on cities, accessible and open, can be used for knowledge gathering, aggregation and cocreation. Develop online NBS impact calculation tools.		[11][29] [30] [31] [32] [33]	DK6
Awareness	**NBS ambassadors**	NBS ambassadors can promote NBS by making benefits and risks communicable to citizens and politicians. Strategically selected NBS could work as flagship projects			DK7
	Climate Change	Climate change is perceived as a new criterion for decision making and can be a driver for changing priorities and the vision of urban planning, raising awareness and changing			DK8
	Ecological memory	Processes that enrich and regenerate ecological memory can improve the understanding of different perceptions of urban nature and lead to higher levels of ownership of NBS projects by local communities.		[34]	DK9
Governance drivers					
Process efficiencies	**Collaboration**	The combination of the different strengths coming from different sectorial affiliations of a diverse stakeholders' partnerships lead to improved efficiencies	[9] [10] [11] [35] [36]		DG1
	Coordination role	A specific role that can serve to improve the coordination between departments can help to plan and implement transdisciplinary and multifaceted projects as NBS.		[37]	DG2
	Action- thinking approach	An action-thinking approach (problem-based governance) could help to focus on a better use of existing finance instruments and to coordinate biodiversity and climate change efforts in implementing strategies on NBS.			DG3
	Capacity building	Capacity building can balance the uncertainty that comes from the newness of the NBS approach.			DG4
Self-governance	**Emerging partnerships**	Innovative NBS projects can learn modes of self-governance from emerging partnerships between civil societies in cities		[38]	DG5
	Grassroots innovations/transition initiatives	Grassroots innovations and transition initiatives as collaborative networks of citizens play a significant role in advocating and practicing NBS in cities as re-establishing green urban commons providing on-the-ground evidence of the multiple benefits		[39] [40]	DG6
Co-creation and participation	**Reflexive/adaptive governance**	An approach thought to include flexible ways to maximize learning opportunities and the experimentation and careful monitoring it is especially suited to overcome barriers related with uncertainty, complexity and system dynamics. Multiple actors possessing different types and degrees of knowledge could engage in a reflective way to update their planning, governance, knowledge production practice over time to continuously address arising risks and uncertainties. More reflexive approaches to urban and environmental governance bring together other drivers as networks and NBS ambassadors.		[9] [4] [36] [41]	DG7
	Involvement of urban government	The involvement of local governments is crucial for opening space for innovative approaches and solutions like NBS through a rapid transfer from concepts to action. An urban government can facilitate collaborative arrangements without losing its government role. Its new dual role (steering and orienting when partnerships exhibit capacity for delivering and regulating and directing when strategic planning is required)		[22] [42] [43] [36]	DG8
	Cross sectorial spaces and partnerships	Enabling cross-sectorial partnerships for NBS design implementation and maintenance. Creating different institutional spaces for cross-sectorial dialogue and interactions of different stakeholders for strengthening/fostering adaptive co-management and knowledge sharing about urban ecosystems.		[18][26] [44][45] [46][47] [48]	DG9
	Co-production	Design knowledge co-production processes to bring openness, transparency in governance processes, and legitimacy of knowledge from citizens/civil society, practitioners and policy stakeholders		[44] [48] [49]	DG10
	Tools to build a common vision	Stakeholders from different natures and backgrounds are unlikely to share a common vision. One way to reach the goal might be to include NBS in local planning and zoning regulations.		[50]	DG11
Economy drivers					
De-risking	**Sharing risks**	Collaborative arrangements enable the distributed responsibilities that can generate a shift from risk aversion to sharing the perception of risk of new approaches like NBS projects	[9] [10]	[51]	DE1
	Public de-risking	Due to the newness of the concept NBS is now in a beginning phase in the field of urban			DE2

	strategies	regeneration. This phase requires a great government support, due to methodologies and ways are not yet completely defined.			
Government support	**Provisioning of incentives to attract private investment**	The provisioning of incentives and/ or the removal of administrative barriers allows the creation of partnerships between government and businesses where citizen associations can participate also. The resource and governance synergies that can be generated in those partnerships can create new opportunities for an efficient uptake of NBS. Encourage methods to transfer the benefits of common goods provided by NBS to the initiators of NBS (e.g. tax reductions or subsidies). Public subsidies and tax cuts can stimulate private investments and make NBS more attractive		[36]	DE3
	Removal of administrative barriers				DE4
	Public-private partnerships	The inclusion of companies and private sector in the implementation and management of NBS projects can help to overcome budget constraints and limitation of resources.		[52]	DE5
Create conditions for new business models and finance schemes		Divesting from dominant solutions as the one and only focus, can leverage private and public funding in strengthening NBS and can create conditions for new business and finance models			DE6
Cooperative competition		A fair competition between private stakeholders, specially between companies, that does not hinder the collaboration, makes some processes more efficient and successful.			DE7
Mid-Long-term financing		Allocation of a sufficient budget for implementing and maintaining NBS projects can give sustainability in tight financial periods. Widely using natural vegetation helps to decrease the costs associated with vegetation care.		[20][9]	DE8
Real estate		Increased commercial and domestic property prices and attraction of businesses		[53][54][55]	DE9
Self-financing and self-management		Self-financing and self-management projects can be sustainable and resilient and are less dependent of external changes.			DE10

3.3. Verification with surveys, case studies and pioneer experiences

The barriers and drivers identified in the literature survey have been checked with:

- Results from the report "Elicitation of needs and definition of urban and landscape planner requirements" developed within Nature4cities project [56] in which six experts from 13 countries were consulted through semi-structured interviews and 75 completed questionnaires were analysed by experts with strong development background in the fields of urban and landscape planning regarding, specifically, NBS.
- Case studies from partner cities (Ankara in Turkey, Milano in Italy, Alcala de Henares in Spain and Szeged in Hungary).
- Pioneer experiences investigated in Spain, France, Austria, Germany, Switzerland, Italy, Turkey and Hungary.
- The verification of the barriers and drivers towards real cases was not homogeneous. The key parameter used pertained the previous experience in NBS projects. When this experience is not predominant (as in the interviews and surveys) the barriers were more evident. The Knowledge and Economic Barriers are the ones that are more recognized although only one of the identified barriers is identified in almost all cases (BK1: Operational unknown). The implementation contexts with more experience in NBS (such as Çankaya and German speaking countries) are more inclined to perceive the possible drivers compared to less experienced cases (e.g. most of the urban planners and municipalities interviewed).

4. Governance Implementation Models

Critical decisions about NBS projects (design, costs, location, scale or levels of management intensity) involve a wide range of stakeholders who surely have different ideas and backgrounds. Moreover, a 'nature-based' perspective has to adopt a 'society-based' perspective also in order to incorporate the notion that human beings have shaped the landscape [57]. These involvement of different groups can bring substantive, instrumental and normative benefits to the process of planning and delivering improvements in environmental management [58] and to the decision regarding role, scope and appropriateness of NBS interventions that will require governance models that can enable NBS with an inclusive, long-term and balanced approach [59].

4.1. Clustering and characterizing Urban NBS Governance Structures

The different urban and environmental governance models that can be found in literature cannot be packed in clearly delimited boxes. Urban and environmental governance is a map of spectrums where the different models coexist in different degrees regarding some key axes [60]. Four dimensions have been considered to define our typology of governance models.

1. Polycentric vs. monocentric governance: One of the most important current trends in environmental governance is the shift from centralized control to the incorporation of lower-level administrative units and social groups into more democratic decision making processes through co-management, community-based natural resource management, and environmental policy decentralizations [61] [62]. Polycentric systems have advantages (resilience by redundancy, efficiency by competition, participation and accountability, facilitation of learning processes and experimentation and cross-scalarity) and disadvantages (economies of scales may be difficult, more complicated decisions, duplication of efforts and dispersed responsibilities) to be take into account in governance models for NBS implementation[63][61]

2. Initiating actor: One classical way to characterize the governance structures considers the main actors promoting and interacting within the governance structures. Traditionally governance has been identified with the governmental institutions at different levels. However, non-governmental or private actors can also be involved in governing public goods like green infrastructures [7]. The typology of actors that are considered in this paper are classified in three main sectors: government, community and market. The initiative will come from one of these sectors and this will be one of the key parameters that will determine the nature and rules of the arrangement and the overall management of the intervention.

3. Levels of participation: Arnstein in 1969 described a ladder of participation writing about citizen´s involvement in planning processes in the United States. The ladder has eight steps that range from non-participation to citizen power. The first two steps (*Manipulation* and *Therapy*) are not participatory approaches. Their goal is to manage to achieve public support for already made decisions through public relations. The next step is what Arnstein called "Tokenism" and comprises *Informing, Consultation* and *Placation.* These steps are one level higher in the legitimation scale, although the power is still retained by the government (by means as one-direction information flow and ritualized and not decisive participation). In the last step, *Delegated power* and *Citizen Control,* public has the power to assure the accountability or even to plan and manage without intermediaries. The intensity of participation can be also be classified according to the range of parties included in the decision making process, the intensity and direction of information flows and the level of influence in the decisions to be made [64].

4. Governance concepts and steering modes for clustering: The governance framework and its capacity to tie different areas and levels of government, has been identified as a critical factor for the success of integrated interventions such as NBS [65]. Glavovic, mainly based on the work of Hartley, differentiates three broad conceptions of governance that theoretically have evolved sequentially but in practice co-exist, overlap and compete [66]: "*Traditional public administration*", "*New Public Management*" and "*Networked Governance*". Van der Steen et al. added a fourth governance concept: "*Societal Resilience"* [67] *(XX) and* . These four concepts have been used to make the clustering of the types of governance models (see Figure 1): government –led traditional governance models (Cluster 1), market-oriented governance models (Cluster 2), community-based governance models (Cluster 4) and collaborative governance models (Cluster 5). Two additional key dimensions are the degree of involvement of public actors (government) vs. private sectors (communities and markets) [68] together with the hierarchical/non-hierarchical distinction. Using this two axes, Hall [60] classifies four frameworks of governance regarding their steering modes. This classification provides the fifth cluster: private-private partnership that considers all governance models between community and market sectors. Based on the previous references and in the triangle connecting government, market, and community, also used by Lemos and Agrawal [61], a framework for governance model analysis and clustering has been developed (see Figure 1).

4.2. Mapping and characterising the models of governance

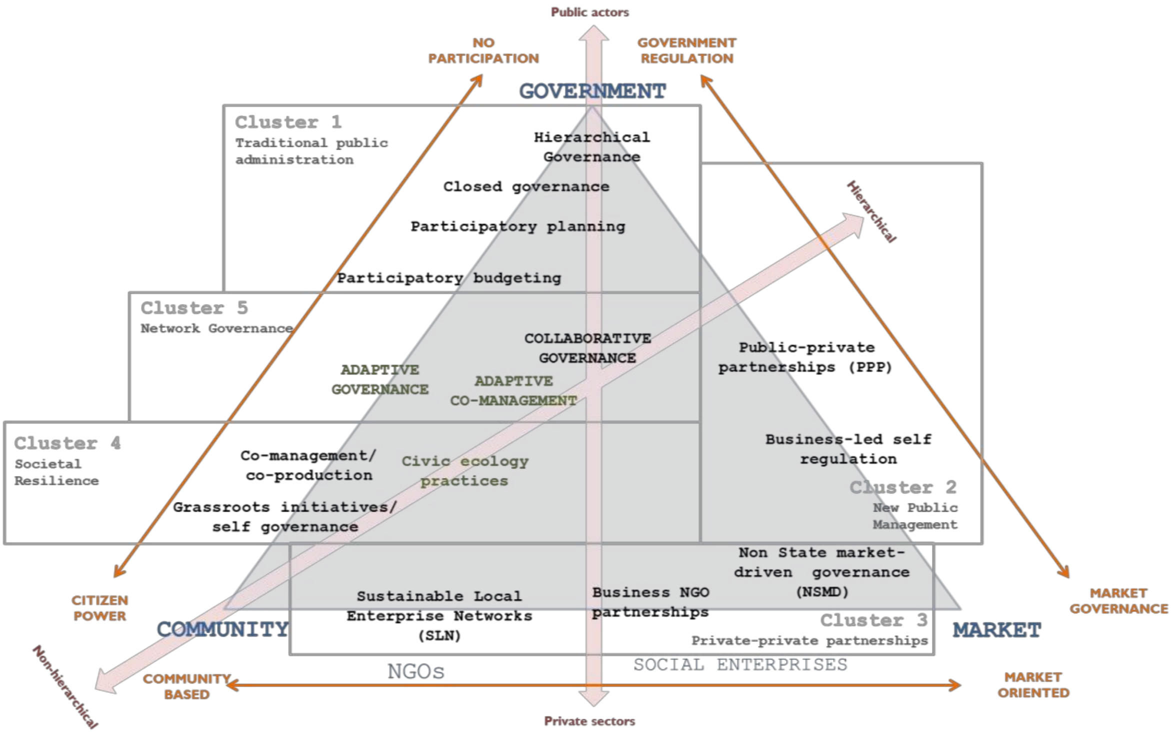

Figure 1. Mapping and clustering of governance models for NBS oriented planning

Many problems and urban challenges addressed by NBS (climate change, loss of biodiversity, resource scarcity…), are too broad and too complex to be solved by the government alone. It is necessary to move the focus from individual actors to network structures, to be able to inform about practices that support the emergence of purposeful network structures for ecosystem governance [69]. The identified governance models are not static or definitive. They can coexist in the same initiatives or change during the different stages of the projects. The Figure 1 shows the different analysed governance models clustered in 5 clusters and distributed according to the involved actors (government, community and market), their position in the spectrum from high to low government involvement and their level of participation. In the following sections, the different models are analysed from different perspectives: how they emerge, involved actors, the degree of government involvement, rules, contextual conditions and tools that can be used. Each cluster is also studied regarding the barriers that can help to overcome, drivers that can be triggered. Their suitability for NBS projects has been determined by assessing the capacity of these urban governance structures to allow processes required for the implementation of NBS such as engagement of different stakeholders, intersectoral coordination, transdisciplinary knowledge generation, socio-ecological innovation and continuous improvement and learning.

4.2.1. CLUSTER 1: Traditional public administration. The first cluster comprises government- and producer-oriented governance models. With different levels of low-moderate participation, the community role is mainly to be a client while the role of the government is to be the commander. The needs and problems are defined by professionals and since a key goal is to maintain stability they are uncertainty averse.

Table 3. Characterisation of Traditional Public Administration governance models (Cluster1)

	CLUSTER 1: Traditional Public Administration		
	Hierarchical governance	**Closed governance**	**Participatory planning & budgeting**
KEY WORDS	Centralized, government led, top-down, hierarchical	Hierarchical, closed participation, top-down	Hierarchical, open participation
HOW EMERGES	Default governance regime	Government defines the problem and the participants	Usually required by law.
INVOLVED ACTORS	Government. Citizens and community are always at the receiving end.	Access is restricted. Governmental actors are organised and complemented with a few non-governmental selected actors.	Government, citizens, NGOs
GOVERNMENT INVOLVEMENT	Leading role	Leading role	Very high
RULES	Instrumental vision on policy Administrations hierarchically controlled by electorally accountable governments. The interaction rules give government a leading role, whereas non-governmental actors follow. Coercion by the government is the predominant interaction type	Government has the power because it controls the resources that can be mobilised. The non-governmental actors can influence if the government allows it. Restricted cooperation. Government assigns certain tasks to the involved nongovernmental actors and then monitors them.	Hierarchically participation. There is a need to formalise the rules of the game and provide well established supporting tools (like websites, guidelines) to rebalance the information asymmetry. The stage when the stakeholders are involved depends of the level of collaboration.
CONTEXTUAL CONDITIONS	Often fails to provide effective solutions for highly contextualized situations	In cases of environmental issues with potentially catastrophic impacts, the predominance of "less than democratic" expert politics could be justified	Some countries have adopted national level instruments to promote different forms of public consultations at local levels providing guidelines and tools.
TOOLBOX	Top-down directives or command-and-control policies.	Top-down directives or command-and-control policies.	Neighbourhood planning. Participatory budgeting. E-tools for citizen involvement Workshops, professional moderation of debates. Interactive mapping
REFERENCES	[57] [75]	[57] [62] [76]	[23] [74] [77] [78]
BARRIERS	BG3, BG3, BG7, BG9, BE1, BE3		
DRIVERS	DG2, DG8, DE4, DE8, DE9		
SUITABILITY FOR NBS	**Low.** Often falls short in efforts to coordinate governance across large-scale ecosystems that cross multiple jurisdictional boundaries. Innovation is limited to some large-scale national and universal innovations being not enough for local innovation required. Large step-change improvements could be possible initially, but less capability for continuous improvement		

4.2.2. CLUSTER 2: New Public Management and CLUSTER3: Private-private partnerships. The idea beyond the involvement of market actors in environmental collaboration is to overcome the inefficiencies of government action by injecting competitive pressures through market actors that are regarded as capable of achieve bigger profitability in the utilization of environmental resources [61]. The different models for this kind of arrangements could be placed in a spectrum that goes from an almost fully public sector governance to an almost private sector governance.

Table 4. Characterisation of New Public Management and Private-Private Partnerships governance models (Cluster 2 and 3)

	CLUSTER2: New Public Management		**CLUSTER 3: Private-private partnerships**		
	Public–private partnership (PPP)	**Business-led self-regulation**	**Non-State Market-driven governance (NSMD)**	**Business–NGO partnerships**	**SLENs (Sustainable Local Enterprise Networks)**
KEY WORDS	Marked-oriented, competitive, top-down	Business-led, decentralized	Market-oriented, decentralized	Hybrid governance, decentralized, non-hierarchical	Self-organizing, complex adaptive systems
HOW EMERGES	Usually from a flexible, opportunistic approach, drawing from experiences in other cases. Not always the most evident solution, but a widely acknowledged crisis can trigger the arrangement.	When government is not perceived anymore as the only source of legitimacy and market forces are strong enough.	NGOs develop their sets of responsible business practices due to the difficulty to influence the government providing recognition in the marketplace to responsible companies	A reactive approach is adopted by companies in the beginning, but partnerships could evolve, where pressures from NGO lead to go from mere compliance to strategic actions	Provide an integrating opportunity for stakeholders to acknowledge a shared asset base and construct a virtuous cycle

INVOLVED ACTORS	Government + private sector	Business sector. Efforts may be undertaken to include community	Environmental and social stakeholders participate with business interests	Markets + NGO	NGOs + civil society members + companies.
GOVERNMENT INVOLVEMENT	Can range from high to low involvement.	Announcers and commissioners	Not necessarily	Medium-low	Not mandatory.
RULES	Private sector involvement does not eliminate public sector responsibilities. Continued government involvement in certain services helps ensure the efficiency of markets by reducing capital risks, increasing access to information, and reducing monopoly	Utilization of market exchanges and incentives to encourage environmental compliance. Corporate self-regulation initiatives create their own (usually voluntary) rules and procedures to guide corporate behavior.	Steering by market parties, regulation on basis of supply and demand. The viability of NSMD is determined by whether it can achieve legitimacy to operate. Authority emanates from the market	Depending of the type i) threat-induced, compliance or charity-driven responses, ii) transactional partnerships for improving profitability or market share, iii) businesses move beyond bottom-line iv) other key stakeholders are involved	Require at least one for-profit business to anchor the network and ensure that it is financially sustainable.
CONTEXTUAL CONDITIONS	PPP are deeply context based.	In neo-liberal contexts	General dissatisfaction with old policy instruments; neoliberal institutionalism and free trade agreements and a requirement for market innovations.	Differences in organizational cultures between business and NGOs due to differing missions and accountability systems.	Depend on mobilizing all four key assets: human, social, financial and ecological (natural) capital.
TOOLBOX	Outsourcing. Joint Venture Public-Private Partnerships	Voluntary agreements, third-party certifications, eco-labelling, corporate social responsibility	Forums for exchanges of expert information, databases of experiences and best practices. Norm generation and community building	Sponsorship. Short-term problem-solving. Sustained dyadic Eco-labelling. Industry sustainability standards.	Re-conceptualization of roles.
REFERENCES	[33] [49] [71]	[80], [81]	[62] [79] [80] [81] [82] [83] [84]	[86] [88]	[89] [90]
BARRIERS	BE2, BE6		BK4, BK5, BG7, BG10, BE1, BE2, BE5, BE6		
DRIVERS	DK3, DK4, DG3, DG9, DE1, DE6, DE7, DE9		DK7, DK8, DK9, DG1, DG3, DE6		
SUITABILITY FOR NBS	**Low-medium** depending the scale of the NBS project (the smaller the scale the easier to implement only market-oriented approaches). Risk aversion of the private sector often result in a choice for proven technology rather than for innovative solutions (such NBS).		**Medium-high.** But currently the required conditions for the more complex models are met only in rare cases. This implies the need for a significant change in relationships between enterprise-based activities in the developing world and broader social, economic and political systems in which they are embedded.		

4.2.3. CLUSTER 4: Societal Resilience and CLUSTER5: Network Governance. Societal Resilience comprises the governance models in the higher steps of the participation ladder when communities have the power for planning and managing without (almost) intermediaries. The Network Governance instead, aims to add the community and local voices to environmental governance models supported by the government with the hope to solve complex problems and allowing a more equitable allocation of benefits [61].

Table 5: Characterisation of Societal Resilience and Network governance models (Cluster4 and 5)

	CLUSTER 4: Societal Resilience			**CLUSTER 5: Network Governance**		
	Co-management	**Civic ecology practices**	**Self-governance/grassroots initiatives**	**Collaborative governance**	**Adaptive governance**	**Adaptive co-management**
KEY WORDS	Open participation, decentralized management, social learning	Small scale, local	Bottom-up, polycentric, self-organisation, self-management	Collaborative, multi-level, polycentric	Environmental governance, decentralized, polycentric, bottom-up	Community-based, resource management, polycentric

HOW EMERGES	When initiated by non-government, government supports implementation. When initiated by the government stakeholders are invited	Often are initiated by lay persons, generally as a community-based response to urban decline or sudden disturbances like hurricanes and war	Decision-making about societal development is no solely in the hands of government, but companies, scientists, media, new social movements and community.	Usually the model is initiated by the government trying to incorporate new resources, efficiency, knowledge and competences to solve complex problems.	May require "windows of opportunity" that appear as significant boost in capital or legitimacy	Usually triggered by a crisis.
INVOLVED ACTORS	Local authorities, citizens, NGOs, researchers	Scientists and NGOs helps to ensure larger impacts and longer-term sustainability, but it is not mandatory	Local authorities, citizens, NGOs, researchers	Involves a large group of governmental and non-governmental actors that engage in competitive and/or stimulating governing activities.	Requires a structure of nested institutions and cross-scale institutional diversity connected by formal and informal networks	Diverse set of stakeholders, operating at different levels, often through networks from local users to international bodies.
GOVERNMENT INVOLVEMENT	Medium	Not mandatory	It could have a semi-passive role	Government retains the formal authority	Medium.	Medium.
RULES	Local authorities have to take the responsibility for the urban environment which means that there is a limit for decentralization as far as public goods and services are concerned	Local authorities have to take the responsibility for the urban environment which means that there is a limit for decentralization as far as public goods and services are concerned	Grassroots movement have their own dynamic and they are an inherently unpredictable. Institutional diversity and multi-scalarity.	Actors are only loosely bound to one another. The model is formally organized and meets collectively. Participants are included in decision making process. Transaction costs are high.	Largely builds on human relationships and trust.	Leadership is essential by providing innovation, building trust, making sense, managing conflict, linking actors, compiling and mobilizing broad support for change. Iterative learning and action
CONTEXTUAL CONDITIONS	How co-operative management schemes are formulated and implemented depends on the task at hand and the responsibility shared	They reflect local environments and cultural traditions.	An active society is requirement.	Theoretically the model can be implemented at local, regional, state, national and even global levels (although at global level the decisions are voluntary)	Developed democracies and high-income countries where policy tends to leave room for and support innovation and bottom-up initiatives	Tailored to specific places and situations
TOOLBOX	Collaboration. Experimentation.			Analytical-deliberative approaches. Participatory evaluation. Collaborative scenario-building exercises. Urban Transition Labs	Assessment of multiple and non-monetary benefits. Qualitative, multi-criteria, iterative and experimental approaches.	Collaboration. Experimentation. Bioregional approach to resource management
REFERENCES	[74] [31], [94] [32] [37] [41]	[23] [95]	[65] [96] [73]	[21] [54] [57] [65] [86] [93] [99] [100]	[55] [61][101] [102]	[30] [41] [91] [102] [103][104]
BARRIERS	BG7, BG9, BG10, BG11, BE1, BE5			BG2, BG7, BG9, BG10, BE1, BE2		
DRIVERS	DK9, DG6, DG10, DE10			DK1, DK2, DK3, DK4, DK5, DK9, DG1, DG7, DG8, DG9, DG10, DE1, DE2, DE3, DE4, DE5, DE6, DE7		
SUITABILITY FOR NBS	**High.** Management of natural resources is one field especially well fitted for these types of governance. Reflexive governance is a model that may be the one applicable for social-ecological innovations such as NBS.			**Very High.** Collaborative governance is an approach thought for dealing with uncertainty, complexity and dynamics, therefore totally suited for NBS projects. "Transaction costs" (costs of consultations, reaching agreement, and enforcing such agreements) could be high		

5. Implementation model's database and results

After developing the theorical model, a database with different real cases was built to link the models with best practices and to study the incidence of them. To systematize all the information, all the identified cases were included in the same "card template" which constitute the narrative. Implementation Models were organized in 56 detailed cards containing: i) Short description of the NBS with picture, ii) Implementation context (location, scale, urban density), iii) Classification/typology, iv) Urban challenges addressed, v) NBS Stakeholders and Governance, vi) NBS financial aspects, vii) Business model, and vii) Enablers and inhibitors. The complete database is available on-line [70]. The Implementation Model (IM) collection has been built at first taking into consideration the availability of information regarding a series of practical experiences that refer to different IM. The main aim was to have a catalogue with a reasonable number of examples. The database now comprehends 56 detailed examples. The analysis was conducted based on online and free information. All the existing databases (i.e. the EEA database [71], Naturvation database [72] and others) are based on the description of NBS classification, scale, and dimension of the expected effects and not on the way in which they can be realized and carried out as full projects. The aim of this database was to give the possibility to users to consult a list of real projects crossing different variables (features or characteristics) in order to build further levels of knowledge about NBS.

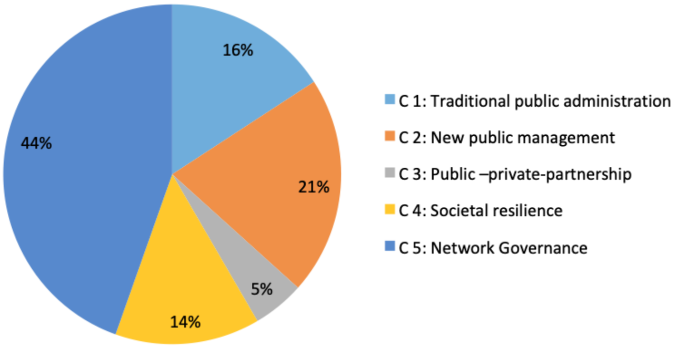

Figure 2. Governance Models incidence in the NBS IMs

The results that emerged from the governance models in the IM database (see Figure 2) showed that the more usual governance models are the ones from the Cluster 5 – "Network governance" (around 43% of the cases). Although, this confirms the theorical conclusion that this type of governance is the most suitable for NBS oriented planning (see Table 5), this correlation between the suitability of the governance models and their incidence in real cases is not so evident for the rest of the models. The second is the Cluster 2- "New public management" (21%) and the third is the Cluster 1- "Traditional public administration" (16%) with a theoretical suitability level of "low" or "medium low". The frequency of these types of governance could be more related with the traditional inertia of government structures than with the suitability of them.

6. Conclusions

The implementation of NBS projects is deeply determined by the opportunity and challenge that involves the novelty and complexity of the approach. As a new concept, it generates uncertainty due the lack of technical and operational preparedness, but it also allows to deploy innovative approaches, new ways to address old problems and more inclusive practices. Collaborative, multisector, polycentric and adaptive governance models have been considered the more suitable governance models for NBS projects, especially when urban scales are addressed. Drivers related to network governance models (such as coordination, co-production, cross-sectorial cooperation and reflexive/adaptive governance) are drivers that address a significant number of identified cross-domain barriers showing the suitability of these kind of governance models for NBS projects. The study of 56 real cases have demonstrated that the type of governance models that fulfils these requirements, "Network Governance" models, is decisively prevalent as compared to the other governance models. This result demonstrates that the collaborative and adaptive governance together with the scale-crossing borders are relevant aspects and play a crucial role in the regulatory and decision-making framework when it comes to NBS implementation in urban contexts. However, frequency cannot be considered as the only indicator for suitability. The significant incidence of less suitable but more traditional governance models, shows the high inertia that remains in urban planning. The work presented in this paper could be the basis to define new institutional and governance arrangements and new finance and business models, that will foster multi-stakeholder involvement, citizens' engagement and empowerment, leveraging both public and private funding of NBS in cities.

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Green Resilient City - A framework to integrate the Green and Open Space Factor and climate simulations into everyday planning to support a green and climate-sensitive landscape and urban development

Reinwald F[1], Ring Z[1], Kraus F[2], Kainz A[3], Tötzer T[4], Damyanovic D[1]

[1] Institute of Landscape Planning, University of Natural Resources and Life Sciences, Vienna, Austria
[2] Green4Cities GmbH, Vienna, Austria
[3] Zentralanstalt für Meteorologie und Geodynamik (ZAMG), Vienna, Austria
[4] AIT Austrian Institute of Technology GmbH, Vienna, Austria

florian.reinwald@boku.ac.at

Abstract. Continued urban growth, densification and the constantly increasing number of days with excessive heat provide challenging conditions for urban green infrastructure (UGI) and intensify the Urban Heat Island effect (UHI). Therefore, new approaches are required to improve the urban ecological function of buildings and to provide high-quality (urban) open spaces that affect the meso- and microclimate in a positive way. Based on the research project "Green Resilient City", this paper shows how climate simulations can support landscape and urban planning and development. A proof of concept for a multiscale tool set for the evaluation, regulation, and optimization of green and climate-sensitive urban planning projects is the overall aim. The tool-set combines a Green and Open Space Factor, as an urban planning index and controlling instrument, as well as three climate simulation models on different scales in order to harmonize them: the GREENPASS® as an optimization instrument on parcel and neighborhood level, MUKLIMO_3 on neighborhood and city level and Cosmo-CLM as evaluation tools on mesoclimatic and regional level. Several advantages arise from the unprecedented combination of these four instruments: It transfers the use of climate models to the planning process, enables the testing and optimization of different UGIs with a focus on how they can influence the climatic performance of the proposed design of an urban development or retrofit project and serves as a scientific basis for urban planning decisions on a political level.

1. Introduction

Half the world's population lives in cities and migration to urban areas is ongoing globally [1,2]. The United Nations estimate urban population to reach 68 % by 2050 [3]. Urban growth and the increasing densification of urban areas with high-density housing and the increase of impervious surfaces threaten green and open spaces. In addition, to the loss of urban green spaces [1] and urban green infrastructure (UGI), there is a constantly increasing number of days of excessive heat due to the interaction of Urban Heat Island (UHI) effect and the climate change related higher temperatures [4]. The UHI effect describes the difference in temperature between the cooler surroundings and the hotter dense built-up urban areas. The main cause for the UHI are sealing of soils and building coverage, as they store energy radiated by the sun. Cities are, therefore affected twofold: the increase of urban growth and the temperature increase due to climate change.

The reduction of the urban heat load is thus a central challenge for future urban development and a number of cities are therefore considering adaptation measures, including the City of Vienna. Additionally, in Vienna, the urban climate has changed noticeably, especially in the last decades [5]. The year 2018 was a record-breaking year with 42 tropical nights counted in Vienna Inner City and it was the fourth warmest summer in Vienna for more than 250 years [6].

Urban green infrastructure as a strategy for achieving resilience against weather extremes and a sustainable, functioning urban system is indispensable in urban planning. Even more so as social and economic demands can be met in addition to ecological ones since society benefits from the ecosystem services provided by UGI. Urban ecosystems are particularly important for the city residents in terms of their climatic (e.g. reduction of the UHI effect), ecological (e.g. increase in biodiversity) and social (e.g. benefits for health, well-being, recreation) function and they contribute significantly to the quality of life in cities [7–10].

Urban structures and green areas influence the urban climate on different spatial scales. For example, roof greening as individual measure of a single building has positive, but limited effect on microclimate. On the other hand, if several roofs within an urban quarter are greened, the range of influence is already greater and can positively affect large areas of the city. If there are several quarters within a city where UGI is sensibly combined, the effect reaches far beyond and can have a positive influence on the entire urban climate and surrounding area [11]. Thus, the sum of several small-scale changes can have a combined impact on the entire city. In order to have a positive influence on the urban climate, urban planning requires new, holistic approaches that take account of different levels of scale. As urban development is also a multi-level planning approach, steering and decision-making tools must be reconciled with the different planning levels.

To address these issues this paper answers following research questions:

- How should a tool set, consisting of several instruments (planning tool and climate simulation models), look like in order to be able to control and evaluate green spaces in the city?
- How can climatic performance be represented by the tool set?
- Which different planning levels can be addressed by the proposed tool set?

2. Methodological approach and introduction of instruments

In an interdisciplinary and transdisciplinary, collaborative approach the research team developed a novel tool set demonstrating its feasibility in a proof of concept. The various input parameters of the individual instruments (Green and Open Space Factor of Vienna, GREENPASS®, MUKLIMO_3 and Cosmo-CLM) were compared, adjusted and coordinated. The focus of the study lays on coordinating different scale models by analyzing data interfaces, harmonizing input parameters and setting the same reference time periods to examine the possibility of using a multi-scale tool set. The aim is to find out whether different, independently used and validated climate simulation instruments can be combined into a multi-scale tool set in order to support everyday planning in the future as an overall instrument. It will be evaluated if the combination of the individual simulation models with the Green and Open Space Factor of Vienna (GFF) can work as proposed in the tool set and deliver useful results to support green and climate-sensitive landscape and urban planning.

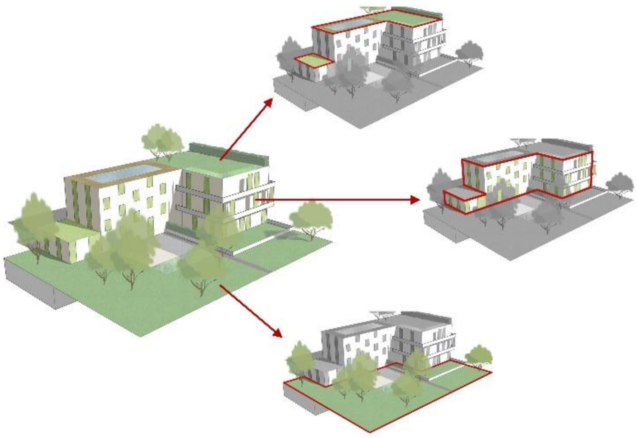
2.1. Green and Open Space Factor of Vienna (GFF – "Grün und Freiflächenfaktor")

Following the example of other cities (e.g. Berlin, Helsinki, Seattle, Stockholm, London) [12–16] a green and open space factor (GFF – in German: "Grün und Freiflächenfaktor") was developed for Vienna. Reacting to the fact that the fraction of green areas decreased especially in the last 15 to 20 years in Vienna, it is now aimed to maintain, and also to expand, existing UGI, because private and semi-public green and open spaces have positive effects for the entire city through ecosystem services.

At present, the floor-space-index (GFZ – in German: "Geschoßflächenzahl"), together with other measures (e.g. degree of sealing, building density, building height, etc.), is the determining factor for urban development. The GFF for Vienna is the counterpart to the floor-space-index. In addition, the GFF considers the ecological, climatic and socio-economic aspects of UGI by factoring in the different ecosystem services and selected elements of UGI. Each of the category contains individual UGI elements and is underlined with a specific factor determining the final GFF.

The calculation method of the GFF of Vienna gives a ratio of the UGI (in square meters) to the respective reference area on the ground floor, façade or roof (Figure 1). Due to the different reference areas, a differentiated consideration of the UGI elements (green and open space, façade greening, roof greening) is possible, as a function of the building size and height.

Figure 1. GFF and its respective reference areas (ground floor, façade and roof)



2.2. Climate simulation tools on different scale levels

The possibilities of the instruments for simulation and evaluation of urban climate are comprehensive and varied, but not yet tailored to the needs of landscape and urban planning. Three different simulation tools, developed and individually validated in previous research projects[1] have been selected to cover the different climatic impact areas and planning scales: the GREENPASS® as an optimization instrument for the microclimatic effects of green infrastructure at parcel and neighborhood level, the MUKLIMO_3 urban climate model as an evaluation instrument for the local scale impact on city level and Cosmo-CLM as a regional climate simulation model to provide projections on large-scale climate developments. In the course of the research project "green.resilient.city", the individual climate simulation instruments are coordinated, cross-validated and harmonized in order to adjust the input and output parameters (Figure 2). On the basis of a first case study (situated in an urban development area: **aspern** Seestadt), GFF and GREENPASS® were adjusted and used jointly in an urban planning competition. The effects of integrating these two instruments by increasing the use of urban green infrastructure could be shown by the urban climate model MUKLIMO_3 on larger scale. In further

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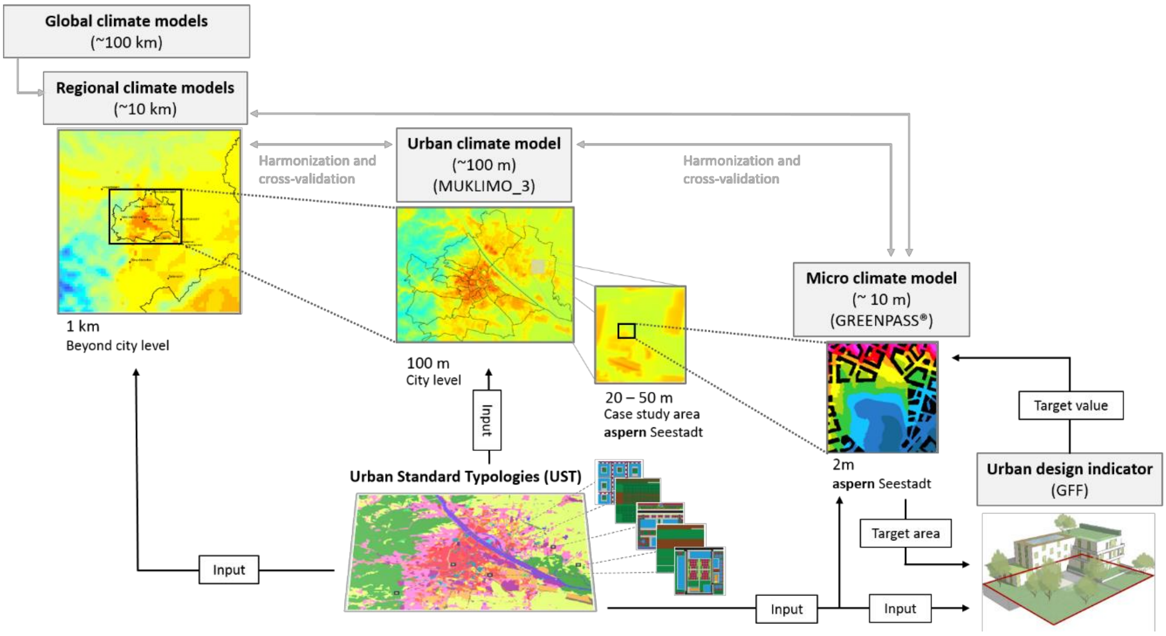
steps, harmonization with the regional climate model Cosmo-CLM and cross-validation of all instruments will be carried out.

Figure 2. GFF and climate simulation tools on different scale levels – downscaling of climate simulations to local scale (Source: Own representation based on ZAMG, 2019)



2.2.1. GREENPASS®

GREENPASS® defines standardized processes to assess and evaluate the climate resilience and cost-efficiency of architecture and urban planning. It combines the holistic high-resolution numerical simulation software ENVI-met with area analyses, evapotranspiration models, cost analyses and qualitative indicators [17]. ENVI-met was developed at the Chair of Environmental Meteorology Group at the Johannes Gutenberg University in Mainz [18–20]. In several European research projects (e.g. "Biotope City is Smart", "Nature4Cities"), the prerequisite for the planning use of the microclimate simulation software was created and linked with other models. Urban and object planning projects up to a size of 40 ha (with an internal resolution of 2 m) can not only be simulated, but can also be analyzed and optimized with regard to thermal comfort, rainwater management, costs for construction and maintenance, CO_2 storage, cooling degree hours, water demand and ecological quality.

For project quick assessment and mesoclimatic urban climate simulations, so called urban standard typologies were developed which assign specific land use data to an urban structure [21].

2.2.2. MUKLIMO_3

Urban climate model MUKLIMO_3 and the cuboid method developed by the German Meteorological Service (DWD - "Deutscher Wetterdienst") allows the investigation of urban heat load with spatial resolution of about 20 m to 200 m and on a time scale, which is suitable for the daily development as well as for the climatological analysis of UHIs. Based on topography and land use data, the urban climate model MUKLIMO_3 [22–25] simulates the radiation balance, wind, humidity and temperature distribution in the city, taking into account potential atmospheric conditions during periods of heat. Using the cuboid method [26] that combines high-resolution urban climate model output with long-term climate information from monitoring stations or regional climate projections it is possible to calculate climatological indices such as mean annual number of summer days, heat days or tropical nights for the 30-year climatic periods. Furthermore, the model can be used to assess the effects of different climate change adaptation measures, including the implementation of green infrastructure or unsealing of sealed surfaces.

2.2.3. COSMO-CLM

The German regional climate model Cosmo-CLM with special urban extensions (CLM-URB)[27–29] which integrate anthropogenic heat emissions [30,31] and a high-resolution sealing layer [32], is used to provide high-resolution climate scenarios. That allows simulations with a resolution of 1x1 km for the greater Vienna area (100x100 km). The simulations are calculated in four nesting steps at 50 km, 10 km, 4 km, and 1 km horizontal resolution. The first three runs are performed with the standard Regional Climate Model Cosmo-CLM. The urban extensions are applied in the 1 km run, with two additional input fields: the urban fraction (URBAN) and annual-averaged anthropogenic heat (AHF). By applying the urban extensions, the UHI effect can for the first time be mapped relatively fine-scaled with regional climate models in the context of large-scale climate developments. For the simulation of the past and the model evaluation ERA40/ERAInterim forcing data are used. AIT performs high resolution model runs for the greater Vienna area for various time slices until 2100. Model output is stored as hourly, daily, monthly, seasonal and yearly values and can be transferred to ArcGIS maps on future climate scenarios for Vienna.

3. Results - Requirements for a tool-set for a climate-sensitive urban development and its elaboration

3.1. Interface definition and data transfer to harmonize the instruments

The GREENPASS® urban standard typologies (USTs) represent an essential link between microclimate and mesoclimate simulations. These USTs have been developed in several research projects (e.g. “Green4cities”) and allow the abstraction of global urban structures. International case study cities (Hongkong, London, Santiago de Chile and Vienna) were analyzed using GIS data and aerial photos [33]. In a first step a set of USTs for each city was elaborated and finally merged to one set of global applicable USTs. Existing sets of USTs have been respected, as the Local Climate Zones published by Oke [34] which are limited to Northern American urban structures. In addition, the GREENPASS® USTs are more detailed in regard to the differentiation of areas, surfaces, materials and green infrastructure, which supports the calculation of the GFF. Furthermore, each GREENPASS® UST is available in four varieties: a worst case, status quo, moderate greening and maximum greening scenario. The scenarios describe the level of integration of urban green infrastructure, ranging from no green for the worst-case scenario to dense green at the maximum scenario. The mesoclimatic simulation models require land use data, such as the degree of sealing, canopy area, etc. The USTs provide this information as a basis for mesoclimatic simulations, not only in one but in four different greening scenarios. This unique approach allows to quickly exchange the scenario for a selected urban area and to increase or decrease the level of integrated urban green infrastructure without changing the building structure.

3.2. Combination of the instruments to form a multi-scale tool set

To incorporate city-specific information on urban structures provided by the USTs into the MUKLIMO_3 model, physical parameters like the degree of soil sealing, percentage of built-up area, percentage of vegetation (trees, low vegetation, green roofs) that are available for each UST category are translated into characteristic land use information that can be handled by the urban climate model. Model simulations at 100 m spatial resolution are performed to investigate urban heat load distribution in Vienna, based on the land use information gathered from the USTs. Subsequently, by implementing variations of the USTs that mainly consider different types of greening measures, their cooling effect can be assessed through an analysis of modification in urban temperature distribution on a daily basis or a modification of climate indices considering 30-year climatological periods. In order to harmonize the different climate models, MUKLIMO_3 model output (temperature, relative humidity, radiation) can be used as input for the microclimate simulations carried out with ENVImet. Similarly, model output obtained by the regional climate model Cosmo-CLM may serve as background climate information for the derivation of long-term climate indices with MUKLIMO_3. Integrating micro-scale urban fabric related information into the regional climate model Cosmo-CLM is challenging. The first step for identifying interfaces between micro- and macro-scale was to incorporate the sealing values of the USTs as input parameters into Cosmo-CLM. Test simulation runs have shown a high sensitivity of the model to changes in the degree of sealing. In further steps, plant cover, Leaf Area Index (LAI) and average building heights will be additionally integrated.

The GFF and GREENPASS® differ in the level of detail. The two instruments were coordinated by means of a tabular comparison. Due to the harmonization, the GFF contains all relevant UGI types used in GREENPASS® with only some exceptions. The GFF is partly more detailed, as social criteria are also included and evaluated. The higher level of detail is the logical conclusion due to the smaller area of use (parcel level). The combination allows the GFF to be calculated for each UST using GREENPASS® greening scenarios. The results show how much greening is possible for each typology. Based on this, target values can be derived which can be used to control the amount of greenery at parcel level.

3.3. Coordination of the tool set with the urban planning levels

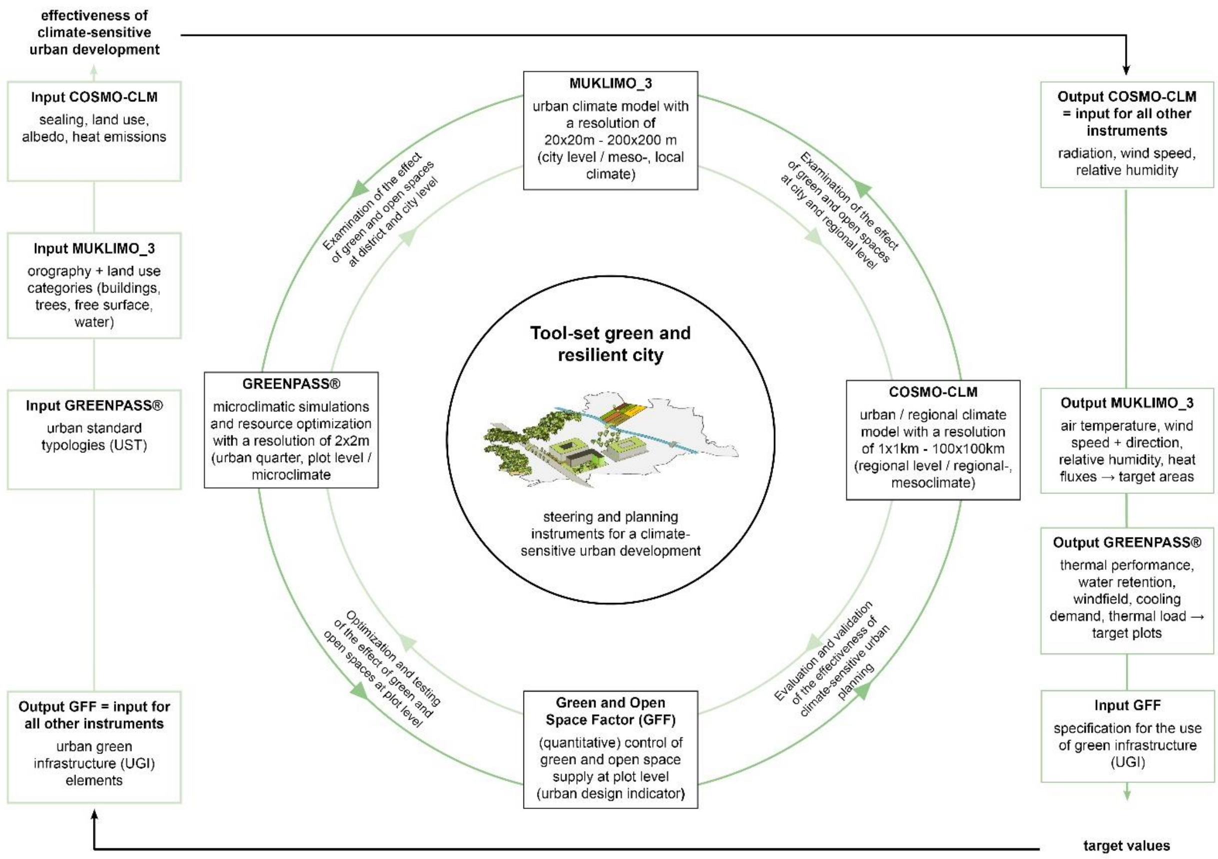
In order to develop a tool set suitable for everyday use in urban planning, the steering and evaluation instruments must be harmonized with the multi-level planning approach of urban development. Therefore, all relevant planning levels and areas of the city must be covered. In summary, these are: (1) metropolitan area (2) city (3) urban district and larger urban development areas (4) urban quarter, smaller development areas (neighborhoods), and the parcel level. These planning levels influence each other, therefore all instruments used must be coordinated within the planning tool (Table 1).

Table 1. Comparison of multi-scale climate simulations and urban planning levels

Planning levels and planning instruments	Climatic levels and spatial resolution	Climate simulations
<u>Beyond city limit/metropolitan area/regional</u> Regional development concepts and strategies	<u>Regional-/meso-climate</u> (1-10 km)	COSMO-CLM
<u>City</u> Urban development concept	<u>Meso-/local-climate</u> (100 m – 1 km)	COSMO-CLM/ MUKLIMO_3/ (GREENPASS®)
<u>District</u> Land-use- and development-plan; Urban development competitions and guidelines	<u>Local-/micro-climate</u> (20-100 m)	MUKLIMO_3/ GREENPASS®/ (GFF)
<u>Urban quarter/parcel</u> Developer completion; Urban development contract; Building permission	<u>Micro-climate</u> (0,5-20 m)	GFF/ GREENPASS®

In contrast to their local impact, the instruments described also show differences in their climatic impact. As explained in the introduction, the sum of measures at microclimatic level can achieve a large-scale effect. In order to improve the climate effectively, control instruments are needed at every scale level. By merging them, the planning levels and climatic scales are linked with each other. This leads to a proposal for a multiscale toolset (Figure 3) for meso- and microclimate regulation, optimization and evaluation in relation to the different levels of urban planning.

Figure 3. Proposal for a multi-scale tool set for climate-sensitive landscape and urban development



*3.4. Application on the basis of a case study in an urban development competition in **aspern** Seestadt*

Case studies are used to test the implementation and applicability of the proof of concept. One of these is located in **aspern** Seestadt, one of the largest urban development areas in Vienna. In **aspern** Seestadt a two-stage urban development competition "Quartier Seeterrassen" was accompanied by the research project and the joint use of the instruments was successfully tested. The GFF and the GREENPASS® were combined and applied in several phases of the competition process (Figure 4).

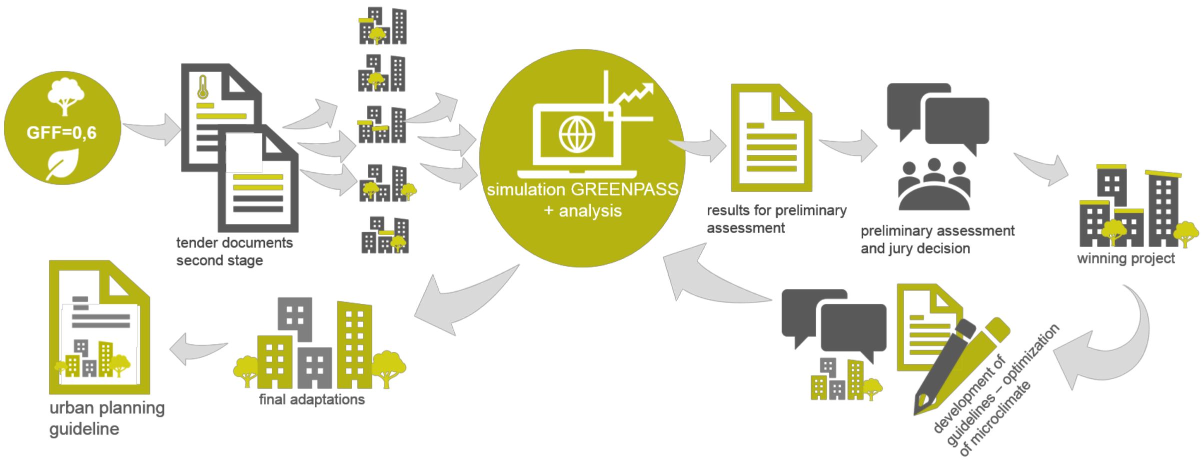
In the tender documents for the first competition phase, the special focus on the microclimate was already announced in the form of general dos and don'ts for a climate sensitive urban development. The existing master plan for the entire **aspern** Seestadt was simulated in order to show the climatic performance of the current state of planning. Based on this, qualitative recommendations regarding the urban structure were given. In addition, as a part of the preparation phase for the second stage of the competition, quantitative specifications were defined with the GFF. A target value was set in order to achieve a sufficient degree of greening.

In the course of the preliminary assessment of the contributions to the competition, the GREENPASS® was used to simulate, compare and analyze the effectiveness of the use of green infrastructure and the effects of the development structure of the various competition entries and compliance with the GFF target value was checked. These results were prepared and served the competition jury as a basis for decision-making.

The monitoring and optimization did not end with the awarding of the prize to the winning project. Based on the results of the previous simulation, adaptations for the winning project were formulated and optimizations made by various specific measures. As there are many different requirements regarding urban development and usability within the framework of an urban development competition, the winning project had to be optimized from a microclimatic point of view. In a workshop with the planning team (architects and landscape architects) adaptations were worked out. Building structures were slightly modified, breakthroughs in the perimeter block were defined for optimal air circulation, groups of trees were moved and façade greening was added to mitigate heat islands and optimize PET (physiological equivalent temperature). The winning design was revised and simulated again to make the optimization measures visible. It was gratifying to see that after the adaptations it became the best design both from an urban planning and a microclimatic point of view. The planning area was additionally simulated with MUKLIMO_3 in order to demonstrate the climatic effects on the entire quarter.

In the urban development guideline, which has to be taken into account when designing the individual building sites, both qualitative recommendations from the GREENPASS® simulations and quantitative specifications with the GFF were included in order to achieve a climate-sensitive urban development. With the GFF, a target value for UGI was anchored in the urban planning model for further planning and implementation processes. It has been shown that the monitoring and optimization of an urban development project by the tool set is feasible and shows positive results. In another case study, the applicability of the whole tool set in existing urban structures will be examined.

Figure 4. Workflow for the implementation of GFF and GREENPASS in an urban planning competition



4. Discussion

The GFF enables a (microclimatic) assessment of buildings, open spaces and UGI at parcel level. On the one hand, it enables accompanying urban planning procedures in order to compare and evaluate submitted development proposals. On the other hand, the need for optimization can be identified for existing built structures. The GREENPASS® can represent the climatic performance of individual building sites or urban quarters. For planning this means the following: By linking and coordinating these two instruments (GFF and GREENPASS®), the microclimatic impact of changes to individual UGI elements at site level can be simulated for an entire urban quarter. Since the urban climate model MUKLIMO_3 and the regional climate model Cosmo-CLM were also linked in the tool set and coordinated with the USTs, the output parameters of the GREENPASS® can be used in these instruments as an input. The advantages of implementing the USTs in the climate simulation models are the intersection with urban structural information and building types. The evaluation with regard to individual UST types makes it possible to generate general statements. Furthermore, greening scenarios can be integrated into the simulations. Thus, it can be shown which building type in combination with which greening type is climatically particularly effective.

The tool set can also be used in reverse order, from large scale to parcel level. The use of Cosmo-CLM and MUKLIMO_3 as climate simulation models on city level and its surroundings, allows the representation of UHI effect and intra-urban hot-spots under current and future climate scenarios. This results in target areas where improvements must be achieved in order to maintain a high quality of life for the residents. These findings can be embedded as initial conditions for the GREENPASS®. Through different greening scenarios, the GREENPASS® can demonstrate how much more UGI is needed within a city quarter. By considering wind direction and wind speed, the GREENPASS® indicates on which parcels specific measures have to be taken. The GFF can then control the use of UGIs on exactly these parcels by specifying target values. The sum of several microclimatic improvements leads to a positive influence on the urban climate.

The tool set supports political decisions with a scientific basis. It serves the city to foresee climatic developments and effects of urban development changes and to demand and achieve targeted measures. As there is not one holistic instrument for analyzing the urban climate at different planning levels and no steering instrument for UGI at parcel level in Vienna yet, the combination of different climate simulation models with the GFF can make a significant contribution to green, resilient urban planning.

5. Conclusion

In summary, it can be stated that the proposed tool set is applicable for the entire city and differentiates between the individual scale levels. Currently, the tool set consists of several components (GFF, GREENPASS®, MUKLIMO_3, Cosmo-CLM) that have to be operated individually. The combination into a single, coherent instrument requires further research. The possibility of controlling, evaluating and optimizing makes it suitable for both urban development processes and for conversions of existing urban structures. Building on this, links can be established to the relevant urban planning instruments in order to develop a regular urban planning instrument to consequently implement a steering tool for green infrastructure in (planning) administration.

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Implementation of a sustainability monitoring tool into the dynamics of an urban brownfield regeneration project

Laprise M[1], Rey E[1,2]

[1]Laboratory of Architecture and Sustainable Technologies (LAST), Ecole Polytechnique Fédérale de Lausanne (EPFL), BP 2225/Station 16, 1015 Lausanne (Switzerland)
[2]Bauart Architects and Planners Ltd, Crêt-Taconnet 17, 2000 Neuchâtel (Switzerland)

martine.laprise@epfl.ch

Abstract. Within the context of post-industrial European cities, the regeneration of urban brownfields contributes to limit urban sprawl by increasing cities density while revitalizing neighborhoods. Yet because of their complex nature, urban brownfields regeneration projects (UBRP) are not automatically sustainable. To foster the integration of sustainability objectives into these projects dynamics, an operational monitoring tool was created. Entitled SIPRIUS+, this tool is a collaborative web-based software combining sustainability indicators adapted to UBRP issues and several management functionalities. Test applications conducted on case studies and presented to the related stakeholders gave positive insights about the potential of SIPRIUS+ to provide decision-making support. However, because of the long duration of UBRP, some aspects inherent to monitoring were not verified and the tool not piloted in real conditions. In order to confront SIPRIUS+ with the reality of the practice and its end-users, the tool is now being implemented for an 18-month period in the Gare-Lac neighborhood project located in Yverdon-les-Bains (Switzerland). The paper investigates how SIPRIUS+ is actually implemented into the project's ongoing urban planning procedure. Then, we analyze preliminary feedbacks to measure the level of adoption of the monitoring approach by the different stakeholders and to identify points of improvement.

1. Introduction

Now that it is clear that urban sprawl generates negative impacts on the environment as well as on the economy and the society, post-industrial European cities must steer towards strategic densification of their built-up areas [1]. In this context, the regeneration of urban brownfields is identified as a major opportunity to increase density within the already built fabric and, at the same time, to revitalize declining neighborhoods [2]. This recognition has spread since the last two decades and many land uses policies across Europe foster urban brownfield regeneration projects (UBRP) as a sustainable land take solution [3]. In Switzerland, the revision of the federal law on land planning (LAT) in 2014 introduced new measures to limit urban sprawl by promoting the densification of the urban fabric [4]. As a direct consequence, public authorities must now prioritize urban development within inner areas of the city, using in particular strategies such as the regeneration of urban brownfield [5].

In today's context looking towards the sustainable city, UBRP have to include environmental, social, economic, and governance considerations. However, even though urban brownfields regeneration is a sustainable land take solution at a territorial level, these operations are not automatically sustainable per se [6]. This is explained first by the inherently complex nature of UBRP: on one side the brownfield site complexities (real or perceived contamination, buildings of variable quality, intermediate neighborhood scale, social stigma, etc.) and, on the other side, the regeneration project complexities (long duration, several stakeholders with different objectives, rigid legal framework, etc.). This adds to the multitude, and sometimes even divergent, parameters of the concept of sustainability to be integrated into the UBRP. Taking simultaneously into consideration these intricate aspects goes far beyond the limits of intuition. To overcome this complexity and to foster a continuous, structured, and proactive integration of sustainability objectives into the project dynamics of UBRP, it is necessary to put systems in place to act on the basis of sound information and to collect it as appropriate [7]. In that order, an operational monitoring tool was created as an outcome of a four-year research project realized at the Ecole Polytechnique Fédérale de Lausanne (EPFL).

Entitled SIPRIUS+, this tool is a collaborative web-based software combining sustainability indicators adapted to UBRP issues and several management functionalities supporting continuous and structured monitoring. We tested SIPRIUS+ on case studies in Switzerland, France, and Belgium and presented the results to the related stakeholders. It gave positive insights about the potential of the tool to provide efficient support for stakeholders involved in the decision-making process of UBRP [8]. However, because of the long duration of UBRP, some aspects inherent to monitoring were not verified and the tool not piloted in actual conditions. In order to confront SIPRIUS+ with the reality of the practice and its end-users, the tool is now being implemented as a pilot experiment for an 18-month period in the Gare-Lac neighborhood project located in Yverdon-les-Bains (Switzerland).

This paper investigates this ongoing pilot experiment. To put the subject into context, the next section presents the functioning of the tool by showing some examples of monitoring visualization results and the outcomes of the interaction with the involved stakeholders. Then, section 3 explains the strategic implementation of SIPRIUS+ into Gare-Lac’s urban planning procedure. Section 4 analyses the preliminary feedbacks, which allows to measure the level of adoption of SIPRIUS+ by the various stakeholders and to figure points of improvement for the next phase of the pilot experiment.

2. The operational monitoring tool

The operational monitoring tool SIPRIUS + is an online hybrid tool that combines two approaches: on one side an indicator system along with its evaluation methodology (from the field of the built environment) and, on the other side, a sustainability monitoring software (from the field of business management). Although the issues of the two fields may differ, the principles underlying the monitoring remain the same. The hybridization of these two existing know-how results in a tool using a synergy of the most relevant elements from both disciplines. Thus, while being specifically designed to deal with the issues raised by the integration of sustainability objectives into UBRP, SUPRIUS+ uses several efficient monitoring functionalities (reporting, visualization, planning, management, communication, etc.). More precisely, it enables a comprehensive, continuous and structured assessment and monitoring of a series of quantitative and qualitative holistic sustainability indicators in three categories: Context indicators (21 indicators), Project indicators (23 indicators), and Governance indicators (11 indicators) [8].

Thanks to these tailor-made indicators, SIPRIUS+ offers not only a view on the project environmental, social and economic performances (Project indicators) but goes also beyond traditional evaluative logics at the neighborhood level. On the one hand, it integrates parameters whose influence exceeds the physical limits of the site (Context indicators). For example, indicators related to mobility, environmental impact, proximity to amenities or urban mixing contribute to the project integration on the environmental, social and economic levels within the local fabric. On the other hand, the tool looks at the project management and its dynamics between the multiple actors of the project, as well as the temporal stakes of the process of regeneration (Governance indicators). For example, indicators such as the temporary uses of the brownfield or the degree of participation of the population help the project managers to measure and adjust the various actions in place, which can contribute to change the brownfield site perception and promote acceptance of the regeneration project.

Taken together, these indicators embody the urban strategies used by UBRP to promote the transition towards more sustainable cities. The monitoring of sustainability, using evaluation of indicators and management functionalities, makes it possible to transcribe these various urban strategies and to visualize their performance through time. Thus, monitoring results can contribute to decision-making, that is the trade-offs to be made according to the UBRP's priorities. To support this idea, we expose here the monitoring results of three representative case studies of UBRP [9]. Indeed, test applications of the SIPRIUS+ tool - previously adapted to the contexts and practices of Belgium, France, and Switzerland - were carried out on the Val Benoit project in Liège (BE), the Pôle Viotte in Besançon (FR), and the Gare-Lac neighborhood in Yverdon-les-Bains (CH). Hereafter, we report the outcomes of the interactions with the stakeholders involved in the case studies.

2.1. Monitoring visualization

SIPRIUS + is a complete monitoring tool, which allows a variety of synoptic visualizations displays of all or part of the indicators in order to facilitate communication according to the target audience. As an example, Figure 1 shows the repartition display for the Expected final situation of the UBRP, that is to say, the foreseeable performances at the end of the regeneration project depending on the elements known at the time of the evaluation. In this case, data are taken from the Masterplans of the three case studies (monitoring performed during 2017 [9]), knowing that some specific indicators were not relevant to the UBRP. The results are distributed according to their levels of performance - Limit Value (VL), Average Value (VA), Target Value (VT) and Best Practice Value (VB) - and represented by a universal color code (from red to dark green). This easy to interpret and to communicate way at looking at the results is a gateway into the monitoring of the UBRP.

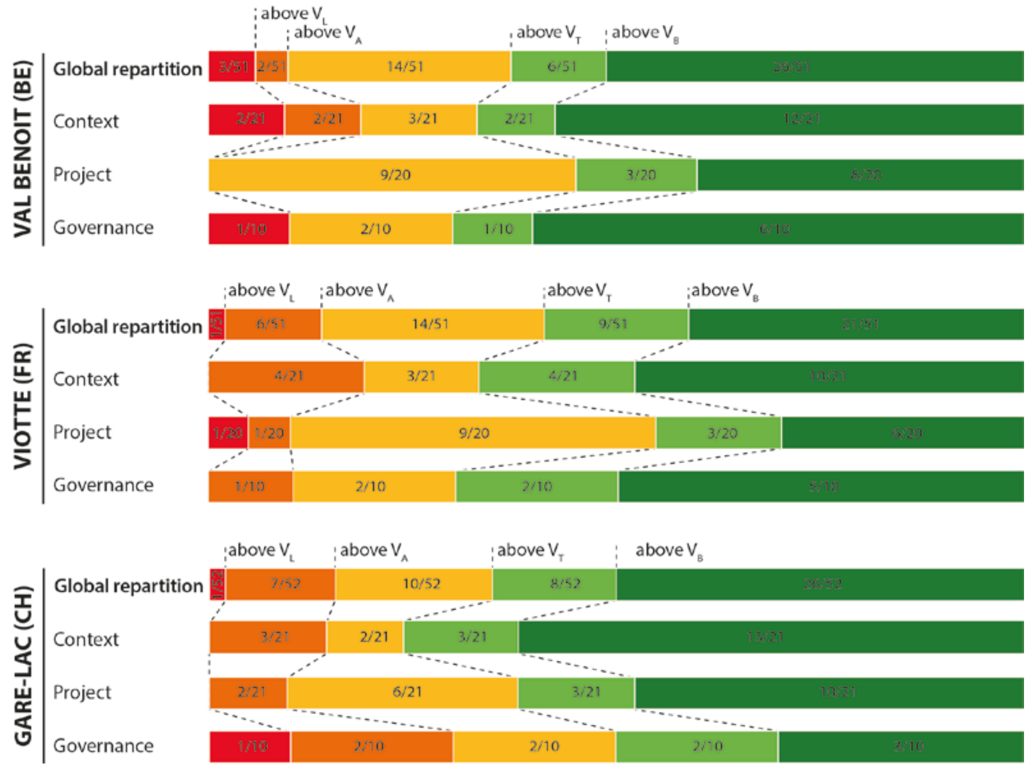

Figure 1. SIPRIUS+ repartition display for the three case studies.

From a monitoring point of view, it is especially interesting to focus on more detailed evaluation results. It makes it possible to see the effects that certain sustainability objectives set by the regeneration project may have on the site improvement, what are precisely the risks, the challenges, and the opportunities. Figure 2 shows the evolution display of three indicators: Context indicator "C2.1 Average annual emissions of NO_2", Project indicator "P5.6 Quality of outdoor spaces", and Governance indicator "G7.1 Degree of information access". We observe that the monitoring proposed by the SIPRIUS+ tool allows an evaluation of the Objectives, the Initial situation, the Current situation, and the Expected final situations. These monitoring results are, by definition, the portrait of a situation in a given moment and are subject to change according to the evolution of the projects. It can be used to compare in an iterative way different options of a UBRP, especially during the preliminary phases when the project is the most flexible and offers room for the integration of high sustainability targets. As a general rule, SIPRIUS+ is not designed to compare projects in different locations, nor to rate projects as certain labels.

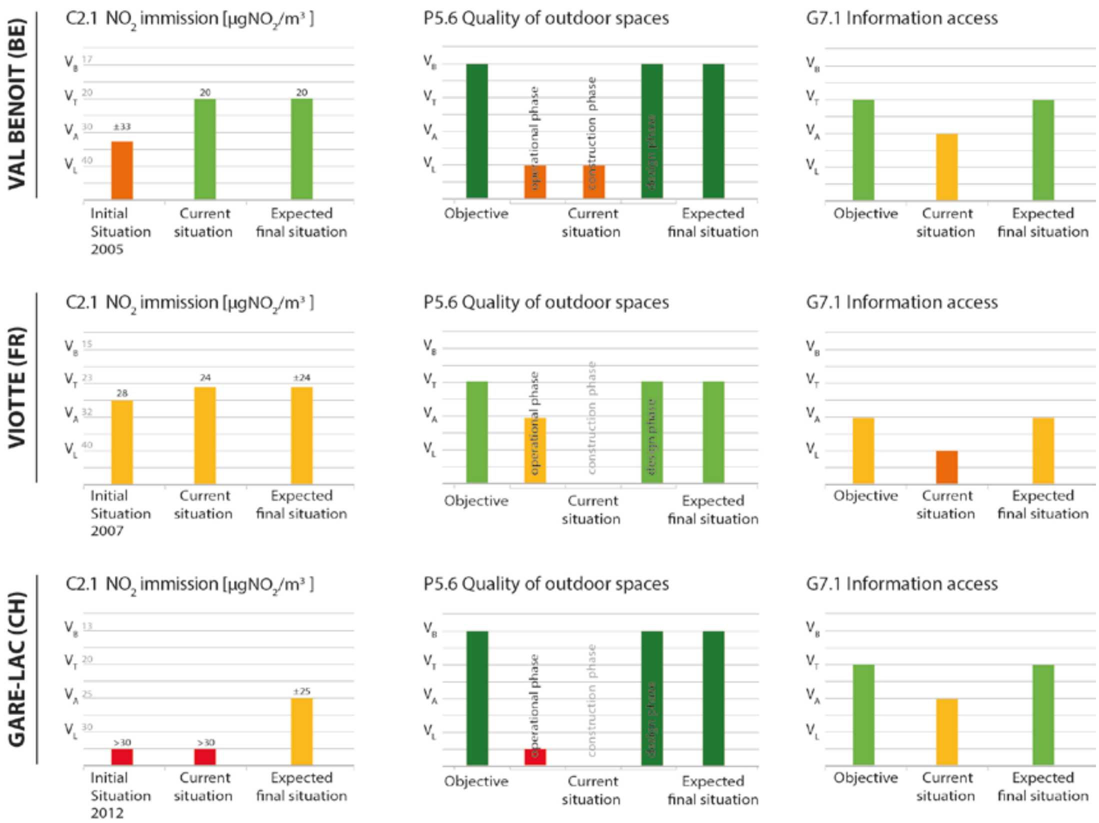

Figure 2. Evolution display of a Context, Project and Governance indicator for each case study. For exhaustive evaluation results see [10].

2.2. Interactions with stakeholders

The three tests applications confirmed the adequacy of SIPRIUS+ to UBRP specificities as well as the proper functioning of the tool [8]. However, because the concept of monitoring involves taking into account the long-term process of UBRP and because SIPRIUS+ team mostly performed the tests applications, some aspects could not be tested. Therefore, as a complementary test phase, we organized interactions with the involved stakeholders of each case study, which took the form of roundtable discussions. The aim was to face the tool and the test-application results to the future end-users. The participants shared a positive perception about the potential added value of SIPRIUS+, qualifying it as a "dashboard" contributing to the decision-making process. They recognized its potential to facilitate the integration of sustainability issues into the project dynamics 1) by simplifying communication in an interdisciplinary manner, 2) by facilitating follow-up of objectives from the initial situation to the regenerated site, and 3) by fostering a virtuous cycle of iteration of the UBRP. It also emerges from these interactions that if the use of such a tool implies a change in UBRP management, to include this practice appears not only possible but also realistic and desired.

3. From theory to experimentation: strategic implementation of SIPRIUS+

Convinced by the potential of the tool, the stakeholders involved in the Gare-Lac neighborhood UBRP in Yverdon-les-Bains (Switzerland) contacted the SIPRIUS+ team to pursue the monitoring already initiated. This pilot experiment started in July 2018 and will allow, during an 18-month period, to confront SIPRIUS+ with the practice reality and its end-users. This section explains the strategic implementation of SIPRIUS+ into Gare-Lac's urban planning ongoing procedure.

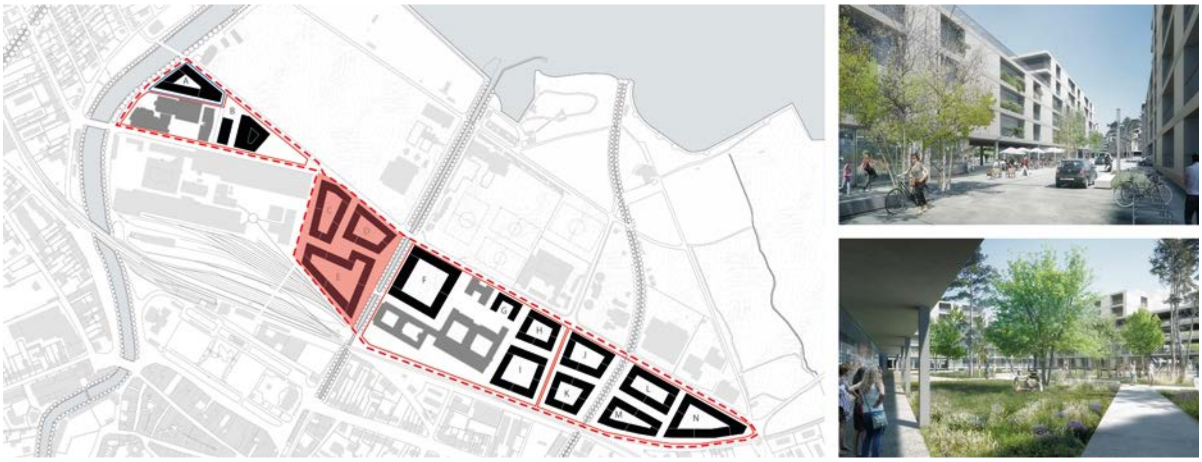

Figure 3. Master Plan of the Gare-Lac neighborhood with Ancien-Stand sector in red (left) and perspectives showing architectural, mobility, and landscape quality principles (right).

3.1. The urban planning procedure

Starting from 2006, the multidisciplinary team led by Bauart Architects and Planners Ltd. developed a Masterplan to transform a 23ha urban brownfield into a new sustainable neighborhood called Gare-Lac (Figure 3). Adopted in July 2015, the aim of the Masterplan is to give guidance for a new mixed-use neighborhood providing space for about 3800 inhabitants and 1200 jobs [10]. In particular, the Masterplan requires an optimal density with a ratio of 1,7 Floor space/Plot area, high architectural and landscape quality, and conformity with the primary energy consumption efficiency and CO_2 emission reduction objectives of the 2000 Watts Society [11]. The future neighborhood is composed of 14 plots, organized in 5 sectors. Each of these sectors will be subject to a land use plan (PA - Plan d'Affectation) in order to develop in further detail the Masterplan. This phasing has for advantage to reduce the risk of deadlock related to technical constraint or opposition, to facilitate discussion with landowners, and to sequence the UBRP development. However, it implies major coordination issues between the different PAs to maintain the principles and objectives provided by the Masterplan.

Starting from 2018, the steering committee (COPIL – Comité de Pilotage) composed of the Urbanism Department of Yverdon-les-Bains municipality, the Association for the development of Northern Vaud, and the Operational Group for Urban Centers from the canton of Vaud launched the planning of the PAs to come. The first PA to be developed is the 3,7ha Ancien-Stand sector (Figure 3). It consists of a two-steps public tender procedure. For the first step, it asks for the setting-up of consortiums composed of multidisciplinary offices with competencies in architecture and urbanism, landscape architecture, mobility, environmental studies, and property expertise. The consortiums will have to develop and make a proposition for the PA Ancien-Stand according to the Masterplan. Then, for the second step, the selected consortium will collaborate in an iterative working logic with COPIL until the final approbation of the PA. COPIL will ensure, among other aspects, the overall PA planning and implementation as well as PA compliance with the Masterplan principles and sustainability objectives. It will be supported in this regard by SIPRIUS+, as a pilot experiment.

3.2. Strategic implementation of the monitoring tool

SIPRIUS+ is designed to monitor sustainability objectives at the neighborhood scale using Context, Project, and Governance indicators. Indeed, the first test-application on the Gare-Lac neighborhood (section 2) - which will serve as a reference for the design of PAs - was performed taking into consideration data from the entire site and the surrounding. Hence to get the same results, the monitoring of the PA Ancien-Stand will have to follow the same methodology. Taking that into consideration, the involved stakeholders could perceive monitoring and evaluation as time-consuming and data collection as cumbersome [12]. Although it is of primary importance for this current urban planning procedure to check conformity with the Masterplan sustainability principles, the monitoring of not one, but several propositions of PAs simultaneously, appears in fact oversized.

To overcome this apprehension, we proceeded here to the strategic implementation of the tool within the PA Ancien-Stand planning procedure adapted to each of the two steps. In that respect, the annex of the call for tender document encloses exhaustive information about SIPRIUS+. It includes SIPRIUS+ catalog of indicators, which gives a detailed description of each indicator, data required to evaluate it, how it is evaluated, and the related references. It also includes the final report showing the results of the test-applications previously realized by SIPRIUS+ team [9].

3.2.1. Selection step For the selection step, in order to gain in efficiency, it is asked to the consortiums to described the sustainability concept of their proposition, what is their understanding of the monitoring principles, and how they will organize to provide the data for each indicator in order to feed SIPRIUS+. COPIL will base its decision upon the propositions quality, which includes several parameters of which the integration of SIPRIUS+ monitoring approach in the project dynamics.

3.2.2. Iterative step For the iterative step, the selected PA Ancien-Stand will be evaluated following SIPRIUS+ usual monitoring methodology. This means that Context, Project, and Governance indicators are evaluated integrating the new data of the proposition and the data from the entire site. The selected consortium will provide the data according to the project evolution. A team of three urban planners from COPIL will perform the monitoring using SIPRIUS+. The aim is to limit in a first instance the number of users during the procedure until PA Ancien-Stand approbation. This strategic implementation of SIPRIUS+ is a significant aspect of the pilot experiment: it eases the workload of both parties and ensures an incremental use of the tool. Moreover, it provides a common basis creating a shared dialogue on sustainability objectives between the consortium and COPIL.

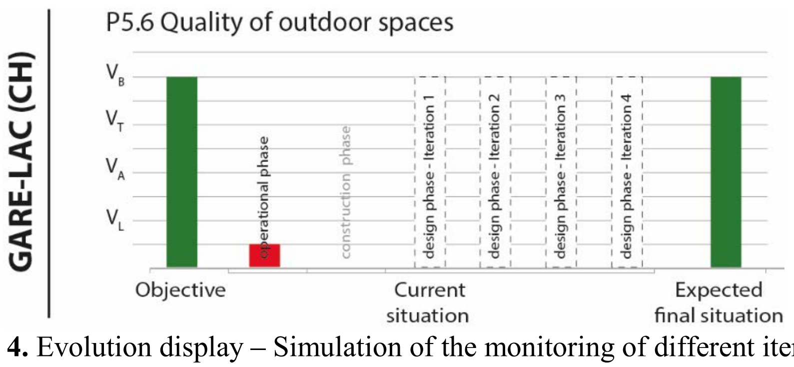

Figure 4. Evolution display – Simulation of the monitoring of different iterations

As an example, Figure 4 shows the monitoring of a Project indicator, which takes into consideration the "Current situation" according to the project advancement (exploitation phase, construction phase, and design phase). In this case, the PA Ancien-Stand corresponds to the design phase. Iterations of the project can be compared in real-time, which gives relevant information about the performances of the PA, consequences of given design choices, and probabilities to meet the sustainability objectives set by the Masterplan. This way, SIPRIUS+ can contribute to the iterative and collaborative working logic between the consortium and COPIL.

4. Preliminary feedbacks and discussion

The selection step of the PA Ancien-Stand planning procedure is currently nearing completion. In total, 10 propositions were received. Among them, four consortiums have not included, or not sufficiently included, the monitoring approach and SIPRIUS+ principles within their proposition. This shortcoming turns out to be critical in the selection of a consortium by COPIL. COPIL will disclose the name of the selected consortium during summer 2019.

This section gathers preliminary feedbacks on this selection step. These feedbacks were collected during an interview with the urban planners' team of COPIL, looking for information about the level of adoption of the monitoring approach in the urban planning procedure so far. We investigate here these preliminary feedbacks by confronting them to the potential added value highlighted previously by the stakeholders during the roundtables interaction (see the 3 points in section 2.2). Then, we identify points of improvement to maximize the benefits of monitoring for the next phase of this pilot experiment, the iterative step, and for further PA procedures.

4.1. Level of adoption of the monitoring approach

The interview revealed that the most qualitative propositions included monitoring principles in a proactive way, using SIPRIUS+ documentation as a "checklist" to verify compliance of the proposed PA Ancien-Stand with the Masterplan sustainability objectives as well as to communicate their performance. Similarly, COPIL uses SIPRIUS+ indicators during the selection step to control that the propositions cover a maximum of sustainability parameters.

It was announced during the interview that two of the three urban planners of COPIL who initiated the PA procedure are now being replaced. As a matter of fact, UBRP are long-term operations and the Gare-Lac neighborhood project is no exception to the rule. Because of that, stakeholders tend to change over time. In this context, the involved urban planners confirmed to rely on SIPRIUS+ to serve as a "dashboard": it will allow to share and transfer the long-term sustainability vision of the Gare-Lac UBRP and to keep up the Masterplan objectives through the project process, such as the 2000 Watts Society objectives.

Although, modest, these preliminary feedbacks are in line with the previously identified potential of SIPRIUS+ (section 2). As a support to decision-making, it can simplify communication in an interdisciplinary manner (point 1) and it can facilitate the follow-up of objectives during the UBRP process (point 2). However, because the iterative step has not started, it is not yet possible to judge the benefits of SIPRIUS+ to foster a virtuous cycle of iteration of the UBRP in that regard (point 3).

4.2. Improvements

This pilot experiment constitutes an innovative way to implement operational monitoring of sustainability objectives into the dynamics of UBRP. Indeed, it presents the advantage to defer on different entities the tasks related to monitoring and evaluation, easing the workload. In the same time, the use of SIPRIUS+ is not imposed but slowly introduced to the external parties, i.e. the consortium. That way, it avoids drastic changes in the usual practice and enhances the tool probability to be adopted later in the procedure. However, we noticed that not all consortiums included monitoring principles into their proposition. The reasons for explaining this neglect must be further investigated (misunderstanding of the monitoring principles, downplaying of sustainability objectives importance, fear of work overload, etc.). In any case, it shows that operational monitoring still a novelty in current practice; the PAs documentation to come could include a more exhaustive explanation about SIPRIUS+ approach.

SIPRIUS+ has the potential to offer a framework to promote the dialogue between the different stakeholders and the sharing of responsibilities on the project. For the time being, the strategic implementation limits the online access to SIPRIUS+ to the COPIL urban planners team. It may have the effect that members of the consortium feel not fully implicated in the sustainability monitoring of the project. Depending on this consideration, we suggest as an improvement to include later on one member of the consortium as a user of SIPRIUS+. This possibility will be discussed with COPIL upon the first round of iteration.

5. Conclusion

The transition towards a more sustainable built environment is the way forward. Urban brownfields regeneration projects (UBRP) can contribute to this important transition challenge but are not inherently sustainable. A research project proposes an operational monitoring tool facilitating the transformation of urban brownfields into tomorrow's sustainable neighborhoods. Entitled SIPRIUS+, the tool was tested on case studies and the results discussed with the involved stakeholders. In order to face SIPRIUS+ to the reality of the practice and to its future end-users, an 18-month pilot experiment is now ongoing on the Gare-Lac neighborhood in Yverdon-les-Bains (Switzerland). It is based on the strategic implementation of SIPRIUS+ into the urban planning procedure. It constitutes an innovative way to implement operational monitoring of sustainability objectives into the dynamics of an urban brownfield regeneration project. It eases the workload related to monitoring and evaluation and slowly introduces the tool to external parties. Preliminary feedbacks confirm the potential of SIPRIUS+ to contribute concretely to the actual practice by offering new means to integrate and follow sustainability objectives. For the purpose of continuous improvement, further investigations are expected at the end of the pilot experiment, including the analyses of the monitoring results as a support to the decision-making process.

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Pocket Mannerhatten - City renewal on the basis of spatial sharing strategies, bottom-up participation and common good-based incentives

Niedworok F

Unterdorf 121, A 6135 Stans

fniedworok@gmx.de

Abstract. Cities worldwide and Vienna as well are facing an increasing pressure on space. Innovative strategies are required to tackle these challenges not only by creating new buildings but also by modernizing existing neighbourhoods. For decades Vienna counts on a gentle urban renewal approach. The question how to tackle new challenges, such as renewal towards energy efficiency, green spaces, alternative mobility or integration of multicultural lifestyles needs to be answered. The project Pocket Mannerhatten pursues the assumption that sharing building space across property outlines can offer an innovative approach for a city renewal. The spatial sharing is combined with a bottom-up-participation process and a compensation-oriented funding system. With the public funding program “Smart Cities Demo” (Austrian Climate and Energy Fund) a realization project will test the concept in Ottakring/Vienna. The multidisciplinary consortium accompanies the inhabitants realizing shared green spaces, community rooms, shared photovoltaic systems, car-sharing and Co-living apartments until the year 2021. In the future, these sharing and cooperation activities should become a city renewal strategy. Due to the slogan “who shares, gets more” and on the basis of a evaluated common good contribution not only monetary but also alternative, non-monetary incentives will be taken into account to foster urban renewal.

1. Introduction to the context and basic concept of the project Pocket Mannerhatten

What if the discourse about sustainability and resource-conscious thinking focus on an organisational approach of problem solving? What if we use our resources consciously in the way that we reorganize existing resources and share them? This essay will follow these questions as underlaying intention to discuss how creating links within an existing urban fabric can offer an approach to use space more efficiently and foster social networks. Urban developments with a growing number of inhabitants, increased land consumption and rising real estate prices clarify the necessity of a discussion about space as a common resource and about new concepts organizing it. The subsequent increased pressure on areas and spaces in cities, rising demand of affordable urban housing, public space and infrastructure as well as social changes and new claims for use and contemporary lifestyles underline this necessity and let municipalities and residents be challenged to find solutions.

As many other European cities, Vienna also faces these challenges. Innovative methods and strategies are required to tackle these challenges not only by creating new buildings but also by modernizing existing quarters in terms of ‘redensification’ or adaption for future needs. For example, the sharing economy creates innovative impulses in this discourse of resource consciousness and the real estate market already started to absorb concepts like co-living and co-housing especially for newly built urban structures [1]. The development and adaption of existing urban structures still needs to be addressed. Since the seventies Vienna counts on a gentle urban renewal approach which supported the development of numerous sub-standard Gründerzeit buildings [2]. Not only single properties but even clusters on the level of a city block with the aim to improve infrastructure, quality of semipublic spaces or too densely built neighbourhoods have been refurbished [3]. What still offers a potential development is the strategic implementation of specific spatial or functional links between properties creating new spatial qualities, uses and opportunities. The project Pocket Mannerhatten pursues the assumption that sharing building space, not only within but especially across property outlines can offer an innovative approach for a city renewal and create useful opportunities. This means that different building areas and functions are systematically linked to create synergies across property lines. Nonetheless it doesn't mean that land tenure and property rights has to be altered as it will be explained in the following. The 'sharing options' include merged courtyards or rooftops, linked green facades, elevators which are being used by occupants of several properties or collectively organized solar power plants or e-mobility solutions [4]. Furthermore the project concepts includes the assumption that spatial sharing opportunities needs to be developed through a participative planning process to create the necessary socialcultural preconditions for sharing. According to the project concept, the spatial sharing and participation process needs to be combined with a compensation-oriented funding system to foster the development and balance the possible additional effort of mediating and integrating further neighbouring stakeholders. All these issues and aspects are worked through by a multidisciplinary team together with the inhabitants of a city block, named "Block No. 61"(due to its serial number of all 260 examined cities blocks), in the 16th district of Vienna. The team aims to develop a pilot project for spatial sharing, a model for a suitable participation process and a public-benefit oriented system with alternative, non-monetary funding opportunities.

2. Characteristics of the urban fabric in Ottakring/Vienna

A significant portion of the built urban fabric of the Gründerzeit in Ottakring/Vienna is characterized by certain attributes which favour the opportunity to link built structures and its functions across their property outlines.

2.1. The street-network and parcelling of Gründerzeit quarters in Ottakring/Vienna

For example the street networks cuts out similarly shaped, rectangle building blocks measuring 120-125m in length and 60-65m in width. This comparatively continuous regularity is found also in the logic and size of the parceling subdividing the building blocks – see ´Figure 1´. The regularity supports the transferability of spatial solutions, for example worked out in a pilot project. The blocks contain mostly 12-16 parcels with the size of 400-500m² with a subdivision of 2 or 3 parcels on the narrow side and 3-5 parcels on the long side. This shows a quite small-sized, intensely structured parceling, for example compared to well-known communal housing complexes of the same time period, and is linked to the ownership structure. Mostly each parcel is owned by one or more private landlords.

It is obvious that the parceling causes a certain proximity of different entities of space, functions or use and question a potential interaction or connection between these different entities. Spatial connections between real estate require vicinity and adjacency. A property crossing rooftop terrace structure or circulation structure needs for example adjacency. A shared parking lot or different community rooms for recreational uses such as fitness, music or workshops and linked across the property outlines by shared access rights require vicinity.

The circulation and access system captures a specific role among all kinds of connections as it forms the precondition for connecting spaces. Austrian building codes demand a maximal length of 40m for the escape path to the exterior or nearest fire staircase. Gründerzeit plots in the examined district are most of the time around 20m to 30m long and only around 15m to 20m long, what shows, that the fire staircase outside of the regarded plot could be reached and connected circulation systems would be possible.

Figure 1. Aerial image showing the street-network and a closer view on the perimeter block fabric

2.2. Gründerzeit perimeter block and characteristic building types

Historic and present building codes defined the way of the perimeter block – see `Figure 1.´ which is characterized by a closed city block with each house adjoining the next one, bordering the street/pavement and forming a courtyard in the middle. The street line and building line unify façades on the side of the street and courtyard. In contrast the heights of the houses vary and also the way the courtyard houses are built as wings or additional single houses. Nevertheless this kind of compact, closed perimeter block offers spatial adjacency as promotive quality for connecting spaces and functions across plots. Although the built urban fabric is characterized by heterogeneity it allows to identify different types of buildings which are either repeated noticeable often or show similarities among them. Types of Gründerzeit buildings which are repeated are for example the corner building, street facing building without courtyard house, street facing building with single courtyard house, L-shaped building and H-shaped building.

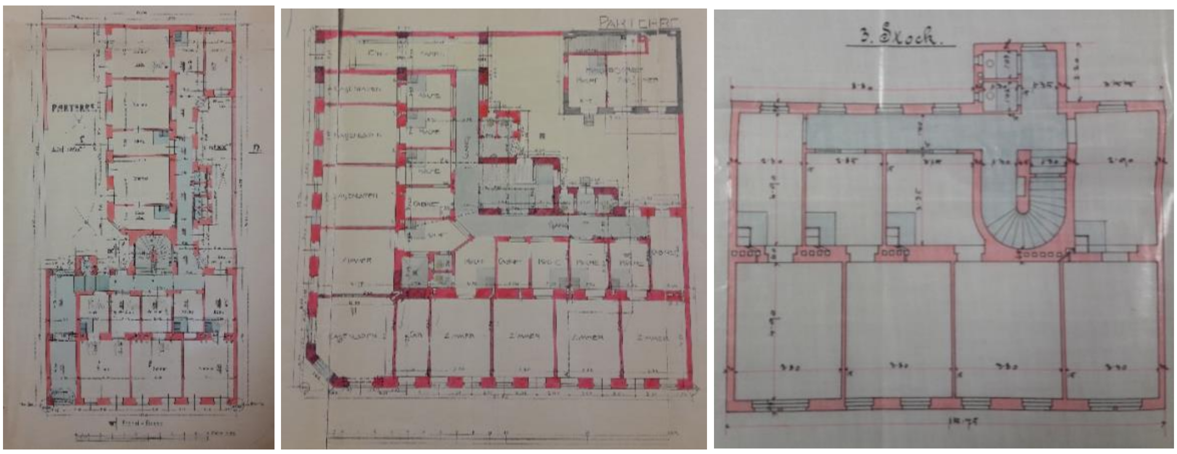

Figure 2. Several historical floorplans of Gründerzeit town houses with corridors blue-colored

In order to argue the capacity of the building structure to be linked the design of the circulation system should be highlighted, especially its positioning towards the courtyard – see ´Figure 2´. This aspects opens up the building to be extended through additional elements such as elevators staircase, bridges without interfering with existing floor plans of inhabited living units. Historically corridors offered shared facilities like water basins (Bassena) and small bathrooms with closets for the floor. In the course of refurbishment developments bathrooms and water supplies have been integrated into the living units and these small spaces had been repurposed. Today these small spaces are used as storage, space for technical equipment or are even empty. As they play no negligible role as functional addition to the living units they are to a certain degree detached and easier to transform then parts of the inhabited livings units. This creates a structural openness to dock on other spatial entities.

3. Opportunities of linking buildings and spatial sharing

Subsequently the question is what kind of connections and links within a built urban fabric can be considered.

3.1. Physical-spatial connections

Basically there can be defined links which have direct spatial impact when built definitions of space are altered in order to connect spaces and create or enlarge common space – see `Figure 3´. This could be: changed or new accesses, linked floor plans creating co-living flats, united roof terraces or courtyard gardens with removed fences and walls or newly built neighbourhood garage.

Figure 3. Floorplans with different physical-spatial connections on the basis of a common circulation

3.2. Functional connections based on access rights

Links between buildings can be created also by changing the logic of access rules and users domain while preserving the existing built structure. This establishes a functional bonding of neighbouring real estate. This bonding could be defined unilateral, for example one house offers a community room to the neighbours, or multilateral, for example two or more houses exchange the access rights of their community rooms.

3.3. Technical-functional connections of building services

Another category of connection is a pure technical-functional one, which means that technical building services such as heating, ventilation, air conditioning and energy supply are connected among parts of the city block. So far as it is possible to generalize these technical-functional connections they imply either an increased efficiency with scaled size of the technical facilities, for example photovoltaic systems. Or otherwise the increased diversity of the extended user group leads to an intensified utilisation of the system, for example when a commercial unit with peak energy consumption during daytime is combined with a living-unit with peak energy consumption beside working hours and on weekends.

3.4. Connections based on spatial references

Further on another category can be defined by sharing moveable goods which have a distinct spatial reference, for example cars, cargo bikes or partly temporarily built structures in public space like pocket gardens. Not necessarily space itself is shared but utilities for which space is needed. The shared use of these utilities can enable changed space requirements when for example cars and parking lots per inhabitant can be reduced on the basis of a car sharing pool.

3.5. Communication networks referred to a specific space

The fifth category which can be mentioned in this argument is the social network and its capacity of interaction, cooperation and communication. Primarily it is not about space, but about inhabitants, users and all other stakeholders referred to space and about their connections and interactions which impact space. An intensely linked neighbourhood will organized and cooperate in a complete different way the inhabitant space then the opposite. This last category underlines how crucial and significant the incorporation of sociocultural aspects is in this context.

4. Sociocultural constraints of linking and sharing space

Beside the mentioned spatial constraints of the urban fabric the sociocultural constraints for sharing are key. In an initial phase of the project Pocket Mannerhatten the analysis of the political administrative system including funding programs, stakeholders in real estate economy and house owners' motivation and action strategies of administrating their real estate helped to understand these constraints [5].

4.1. Constraints of the political-administrative system

The logic of the political administrative system and connected with it the mostly complex logic of permissions and funding programs considers either a single real estate or a single owning entity. It is obvious that the proprietorship form the basis of these socio-political constraints and consequently the proprietor owns the power of decision how buildings can be linked in terms of physical-spatial links of category 3.1. Especially all provisions which change space physically or the technical building services needs the approval of the landlord or if it is a group of landlords at least the majority of landlords. This doesn't mean that tenants inhabiting the real estate don't have opportunities to participate in sharing and linking real estate, but in a different way regarding the previously mentioned categories of sharing opportunities.

4.2. Intention and motivation of landlords as initiators

Therefore it is necessary to understand also what landlords motivates to share space or connect their real estate with each other. Due to the analysis done by Witthöft G and Hölzl D landlords can be differentiated in their way of managing real estate into twenty types. Among these action types there can be found for example “the Big Player”, large international profit orientated real estate companies without local bonds, “the Traditionals”, which live in their real estate, avoid change and new ideas, and regard the financial return as secondary or “the Motivated”, which inherit recently real estate, are young, decisive and eager to improve their real estate. The analysis shows that there are specific types of landlords which form a group characterized by a probable distinct openness and willingness to commit themselves to an intense dialog and negotiation for synergies or social qualities. In the research area “Block No 61” four landlords of the seventeen houses decided to take part in the current implementation project and work out solutions of sharing space. Three of these four use their property as either principal or secondary residence, which leads to the interpretation that inhabiting the real estate let a landlord be more probable to consider a variety of qualities and be open for alternative possibilities such as sharing space in a neighbourly network.

At the same time two fundamental motivations of sharing can be considered: one which is rooted in voluntariness and lifestyle culture and one which is rooted in economic benefits and necessity. Although sharing can enable economic benefits for the participants it should not deceive that the process of negotiation and communication to reach an agreement among the participants could be time- and consequently money consuming. If the participants organized themselves it requires respective abilities of communication and negotiation to establish a required foundation of trust, understanding, fairness and cooperation. At best there exists already suchlike environment in the neighbourhood. The examined neighbourhood network of “Block No 61” indicated a minor developed contacts across different real estates which is represented by two statements of landlords.

One landlord acknowledged after participating in one of the Pocket Mannerhatten workshops that she always considered the space defined by the walls of her apartment thinking of her apartment. After participating in the workshop she rather considers not only the building containing her apartment but the whole city block or neighbourhood. Another landlord living for years in his house stated that he would accredit the project Pocket Mannerhatten being a success already before something is built because he never got in contact with so many neighbours. The last statement makes also clear that mostly extrinsic impulses and professional support -not only in technical fields- can be needed to enable an initiative.

5. Enabling and fostering a renewal process based on space sharing

As explained in the paragraphs before, although the urban fabric offers preconditions which favour spatial connections of different categories and although there can be found landlords who are willing to develop and realize these spatial connections as decision-makers, some kind of incentives and promotion must catalyse the development. On the one hand more stakeholders makes the development process more complex and expensive and on the other hand there comes along a certain uncertainty of control with more stakeholders, especially in neighbourhoods with a high degree of anonymity. The question arises in which way the development can be catalysed.

In order to activate and address possibly interested landlords the project consortium Pocket Mannerhatten developed a certain concept of participation to be multiplied. This concept includes several steps of involvement in interviews, site inspections and workshops containing also a role game in form of a board game to experience or learn about spatial sharing strategies on the basis of a Gründerzeit city block.

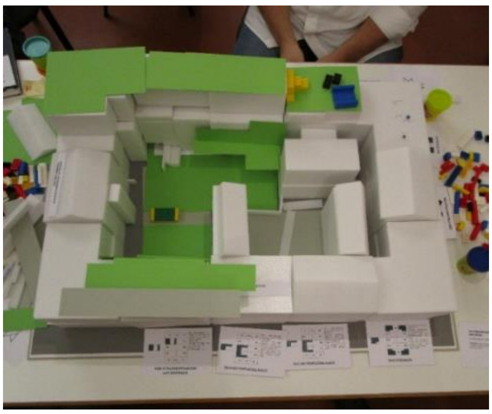

Figure 4. Impressions of a workshop with landlords playing a board game for spatial sharing

5.1.The role of Viennese institutions fostering city renewal processes

Traditionally the Viennese quarter management “Gebietsbetreuung Stadterneuerung” as key element for the gentle way of city renewal had been in charge of fostering different bottom-up city development initiatives and the question would be if this process could be multiplied through this institution. As public institution it is open to all residents and offers professional services of architects, city planners, lawyers and social workers. The local city quarter offices provide consultation and information regarding tenancy and building law, subsidies, refurbishment, initiatives in public space and coordinate participation processes as well [6]. Since the nineties the initial thirteen local offices, each responsible for certain districts, had been reduced continuously. Since January 2018 the remaining eight local city offices had been reduced to five local offices being in charge still for the whole area of the city of Vienna [7]. Against this background of economized, down-scaled public institutions it seems doubtful that existing public institutions such as “Gebietsbetreuung Stadterneuerung” might involve in additional areas of responsibility.

Another -partly public- institution is the non-profit organisation “Wiener Wohnfonds”, which is in charge of the city refurbishment as well and coordinates residents, property developers and city administration units. In contrast to the “Gebietsbetreuung Stadtsanierung” the “Wiener Wohnfonds” executes different funding programs for refurbishment and is less involved in local neighbourhoods. Interestingly these refurbishment funding programs know a across properties coordinated strategy for deconstruction of too densely built building structures as a special case to fund, but not as core strategy differentiate into different possible provisions. Both institutions represent required catalysts for the development: initiative, know-how and financial resources.

5.2. Alternative approaches and concepts for fostering city renewal

The project Pocket Mannerhatten follows two research questions in this context: is it possible to develop a non-profit or social business which complement the services of the “Gebietsbetreuung Stadterneuerung” in order to implement space sharing strategies beyond the pilot project and can there be found alternative resources other than financial one which help to foster the development as well.

The Viennese practice of urban contracts in the field of newly built housing and commercial complexes gives the opportunity to negotiate different special permission and to certain obligations benefiting the public. It is interesting to analyse that not only financial incentives are key to foster urban development, but also incentives which belong to the field of permissions, regulations or other provisions organized by public authorities. For somebody who would like to start a commercial unit it might be more important to be allowed to locate it at a certain place and if it is proved that existing restrictions count also for the individual situations. For somebody who builts housing units it might be interesting to be allowed to built one floor more or balconies facing the street to make a refurbishment attractive and profitable due to rising land prices. For someone who wants to establish a retail unit in a densely built area it might be valuable, if the public space around the unit offers parking lots for customers. For a group of residents who wants to organize electric car sharing it might be interesting to have a public recharging station and so on. For the city council and urban planning this approach would not only amplify possibilities of incentives for developments and let financial resources be spared but establish a steering mechanism as well.

Critical is to find a transparent, just and accredited method to evaluate, rate and assign these alternative incentives as there is no legal foundation or law in Austria which declares to assign certain alternative incentives for space sharing. The project Pocket Mannerhatten assumes that each provision for space sharing generates value or positive impact not only for its single real estate but also for an extended area or group of people. Of course this might differ dipending on the kind, on the scale and duration of provisions.

The ongoing project Pocket Mannerhatten proposes the term “common good potential” to discuss the additional value of linked real estates and space sharing addressing an area and a group of people beyond a single real estate and addressing the most extensive possible consensus what might be the “common good”. The logic of the term implies that not only any provision for space sharing which causes a wider area or group of residents to benefit or any provision which enables a more extensive consensus about the common benefit is ranked higher in a possible evaluation. But it considers the aspect of community itself with all its constraints such as justice and solidarity. It does so by defining how or what is understood as common and to what kind of community it refers, might it be the neighbourhood, the quarter or the whole city. By doing so the process of definition creates community and correspond to the spatial provision of linked buildings fostering interaction and cooperation of residents.

Is it used as basis for assigning incentives or funds this logic would lead to a kind of self-organizing domino-dynamic. The more areas and people participate, the more their provisions orientate towards contributing to the common good, the more intense will be the incentive. It is subject of the ongoing project Pocket Mannerhatten to research and develop a concept how space sharing provisions will be evaluated and opposed to possible incentives. Through different workshops, interviews and negotiations together with stakeholders of the city administration and participating landlords this common good based incentive system should be tested in the course of the project. According to the development of the project Pocket Mannerhatten as pilot project the concept with all its aspects should be integrated into the city renewal strategies of Vienne or multiplied to other cities.

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Modelling of a sanitary landfill for developing countries to improve the reliability of Life Cycle Assessment studies

Gutierrez K G[1], Fernandes M A O[2], Chernicharo C A L[2]

[1]Federal University of Amazonas. Rua 29 de Agosto, 786 - Centro, Humaitá - AM, 69800-000.
[2]Federal University of Minas Gerais. Av. Pres. Antônio Carlos, 6627 - Pampulha, Belo Horizonte - MG, 31270-901.

katiaggutierrez@hotmail.com

Abstract. In developing countries, such as Brazil, the main destination of municipal solid waste is sanitary landfills. In Life Cycle Assessment (LCA) studies, the entire life cycle of the product or process is considered, therefore it is necessary to take into account the destination of the waste and by-products of the process in question. For a reliable and representative LCA study, these destinations have to be illustrative of the place where the study is conducted in. Regarding the treatment and disposal of organic solid waste, the main LCA databases, such as Ecoinvent 3.0, consider sanitary landfills modelled in European standards, which include processes that are not common in developing countries. In light of this reality, the aim of this study was to model a sanitary landfill that corresponds to the case of the said countries and provide a methodology to improve the significance of environmental studies, which can also be used with primary data. The model used literature data based on Brazilian reality, considering the operation of the landfill (transport and emissions and diesel usage in the spreading of the waste); biogas generation and treatment; leachate generation and treatment using stabilization lagoons and its emissions. When compared to landfill based on European reality, differences up to 80% can be observed in some potential environmental impacts.

1 Introduction

In Brazil, solid waste management is defined according to National Solid Waste Policy, instituted in 2010, which establishes principles, goals and responsibilities in this topic [1]. Among its main points, there is the elimination of open dumps, which is an inadequate waste destination, where there's no control over the type of waste deposited or the generation of byproducts. The utilization of open dumps as a final destination for solid waste leads to high damage to the environment and the surrounding communities.

These irregular dumps were the final destination of 68% of the municipal solid waste (MSW) in 2000 and 49% in 2008 [2]. The law that created the Policy determined that from 2014 the use of open dumps would be prohibited, but the waste from 1.560 municipalities, which represents 28% of the total number, still had the dumps as final destination [3]. Although this movement promoted more sustainable processes such as recycling, it still has low representation in the national waste destination scenario, given that only 32% of all produced recyclables were retrieved in 2017 [3].

Faced with this situation, the reduction in the number of dumps was followed by the increasing in sanitary landfills participation as final destination of the MSW, going from 17% in 2000, to 29% in 2008 and 40% in 2017 [2, 3]. Landfills are a common destination in developing economies and they seek the minimization of environmental impacts through soil waterproofing, construction of drainage and collection systems for biogas and leachate while it also has to have a joint closure plan and use for the area after its service life. These landfills aren't, however, designed to receive only inert waste, but also MSW, which in Brazil has the approximate content of 51% organic matter [2]. The degradation of these residues with high percentage of organic matter in the landfill leads to the production of by-products such as leachate and, above all, biogas, which can be harnessed energetically, although it is still incipient in the country [1].

As a way of comparing possible waste management strategies, there's the Life Cycle Assessment (LCA). This methodology is used for quantification of environmental impacts related to a product of service through the inventory of its used resources, waste generated and emissions in the complete life cycle of the product. The LCA allows the identification of hotspots, scenarios tests and comparison of alternatives, consisting of an important environmental management tool. An critical step of the LCA is the Life Cycle Inventory (LCI), where the inputs and outputs of the analyzed process are identified and quantified. Subsequently, the data present in the LCI will be converted into impact potentials. Therefore, special attention is needed at this stage because it will be determinant for the results and consequently for the conclusions of the study.

In order to consider the complete life cycle of the product or service, it is also necessary to consider the destination of the waste generated, and for this study to be representative, it should be illustrative of the place where the study is conducted. However, the application of LCA to evaluate the environmental performance of solid waste management systems is still elementary in developing countries [4, 5]. Given that the systems presented in studies from developed countries may not be suitable for developing countries [5], mainly because of differences in waste characteristics and because they include steps and processes that are not part of their realities, there is a clear need for more studies on the management of solid waste in the developing world. Currently, the work in this subject is concentrated in Asian countries [6].

The literature review conducted by Ibáñez-Forés *et al.* (2018) identified researches involving solid waste management in Brazil and showed that the vast majority of them didn't national data. Among the studies cited, Mendes *et al*. (2004) and Ibáñez-Forés *et al.* (2018) inventoried sanitary landfills using European data [7, 8]; The work of Reichert *et al*. (2014) also compared waste destinations and the modeled landfill was from a large municipality, where there is energy generation and commercialization from the biogas produced, which would not be applicable to small municipalities [9]; and the work of Leme *et al.* (2004) focused only on the generation and use of landfill biogas, using data from the Intergovernmental Panel on Climate Change [10].

The sanitary landfills available in LCA softwares are not compatible with Brazilian reality either, since processes modeled by the European Life Cycle Database (ELCD) and Ecoinvent 3 follow European standards. In the first one, for example, the considered treatment of leachate is through the use of activated carbon and flocculation techniques, and the second one considers the incineration of the sludge generated in the leachate treatment. None of these methods are representative in the Brazilian scenario and the use of these processes in a LCA study would not lead to a verifiable result.

Given the large number of Brazilian municipalities, 5.570, the number of sanitary landfills, 2.239 [2] and the growing trend of this number given the current national policy, it becomes increasingly necessary to access a landfill model for the implementation of other LCA studies, in order to produce results that are more representative of the country's reality.

Therefore, the goal of this work is the establishment of an emission quantification methodology to be reported in LCA softwares. Based on the characteristics of landfills located in small Brazilian municipalities and the commonly adopted waste management technologies, a life cycle inventory of a sanitary landfill was constructed, capable of better matching the reality of Brazil and other developing countries, to improve the relevance of LCA studies. The modeled process includes the operation of the landfill (transportation, fuel consumption in the disposal and compaction of the waste), degradation of the solid waste, generation and treatment of biogas and leachate. The implantation and decommissioning of the landfill were not considered.

2 Materials and methods

2.1 The LCA methodology

LCA is used to assess potential environmental impacts related to a product or process through the inventory of its resources, wastes and emissions. As a management tool, LCA makes it possible to compare the technical aspects and environmental performances of alternative scenarios, and to identify hotspots as well as opportunities for improvement in the life cycle under study.

As described in ISO 14040 (2006), an LCA study is organized in four stages [11]. The goal and scope definition stage addresses the purpose and scope of the study by establishing the system boundaries. The following items should be described: the goal of the study, the processes included and what basis is to be used, for example, the functional unit. The second stage is the life cycle inventory (LCI), which consists in the identification and quantification of the inputs and outputs of each unit process that takes place within the established system boundaries. In the impact assessment stage, the inventory is converted into environmental indicators for the impact categories that will vary depending on the method used. The final stage includes analysis of the results and assessment of conclusions based on the points mentioned in the definition of the goal and scope.

The present work focuses on presenting the LCI of a sanitary landfill that can be applied to small municipalities in countries under development so they can be used in LCA studies to improve its reliability.

2.2 Methodology for the construction of the Life Cycle Inventory of the sanitary landfill

In this stage, the sanitary landfill was inventoried with the methodology first developed in Gutierrez (2014) [12]. Since Brazil is a country of continental dimensions generalizations were made necessary based on nation-wide data to guarantee its significance. The landfill is equipped with systems to capture and treat the biogas (flairing) and leachate (in a system composed by an anaerobic lagoon followed by a facultative lagoon. A flow diagram of the process is presented in Figure 1.

Literature data focused on landfills for small municipalities was used to calculate the inventory for the processes considered in Figure 1, given that the goal of this study is to provide a general landfill model. However, if primary data is available, the methodology here presented can also be used to estimate the inputs and outputs, which would help to provide a more reliable result in specific situations.

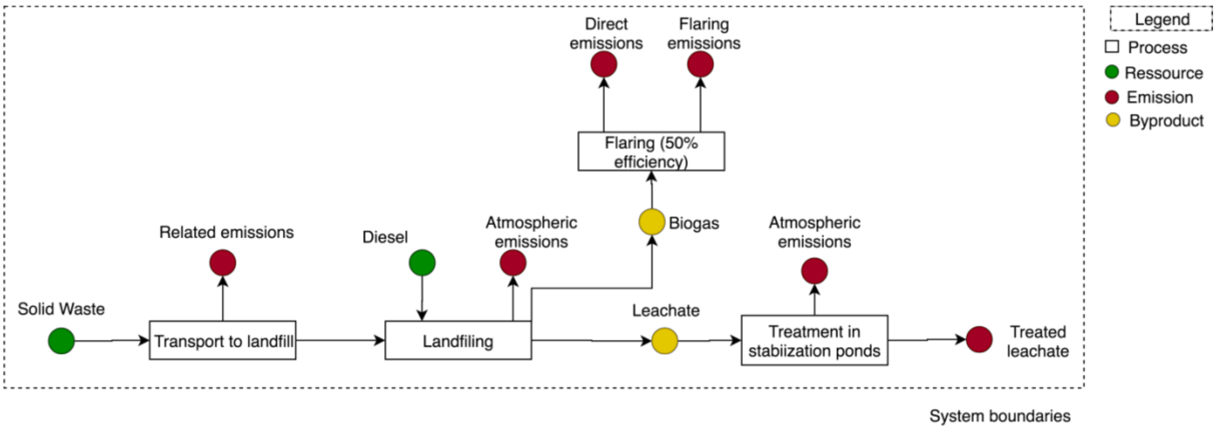

Figure 1: Landfilling flows diagram

2.2.1 Waste transport to landfill

The first stage considered is the waste transportation from the urban center to the landfill. The exclusive use of trucks (3,5 tones of load capacity) and the way-and-back distance was estimated to be 15 kilometers, which was considered to be a reasonable distance for a small municipality. The emissions related to the transport were reported within the software in the unit tkm – that includes the mass transported (in tones) and the distance travelled (in kms)

2.2.2 Waste spreading and compactation

These emissions refer only to the operation of the landfill, specifically to the stages of waste spreading, compacting and covering. The diesel consumption was taken into account according to Rodrigues *et al.* (2008), which measured the average use in a municipality with 25.000 inhabitants and the atmospheric emissions due to the diesel burning in the dump truck and the bulldozers used in the landfilling and covering of the waste [13, 14].

2.2.3 Methane generation

The methane production was calculated according to the degrading of biodegradable matter present in the solid waste. The estimated percentage of organic matter in brazilian MSW is 50% and 60% average moisture content. A 60% destruction of volatile solids (VS) in this MSW during landfilling is stated under a density of 237 $kg.m^{-3}$, following the production of 0,25 m^3 $CH_4.kg$ VS^{-1} [15]. It's then possible to calculate the biogas volume, considering the average methane content of 55% [16].

2.2.4 Direct air emissions

It was considered that 50% of the biogas produced was not captured by the drainage system, therefore released as direct emissions to the atmosphere [17, 18]. The biogas characterization presented in Tchobanoglous *et al.* (1993) was used, as it is in accordance with national experiences [16, 19].

2.2.5 Flaring emissions

A 50% efficiency was also considered for the flaring [20]. The losses were taken into account as methane emissions and the emissions deriving from the burning were based in the emission factors presented in Beylot *et al.* (2013) [21].

2.2.6 Leachate production

The software 'Water surplus for sanitary landfills' provided by the Brazilian National Institute of Meteorology (INMET) was used to estimate the leachate volume produced in small-sized landfills [22]. It was observed that in most simulations the water surplus represented approximately a quarter of local precipitation, so this percentage was used. This rate is also in accordance with the estimations proposed by the Swiss method of leachate prediction, based on the degree of compaction of the waste is its specific weight [23].

A mean annual precipitation of 1.500 mm was considered, disregarding other contributions and losses. The Environmental Company of the State of São Paulo (CETESB) indicates that for small municipalities the construction of the landfill using ditches is acceptable and even advised, so a depth 3 m for the ditches was estimated [24]. Using this data and the waste specific mass of 1,05 $ton.m^{-3}$, the necessary surface for landfilling a ton of waste would be 0,317 m^2. The water surplus of 375 mm (25% of the average precipitation considered) produced 0,375m^2 of leachate for every m^2 of landfill, or 0,119 m^3 of leachate per ton of waste landfilled.

2.2.7 Leachate treatment and emissions

The emissions to water refer to the leachate produced in the landfill after treatment in an Australian lagoon system (composed of an anaerobic lagoon, with a height of five meters and followed by a facultative lagoon, with a height of two meters), which is commonly used in the country. The large amplitude observed in the leachate composition data in national landfills led to the adoption of values related to a real landfill, located in the State of Minas Gerais, aged 1,7 years. A sanitary landfill with an approximate age of two years was considered since it is believed that, under Brazilian climatic conditions, landfills of that age are already close to stabilization in terms of biodegradability [25].

The efficiencies found in the treatment of the treatment ponds indicated values well above those proposed by von Sperling (2014) for the Australian lagoon system [26]. Dias (2012) shows in her research that the water retention time of the leachate in the real landfill was high, arriving, at some times of the year, to a value 15 times greater than the one of design, and discusses that this situation is common in the country [25]. In view of this uncertainty and in search of greater significance for the simulated landfill, it was chosen to follow the efficiencies suggested by von Sperling (2014), for the system which, although originally developed for domestic sewage treatment systems, has been a reference for leachate treatment projects.

The atmospheric emissions from the treatment of leachate were considered according to the International Panel on Climate Change (IPCC, 2006), which reports them in the form of methane emission] These emissions are presented as a function of the BOD removed by the systems (in kg BOD), pond height and maximum methane production capacity for domestic sewage (0,6 kg CH_4 .kg BOD^{-1}).

3 Life Cycle Inventory of the Sanitary Landfill

Table 1 presents the Life Cycle Inventory of the modeled sanitary landfill. The table refers to the landfilling of 1 ton of MSW.

Table 1: Life Cycle Inventory for a sanitary landfill

Process	Input/Output	Parameter	Unit	Value ($t.waste^{-1}$)
Landfill transport	Input	Solid waste	ton	1,00
		Distance	km	15,00
		Transport	tkm	15,00
Landfill operation (spreading/compating)	Input	Solid waste	ton	1,00
		Diesel	kWh	4,32
	Output	Biogas to flaring	ton	75,00
		Biogas as direct emission	ton	75,00
		Leachate	m^3	0,38
		CO - diesel burn	ton	3,59E-06
		NOx - diesel burn	ton	7,78E-06
		Particulate matter - diesel	ton	7,78E-08

		burn		
Biogas direct emissions	Input	Biogas as direct emission	ton	37,50
	Output	CH_4	ton	2,50E-02
		N_2	ton	9,08E-04
		NH_3	ton	2,27E-04
		CO	ton	4,54E-05
		SO_2-	ton	2,27E-04
Biogas flaring	Input	Biogas to flaring	ton	37,50
	Output	CH_4 - leak before flaring	ton	0,01
		NO_x	ton	6,51E-06
		CO	ton	7,60E-06
		Particulate matter	ton	2,45E-06
		SO_x (as SO_2)	ton	8,00E-05
Leachate treatment	Input	Leachate	ton	0,38
	Output	Treated leachate	ton	0,38
		CH_4 leak	ton	1,37E-05
		BOD	ton	3,82E-05
		COD	ton	9,12E-05
		TSS	ton	1,77E-05
		N-NH_3	ton	2,02E-05
		N-org	ton	1,50E-06
		P	ton	6,19E-07

4 Discussions

The inventory in Table 1 was inserted in the software SimaPro and analyzed using the ReCiPe 2016 method. The impact categories were chosen based on which ones would better demonstrate the processes involved in landfilling, such as diesel usage, transportation, emissions to air and water. Finally, the chosen categories were global warming, fine particulate matter formation, terrestrial acidification, freshwater eutrophication, and terrestrial and freshwater ecotoxicity. The results are presented in Figure 2.

As it can be seen in the graphs, the biogas leaks represent most of the impacts related to air emissions. The transport is responsible for the vast majority of the impacts related to ecotoxicity. which can be related to distance in which landfills are usually located. The potential impacts in eutrophication are mainly caused by the leachate treatment.

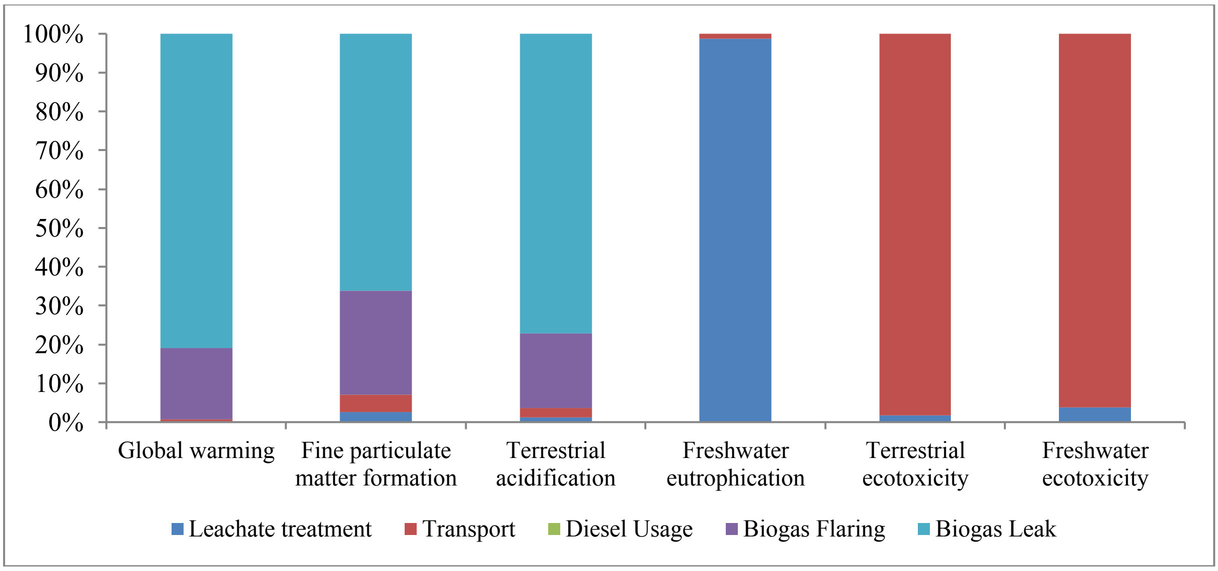

Figure 2: Sanitary Landfill analysis

Figure 2 presents the comparison of the modeled landfill with the one present in Ecoinvent v3 (*Municipal solid waste {RoW}| treatment of, sanitary landfill | APOS, U*). According to the information available on the database, the process considers the technology available in Switzerland in 2000 and includes short-term emissions to air via landfill gas incineration and landfill leachate; burdens from treatment of short-term leachate in wastewater treatment plant, including WWTP sludge disposal in municipal incinerator; and long-term emissions from landfill to groundwater after base lining failure [28].

The differences between the potential impacts of the two processes are visible in the graphs. The destination of the by-products, especially of the sludge, is a big difference between the models. According to the studies of Dias (2013), the Australian lagoons system design, initially intended for the treatment of domestic sewage, function mainly as an evaporation tank, with no sludge production in the bottom of the lagoon [25]. Sludge treatment, therefore, was not considered.

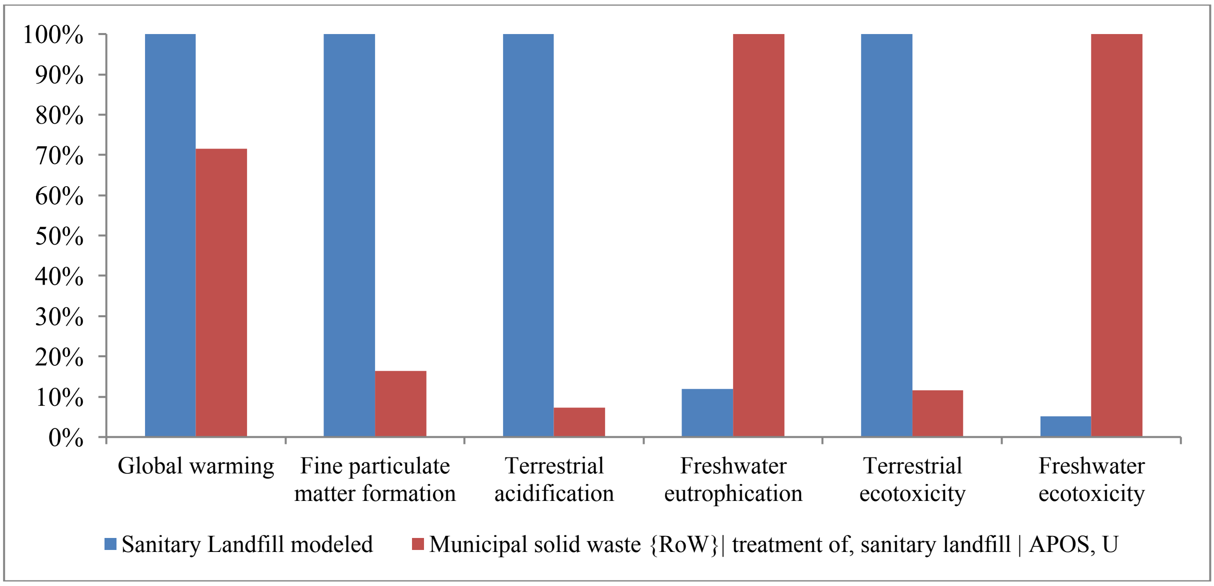

Figure 3: Comparison between the landfill modelled and one available in Ecoinvent 3

5 Conclusion

This work presented a model of a sanitary landfill that would correspond better to the reality of developing countries, especially in Latin America, aiming to improve the reliability of LCA studies. The life cycle inventory is based on average Brazilian data and literature data concerning the processes considered, focused on sanitary landfills for small municipalities. The methodology is adaptable to specific cases and can also be used with primary data to estimate emissions and environmental impacts.

When compared to a landfill available in the LCA database Ecoinvent v.3, based on European data, differences between the two could be observed. Regarding, fine particulate matter formation, terrestrial acidification, eutrophication and terrestrial and freshwater ecotoxicities, the difference in potential environmental impacts was greater than 80%. As for global warming, the difference was around 30%. These observations illustrate disparities between waste management technologies and how the usage of either systems can shift the conclusions of an environmental study, reaffirming the need of a representative model to estimate the environmental impacts of such technologies.

6 Recommendations

- Collection and use of primary data over literature data to improve the significance of the model.
- The consideration of leachate leaks to groundwater and soil.
- Obtaining regionalized data for the study site.

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Bike Model District “Alte Neustadt” in Bremen

Dietz J, Hoppe M, Kollmann S, Mansfeld U

School of Architecture Bremen, City University of Applied Sciences,
Neustadtswall 30, 28199 Bremen, Germany

justus.dietz@hs-bremen.de

Abstract. How to transform existing urban structures into zero emission cities by 2050 - especially if money is rare? The School of Architecture Bremen (SoAB) at the City’s University of Applied Science have initiated an innovative and collaborative project for the further development of the university’s neighbourhood, the “Alte Neustadt”. SoAB participated in the national climate protection by bicycle traffic competition and was granted funding for the transformation of the district into Germany’s first bicycle zone. In cooperation with the city district, NGO's, cultural institutions, and other neighbourhood organisations, a network of bicycle streets in connection with new bicycle highways will be installed. By 2020 comprehensive new bicycle parking areas will be finished, as well as new cyclist and pedestrian friendly crossings over the main roads. The campus’ main street will be transformed into an “Open Campus” for the university and the neighbourhood. A multifunctional “Bike Repair Café” with cargo bike sharing and bike rental facilities will enhance the district’s transformation even further, thus creating a space to reflect environmental problems to be solved. The bike model district “Alte Neustadt“ is just a small step in the right direction, but a huge improvement of the district’s quality of life.

1. Introduction

Bremen was among the first cities in Germany to establish own cycle paths (Froitzheim & Lüers, 1988). The idea of bicycle boulevards – roads on which cyclists have the right of way – found its origin here and spread all over Germany.

Today, the people of Bremen use their bikes for one in four journeys. This means that the proportion of journeys made by bicycle in Bremen is well above the average of comparable cities such as Dresden, Dusseldorf, Frankfurt am Main and Leipzig (SUBV, 2013). Looking at the top ten list of bicycle friendly cities 2017, however, Copenhagen, Utrecht and Amsterdam lead the list, whereas Bremen is not even mentioned. A recently carried out study by the German Cyclists' Federation (ADFC) illustrates the German bicycle dilemma: Bremen is rated as the most bicycle friendly German City, compared to other Cities with an equivalent number of inhabitants (ADFC, 2018). Rated according to the German school grading system Bremen reaches a 3,5, which means something between “satisfying” and “enough”, far away from “excellent” or just “good”.

Things, however, are starting to change: in 2016, one of Bremen’s central districts “Alte Neustadt”, applied for funding to become Germany’s first bike model district on an initiative by the School of Architecture Bremen (SoAB). The application was supported by the municipality, NGO's such as the General German Bicycle Association, cultural institutions e.g. the local swimming pool, and other neighbourhood organisations.

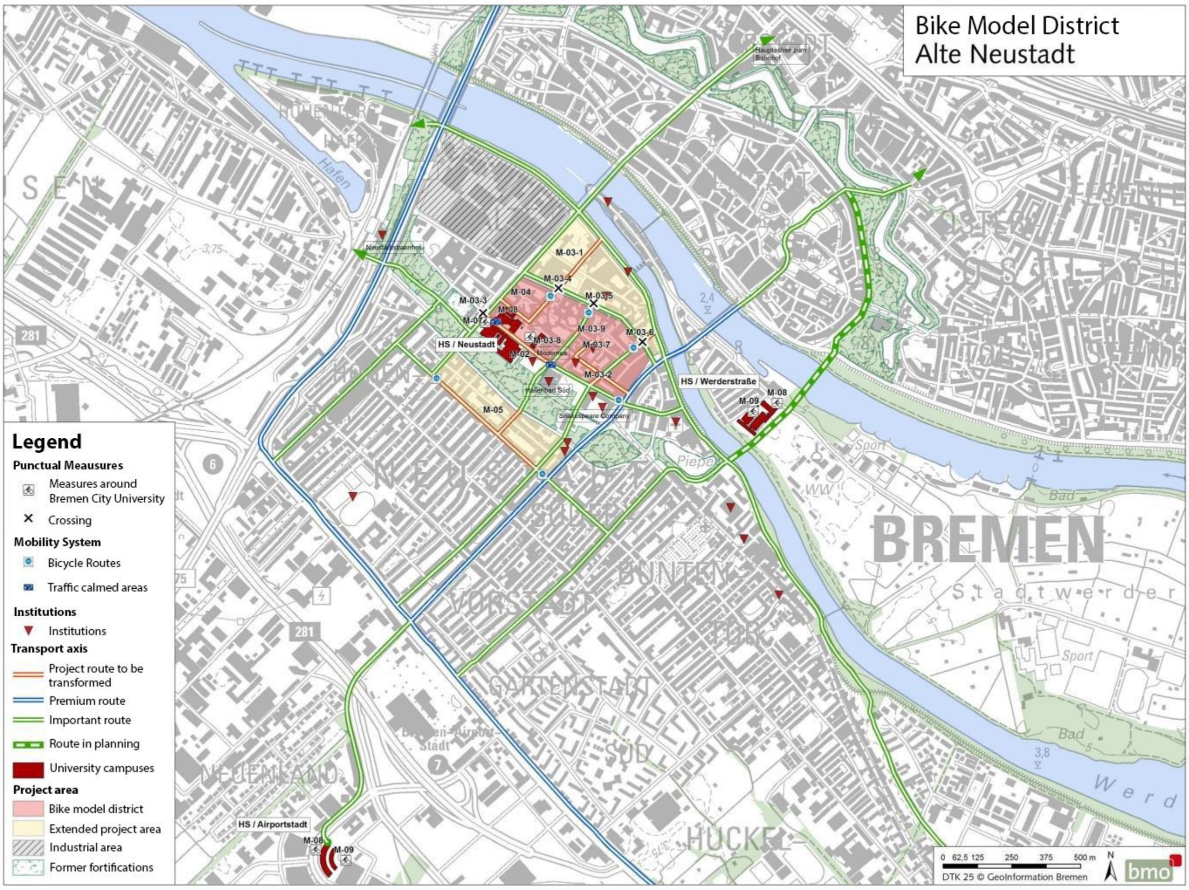

Figure 1 Bike-Model-District “Alte Neustadt” Bremen

2. Bike Model District “Alte Neustadt”

2.1. Objectives of the Bike Model District

The transformation of “Alte Neustadt” (Figure 1) into a bicycle zone aims to bring improvements not just for cyclists, but for all road users and residents by offering a coherent network of bicycle lanes, parking facilities, uniform signage and other facilities in order to make cycling the preferred mode of transport.

2.2. Ten Measures to be taken

In order to achieve equal mobile coexistence of the different traffic and interest groups in the district the following individual urbanistic and structural measures have recently been realized, constituting the new bike-model-district:

- *Bump-free Cycling*

Bumpy cobblestone streets get a paved strip or are completely redeveloped. Driving becomes quieter, safer and more comfortable for everyone.

- *Bicycle Boulevards*

Within the bike model district, a network of bicycle lanes becomes a cycling zone where bicycles are given priority over motorized private transport. Cyclists are allowed to cycle side by side, the general speed limit is 30 km/h, and car parking is clearly marked.

- *Network of Premium Bicycle Routes*

Bremen's traffic development plan for 2025 suggests several premium cycling routes within the city area These will connect the city districts over long distances, making them more attractive for cycling. The "Alte Neustadt" will be well connected to this premium route network, motivating especially students to come to university by bike (Figure 2).

- *More space and safety due to pavement enlargements*

Sidewalk enlargements at intersections and junctions and intersections make crossing safer for everybody, especially for younger children or slower people, by providing a better overview. At the same time, they keep the junctions free for larger vehicles of the fire brigade, refuse collection and delivery traffic (Figure 3).

- *Safe and Easy Crossing of Main Roads*

The crossing of the main roads on the edge of the bicycle zone will be facilitated for pedestrians and cyclists by measures such as pedestrian refuge islands, traffic signals and speed limits.

- *Bicycle Parking*

In the residential streets new bicycle parking facilities provide safe parking. At the City University's 3 campuses easily accessible and partly covered bicycle parking spaces will be created. In total, over 600 secure bicycle parking facilities will be installed.

- *Bicycle Repair Café*

A bicycle repair café will be built on the City University's Neustadtswall Campus. Housing a serviced workshop, a café, and space for small events, it will be the highlight of the bike model district. Addressing not only the students, but all interested people and cyclists, it connects the university campus with the neighbourhood (see 0for more detail).

- *Remodelling Neustadtswall Campus*

The main connection between the different university buildings, Neustadtswall, will be the centre of a redesigned campus. A raised road surface, the renovation of the sidewalks and a traffic-calmed area ensure an accessible and pleasant environment for more than 10,000 students and employees.

- *Rental Stations for Bicycles and Cargo Bicycles*

All three university campuses will be provided with rental bike stations that are connected to a city-wide rental bike network. The bikes, along with cargo bikes available at the Bicycle Repair Café, can be rented by everybody.

- *Air Pump and E-Bike Charging Stations*

Air pumps and e-bike charging stations will be built at all three university campuses, integrated into the covered bicycle parking facilities.

Figure 2 Network of Premium Bicycle Routes

Figure 3 pavements enlargements at crossings

This bundle of measures is expected to increase the percentage of students and university staff that come by bike every day as cycling will be far safer and thus more attractive in the future. Especially the cargo bikes provided at the Bicycle Repair Café will help to reduce the number of journeys usually carried out by cars, e.g. when students need to buy beverages for the next campus party.

3. The Bicycle Repair Café at Neustadtswall Campus

3.1. Intention

The heart of the Bike-Model-District will be the new Bicycle Repair Café at the City University of Applied Sciences' Neustadtswall campus. It will be completed by summer 2019. It will primarily serve as a meeting point for cyclists, not only for the university itself, but the surrounding neighbourhood as well. Visitors will find professional assistance for minor bicycle repairs. In addition, the Bicycle Repair Café will serve as a place for research and teaching, as well as an object of investigation for sustainable architectural concepts.

3.2. Design and construction principles

The building's design and construction reflect the ideas of sustainable building, especially in its geometry, structure and the choice of construction materials. The gross floor area of the wooden structure will be approximately 140 square metres. A compact building core containing ancillary and technical rooms divides the building into a café and a workshop area. Both areas can also be used as event rooms. The characteristic structural elements are the funnel-shaped wooden roof, made of prefabricated BSP-elements, as well as the transparent facades, which ensure a high degree of connection to the outside space.

3.3. Historical context

Situated in front of the university's historic main building (Figure 4), the historical context also had to be taken into account for the building's design. Since the neighbouring buildings are under a so-called "ensemble protection", the city's highest monument authority along with the city's design advisory

Figure 4 Situation of the new bicycle repair café in front of the university's historic main building

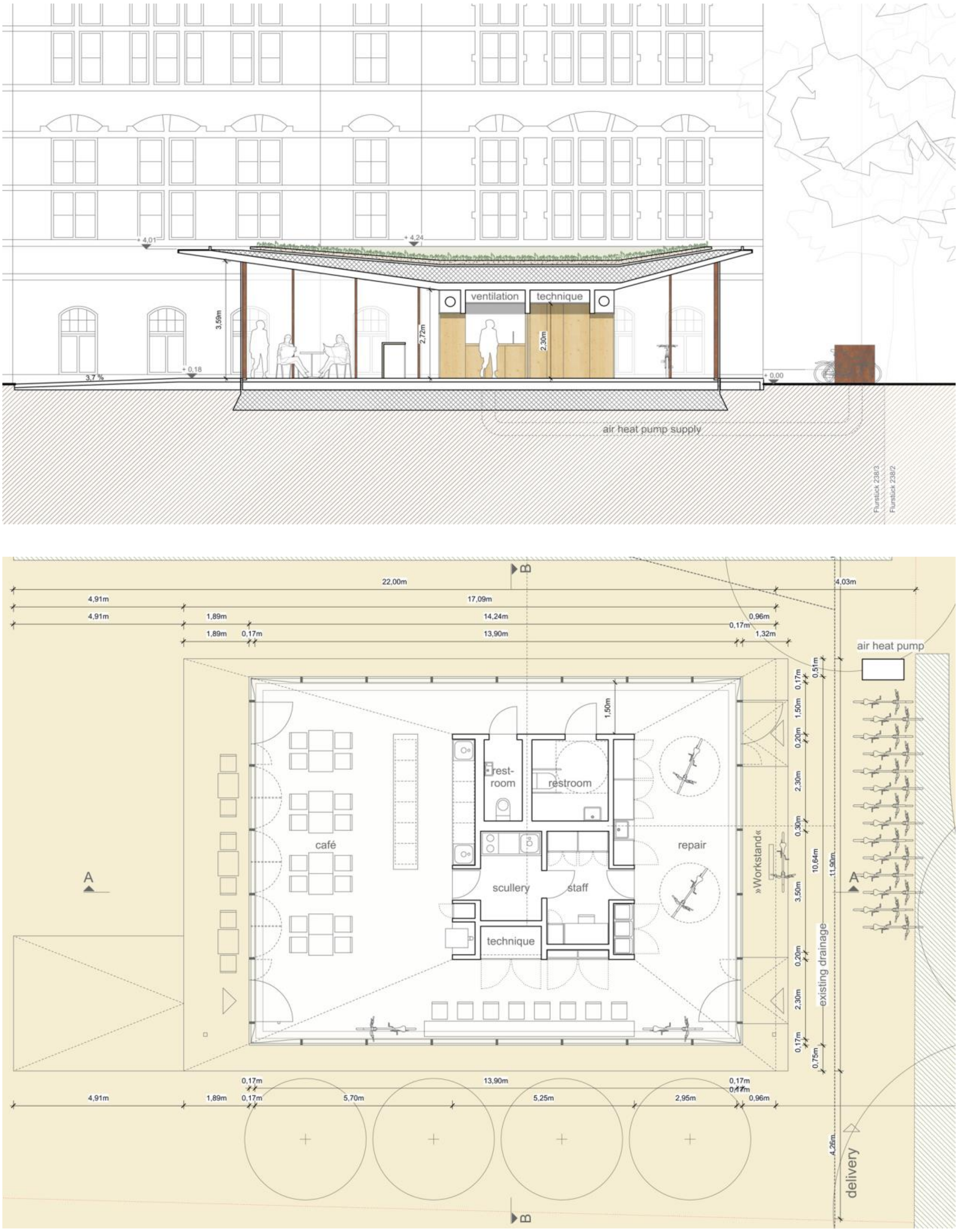

Figure 5 Section (above) and floorplan (below) showing the technical and structural core of the building, defining the usage areas

board were involved in the whole process. This means that monument protection and cityscape/urban planning requirements always had to be weighed against the requirements for an energy-optimized building.

The preservation of the trees on the forecourt of the listed main building was mandatory and maximum of transparency was desired. This stands in contrast to an energy-optimized building, because in summer too much energy is expected from direct solar radiation and in winter too much heat loss is expected from large glass areas. However, a careful analysis of the location, including detailed shadow studies for example, allowed both concerns to be combined and taken into account in the planning. In summer, large parts of the building are shaded by the neighbouring buildings and the existing trees. A further contribution to the shading of the north-west façade is made by the preserved ornamental apple trees.

3.4. Sustainability Concept

The overall intention is to reduce CO_2 emissions over the whole life cycle of the building, wherever possible. In addition to using materials from renewable resources or recyclable materials and an ambitious energy concept (3.4.2), the folding roof geometry also contributes to the sustainability of the building. It allows to use slimmer material cross-sections and thus saves material.

Furthermore, the Bicycle Repair Café will serve as a meeting point for students, university staff and neighbouring residents, opening up the campus to its neighbourhood, thus contributing also to the social aspects of sustainability.

3.4.1. Building envelope

The building envelope meets passive house standards (Ψ < 0,01 W/(m²K), n50< 0,6/h). The four facades are fully glazed with three-pane safety glass (U < 0,6 W/(m²K), g < 0,4). The facade columns behind them are made of untreated tubular steel and are therefore easy to recycle. The wooden roof construction is designed as a warm roof construction (U < 0,1 W/(m²K)) and carries a retention roof that regulates the climate both in the urban space and in the building. In summer it protects the building from strong heat input via the roof and in heavy rain it relieves the public sewerage network by absorbing part of the rainwater.

Table 1 Estimated U-values of building envelope

building component	U-value
opaque walls	0,1 W/(m²K)
transparent walls	0,6 W/(m²K)
doors	0,8 W/(m²K)
roof	0,1 W/(m²K)
Floor plate	0,15 W/(m²K)

3.4.2. Energy concept

The main idea behind the energy supply is to ensure that as little CO_2 as possible is emitted as a result of the energy requirements of the Bicycle Repair Café for heating, cooling, ventilation and hot water as well as for general electricity. The building is not regarded as an autonomous unit, but as part of a regional overall energy system. The energy supply is adapted to the

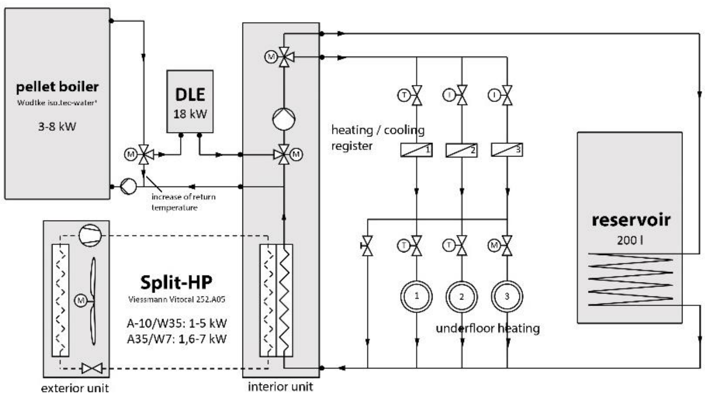

Figure 6 Hydraulic scheme

changing boundary conditions of the energy turnaround and takes into account the economic efficiency.

The energy concept pursued here for the Bicycle Repair Café is deliberately not based on current building definitions such as zero-energy or plus-energy house. These definitions allow an energy or CO_2 credit of the regenerative electricity generated at the building with its energy demand or CO_2 emissions in winter.

The Bicycle Repair Café is to be operated only from regionally available regenerative electricity. Heating and cooling are provided by an electric air heat pump. If there is a surplus of energy, this is stored in two battery memories and returned to the system when required. If no regenerative energy or stored energy is available, the pellet stove connected to the system is activated (Figure 6).

3.4.3. Materiality

For all components, two design variants will be compared before the execution, on basis of a life-cycle assessment, focussing in the primary energy demand (PE renewable, non-renewable) and CO_2 emissions.

Special attention is paid to the use of renewable raw materials. If the use of materials from non-renewable raw materials is necessary, easily recyclable materials or materials from recycled raw materials are used. Accordingly, the main construction is made of wood (BSP). The facade construction is made of untreated steel and is therefore easy to recycle. In general, composite materials are not used in order to ensure that recycling is as complete as possible. Foam glass is used for insulation materials, vacuum insulation panels in special situations, when thin, efficient insulation is necessary.

4. Expectations

The project is supported by various departments of City University of Applied Sciences Bremen. Several institutions contribute their individual expertise in the fields of climate-friendly architecture, building services engineering, building automation, structural design, etc. to the building development.

Table 2 Planning Team

	Institution
Justus Dietz Michaela Hoppe Steffi Kollmann Ingo Lütkemeyer Ulrike Mansfeld	School of Architecture Bremen, City University of Applied Sciences Bremen
Prof. Rolf Strauß	Nature and Engineering, Department of Mechanical Engineering, City University of Applied Sciences Bremen
Prof. Martin Speth	School of Architecture Bremen, City University of Applied Sciences Bremen / Drewes + Speth Engineers, Hannover

This involvement of several university teachers in the design and planning process ensures the integration of the experimental building into future teaching and research. Students will be involved in the post occupancy evaluation, e.g. recording the thermal behaviour of the building or mapping the resulting energy demand. The building will serve as a case study for life cycle assessments. Due to the easy accessibility of the technical components these can serve as practical examples for architecture and engineering students. Being open to the public, the building will also contribute to a better distribution of scientific outcomes to the public.

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Climate-resilient urban planning and architecture with GREENPASS illustrated by the case study 'FLAIR in the City' in Vienna

Kraus F, Scharf B

GREENPASS GmbH, Vienna, Austria

florian.kraus@greenpass.at

Abstract. Urban growth and climate change are 2 of the main challenges worldwide [20]. Cities are growing rapidly while average temperatures are rising, and extreme weather conditions, as heavy rain events, are becoming more frequently. Soon 4 out of 5 EU citizens are living in cities [6]. The results are increasing costs for health expenses and infrastructure damages. Urban planning processes have to consider future climate conditions and the impact on people, buildings and the urban environment. Until today there was no simple solution to measure and calculate the climate impacts of urban developments. GREENPASS® is a technological breakthrough, the world's first software-based technology for climate-resilient and resource-efficient urban development. After 9 years of scientific research and development the technology can easily be used by urban planners as architects and be integrated into existing urban planning workflows and processes.

With GREENPASS® the impact of buildings, materials and plants on urban climate become measurable and comparable in a standardized way – powered by ENVI-met®. It supports optimization of investments towards effects of Green Infrastructure (trees, green roofs and walls, ...) such as cooling, thermal comfort, water retention and carbon sequestration. GREENPASS® allows to identify the optimal solution for any urban development. Supported projects receive finally a GREENPASS® certificate on their overall performance. The technology has already been applied successfully for more than 25 projects within Austria and Europe [3] and will be explained more in detail using the case study of 'FLAIR in the City' - the world's first GREENPASS® Gold-certified residential building, located in Vienna/Austria.

1. Background

Urban growth and climate change are 2 of the main challenges worldwide [20]. Cities are growing rapidly while average temperatures are rising. Along with climate change not only heat waves occur more frequently, but also heavy rain events that may cause pluvial flooding. Soon 4 out of 5 EU citizens are living in cities [6].

The results are increasing costs for health expenses and infrastructure damages. Urban planning processes have to consider future climate conditions and the impact on people, buildings and the urban environment. Green Infrastructure is accepted as one key measure of urban climate change adaptation and improvement of urban climate resilience. This has been acknowledged by many official entities as the UN, IPCC, IUCN, EEA, EC, national and regional governments and authorities [1][5][7][13][15][19].

While all the named guidelines and recommendations are of high value, they remain generic and conceptual. Planning processes request detailed information of benefits and costs of green infrastructure to allow decision making.

2. GREENPASS® technology

The GREENPASS® technology is the worldwide first software-based technology for climate resilient and resource-efficient urban planning and architecture. It has been developed in the last 9 years within international R&D projects with more than € 4. Mio of funding [7][8][14][15].

The GREENPASS® technology consists of the GREENPASS® Toolbox, GREENPASS® Software and GREENPASS® certification and includes ENVI-met® microclimate simulation for climatic inputs within the planning-, evaluation- and optimization process [10][11][17][18].

2.1. GREENPASS® toolbox

An international review of planning processes [7] revealed that worldwide, planning processes follow a standardized pattern, starting with preliminary design, followed by concept design and detailed design. To every phase of the planning process different resources (personnel and budget) are allocated.

The GREENPASS® toolbox (see **Figure 1**) accounts for that and provides tailored services for every phase of the described planning process in accordance with the given resources and budget [10]:

- Assessment for preliminary design phase (01): low detail grade and low resources available (budget and time)
- Pre-certification for concept design phase (02): low detail grade and moderate resources available (budget and time)
- Certification for detailed design phase (03): high detail grade and high resources available (budget and time)

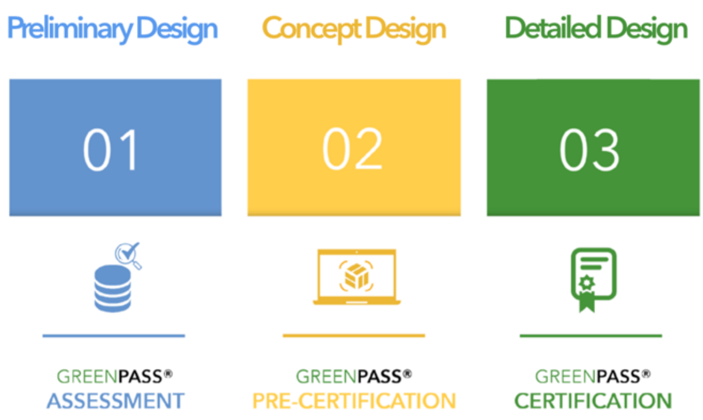

Figure 1. *GREENPASS® Toolbox delivers the tailored tool for the respective planning process phase for a worldwide application*

2.2. GREENPASS® Editor

The GREENPASS® Editor is an independent GIS-based software and the crucial interface between scientific world of microclimate simulation and practical planning world. Common planning data, like CAD (.dxf) or GIS (.shp), can be imported to the software in a straight and easy way. The planning project can then be edited within the software, e.g. assigning materials from a comprehensive data base (linked with ENVI-met®) to project elements, adding green infrastructures etc. The software finally automatically transforms the modelled data to a digital simulation model in ENVI-met® compatible data file format (.inx) [8].

2.3. GREENPASS® Certification

The GREENPASS® Certification is an ongoing optimization process with the aim to deliver the best results on climate resilience and return on investment. To that end it is comparable to many other fields of planning in the detailed design phase. The final design of the project is rewarded an official certificate.

The certification system is based on existing building certification systems like, DGNB, LEED or BREEAM. The comprehensive set of in total up to 28 certification indicators allow to analyse each project and progressively optimize it with regard to three overarching topics: climate resilience, water management and costs. The analyses provide detailed information on exemplary the effects of building structures, greenery elements and surface materials on the thermal comfort, the wind flow, water run-off, CO_2 sequestration, cooling degree hours, air temperature, water demand, and many more. And relates these to installation and maintenance costs for green and blue infrastructure [10][17].

Additionally, to the project plans, three standardized and rule-based reference scenarios are applied and simulated within the certification frame. The reference scenarios are based on the actual architectural planning inclusive landscape design, changing the materials and implementation of green infrastructures as follows:

- Worst case scenario: e.g. 100 % sealed with asphalt
- Moderate greened scenario: e.g. 50 % of flat roofs - extensive green roof, façade greenery with focus on S exposition, 50 % unsealing of private roads, sidewalks, parking lot, additional trees
- Maximum greened scenario: e.g. 50 % of flat and inclined roofs - intensive green roof, façade greenery with focus on S, W and E exposition, 100 % unsealing of private roads, sidewalks, parking lot, additional trees

These scenarios subsequently form the framework for the certification evaluation and support the optimization process. The official GREENPASS® certificate is a planning certificate and available in: Platinum, Gold, Silver and Certified (see **Figure 2**). Two years after completion of the building construction, the evaluated measures will be controlled by a reviser for quality management purposes, if they got implemented correctly and flourishing well. Otherwise, a re-certification will be offered or in worst case the certification will be officially revoked.

Figure 2. *Official GREENPASS® certification for building projects, districts and entire cities*

3. Case Study – 'FLAIR in the City'

'FLAIR in the City' is a residential building project with a size of app. 0.6 ha, located in the south of Vienna in 'Atzgersdorf'. The building plot is part of the 'Carré Atzgersdorf' masterplan for an app. 7 ha large integrative urban development area in the 23rd district of Vienna and aims to be the first realized building plot of the ensemble with 133 apartments [12]. The plot shapes the southern part of the masterplan area and is located adjacent to the public ‘Bruno-Morpurgo-Park’ in the south of the area, which also brings climatically benefits for the building plot (see **Figure 3**).

Figure 3. *Localization of the GREENPASS® case study ‘FLAIR in the City’ in the south of Vienna*

The co-creative multi-year development process inclusive public participation started 2014 with the zoning map. 2015 ‘FLAIR’ developer provided the building plot for an urban gardening initiative, called ‘Freiluftsupermarkt’, as temporary use. The GREENPASS® certification was applied in the detail planning phase in December 2015, in cooperation with ‘FLAIR’ developer and the Municipality Department of Vienna for Environmental Protection (MA22). The progressive planning and optimization process together with the developer and architectural team was finalized in September 2016. The ground-breaking ceremony took place in August 2018, while the building project is actual still under construction and will be finalized expected in 2020 (see **Figure 4**).

Figure 4. *‘FLAIR in the City’ planning and construction process timeline*

3.1. Data processing

For the generation of a digital simulation model for microclimate simulation, respective data is needed. Beside an architectural model (see **Figure 5**), the team from “uma architects” provided the data in .dwg and .pdf formats. The plans were edited in the respective data layer structure with containing information’s, based on GREENPASS® data specifications.

Figure 5. Architectural model of the draft version of the residential building complex 'FLAIR in the City' in concept design phase from 'uma architects'

Based on the project plans the rule-based reference scenarios have been elaborated. For every scenario a digital simulation model with a horizontal cell resolution of 2 m was generated (see **Figure 7**). The models have a size of 150 x 300 m inclusive surrounding buildings and park adjacent to the building plot.

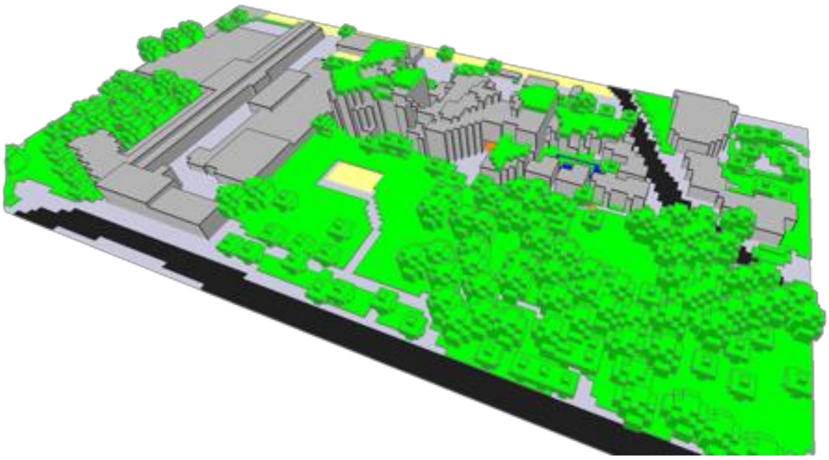

Figure 6. Digital simulation model for ENVI-met®, based on the architecture draft version inclusive surroundings: Scenario Planning

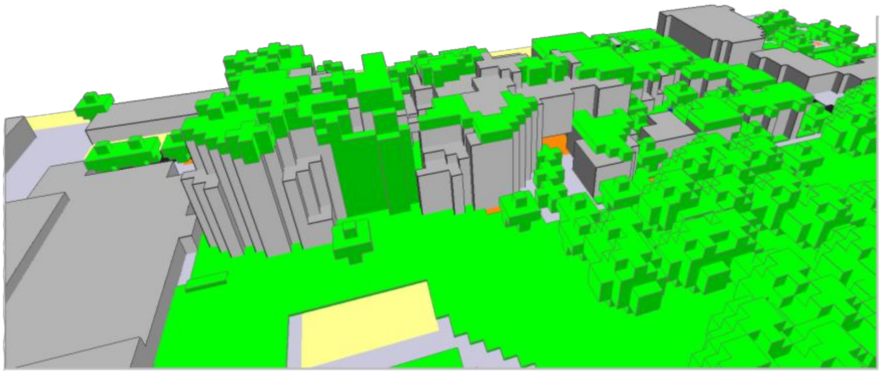

Figure 7. Digital simulation model for ENVI-met®, based on the architecture draft version inclusive surroundings: Scenario Planning optimized

3.2. *GREENPASS® results*

The microclimate simulation input is generated by ENVI-met® [1][19], one of the worldwide most famous and validated software for microclimate simulations. The following figures show exemplary results of the evaluation and optimization process for 'FLAIR in the City' – in form of the Key Performance Indicator (KPI) - Thermal Performance (PET).

- KPI - Thermal Performance - PET (physiological equivalent temperature) on 21st July at 3 pm and 1.8m height for scenario planning and planning optimized (see **Figure 8** and **Figure 9**)

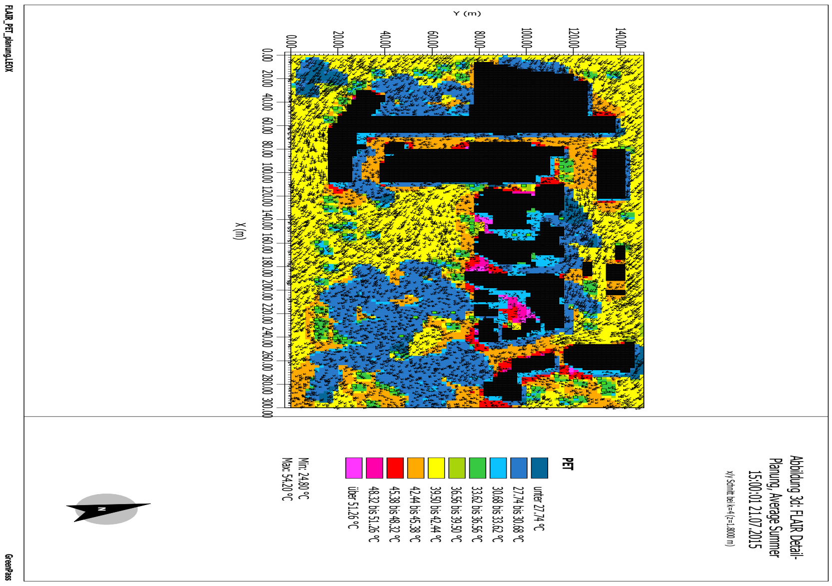

Figure 8. GREENPASS® KPI - Thermal Performance (PET) for 'FLAIR in the City' on a hot summer day (21st July) at 3pm and 1.8m height - for the scenario planning

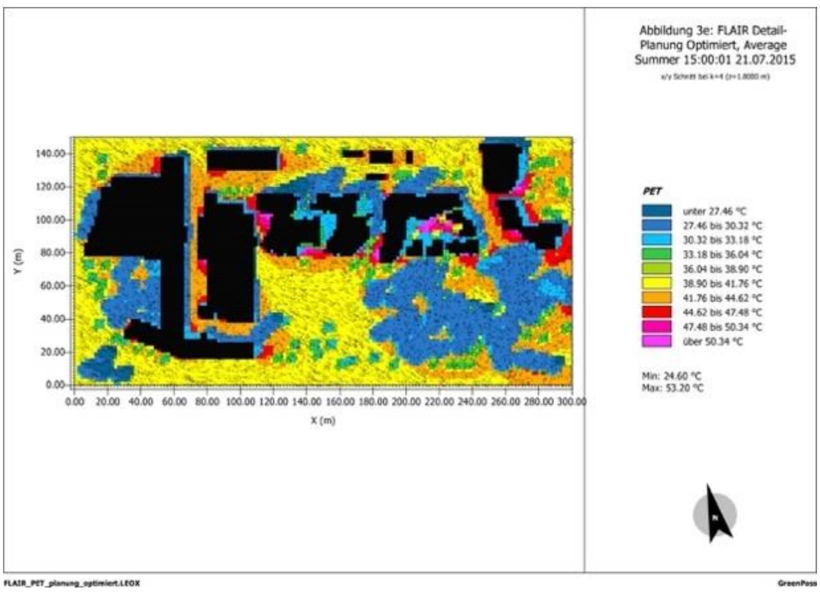

Figure 9. GREENPASS® KPI - Thermal Performance (PET) for 'FLAIR in the City' on a hot summer day (21st July) at 3pm and 1.8m height - for the scenario planning optimized

3.3. *Optimization process*

The project optimization was performed in close cooperation with the architectural team and the developer in an iterative process. **Figure 7** shows the design amendments via Green Infrastructure leading to an improved thermal comfort (PET) as well as Thermal Comfort Score for the optimized planning, in comparison to the former planning scenario (see **Figure 10** and **Figure 11**).

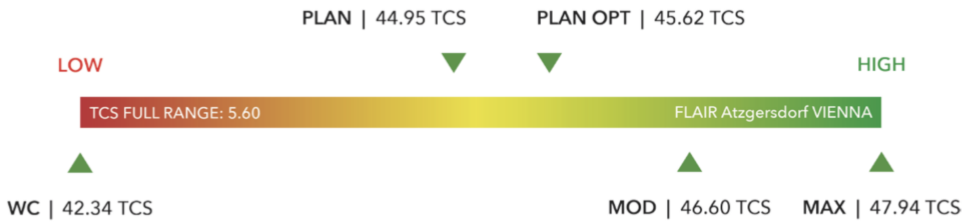

Figure 10. GREENPASS® TCS bar for different scenarios of 'FLAIR in the City'showing the performance ratio

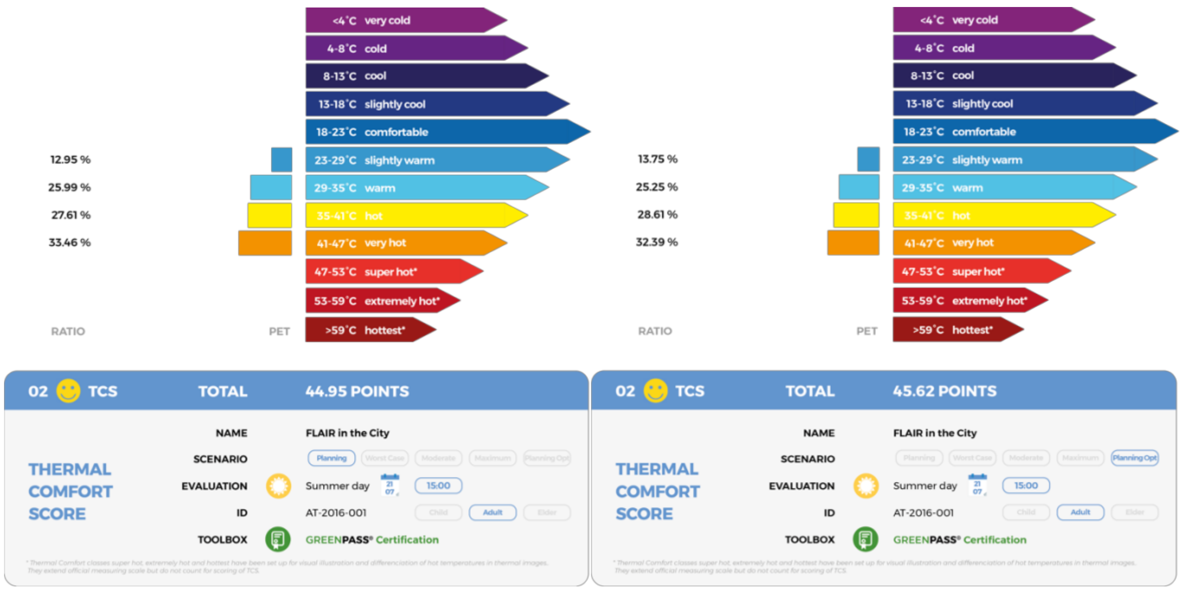

Figure 11. GREENPASS® KPI - TCS – Thermal Comfort Score for 'FLAIR in the City' Planning and Planning optimized

3.4. *Certification results*

The overall results of the GREENPASS® certification show that the planning area has been optimized with regard to climate resilience and the use of green and blue infrastructure and their multiple effects. A cost/benefit analysis enabled the most cost-efficient and resource-efficient solution to be found. The original 'FLAIR in the City' planning design had the performance of a total degree of fulfillment of 67 % (see **Figure 12**).

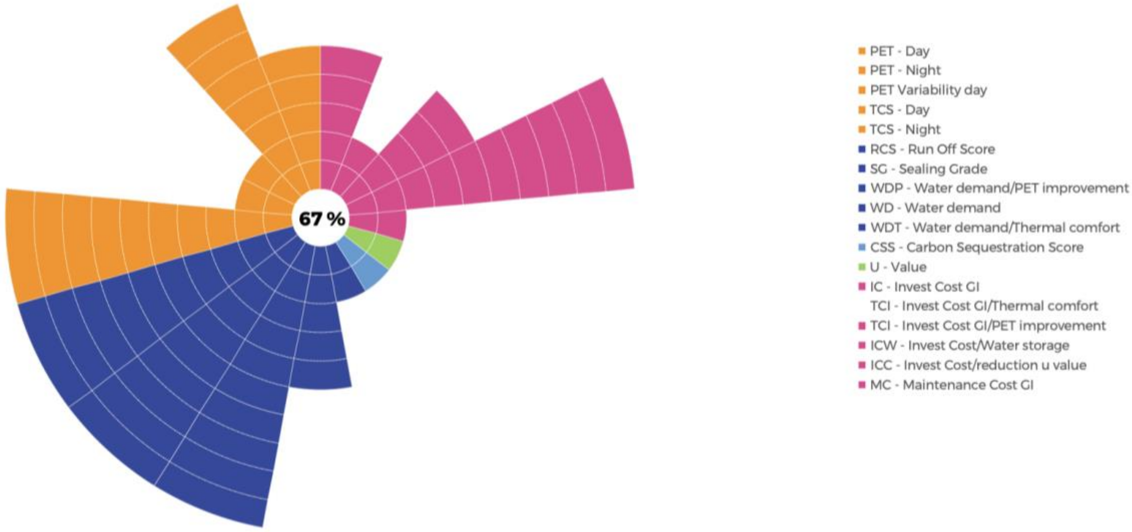

Figure 12. GREENPASS® Assessment Flower - 'FLAIR in the City' Planning – 67 % total degree of fulfilment

The optimized planning for 'FLAIR in the City' reaches with 79 % total degree of fulfillment finally the worldwide first GREENPASS® Gold certificate. The results are presented in form of a comprehensive and detailed report (app. 100+ pages) and summarized in a project factsheet including project details, evaluation results and performance facts. The results per indicator and urban challenge are further shown in form of an assessment flower graphic (see **Figure 13**).

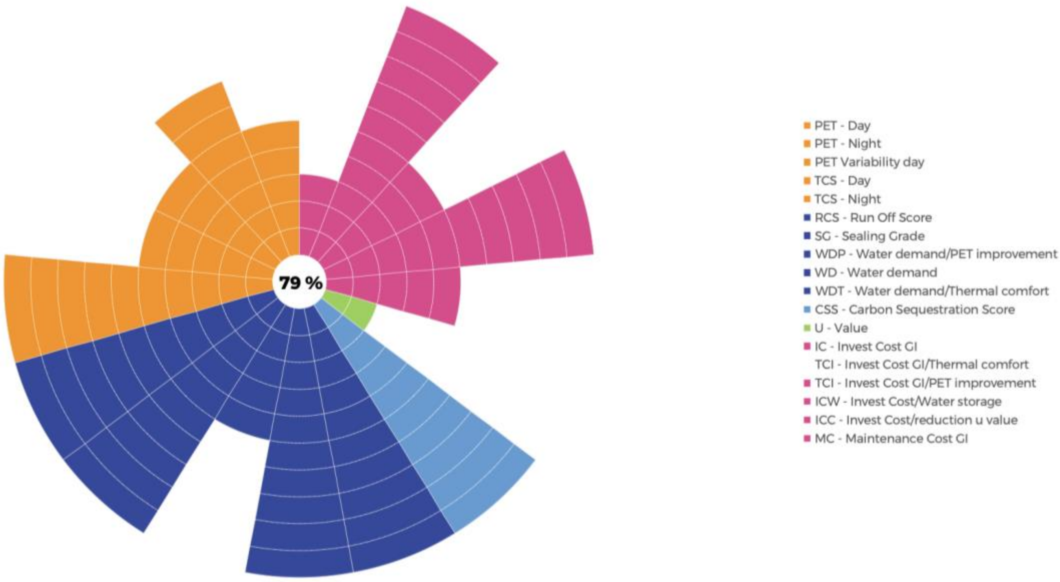

Figure 13. GREENPASS® Assessment Flower - 'FLAIR in the City' Planning optimized – 79% total degree of fulfilment

The performance facts show e.g., that the planned actions have a cooling performance of up to 1°C air temperature and 10°C PET (see **Figure 14**). Regarding the average run-off coefficient, 'FLAIR in the city' performs with an average of 0.2 again very well. For the performance, the plants have a need of 1.312 m^3 of water by same time saving 274 m^3 of water recurrently, depending on the intensity of rain fall events. And many more (see **Figure 14**).

Figure 14. GREENPASS® facts – 'FLAIR in the City' – 1st GREENPASS® Gold certified project

4. Discussion

For an effective climate change adaption of urban areas, the optimization of urban development projects is nowadays crucial. Therefore, every single urban development project should consider microclimate and urban climate related aspects, to optimize the quality of life for residents and citizens.

GREENPASS® has been successfully used for optimization purpose to improve the planning regarding climate-resilience, water retention and cost. A typical microclimate simulation provides only thermal maps (e.g. PET, PMV, UTCI, AT, …) and wind flow information. An optional evaluation of planning projects remains only on a descriptive level. A comparison of different designs and actions, as well as the interpretation and understanding of results is hardly possible and limited to urban climate experts.

Compared to classic microclimate simulations, GREENPASS® additionally delivers now a decision support for urban development planning and architecture, due to a standardized certification process, sophisticated Key performance indicators (KPIs), clearly defined reference scenarios and an easy understandable graphical presentation of results. In an iterative planning process, hot spots can be analysed, defined and optimized in cooperation with the developer, architects and other involved trades. Because the building structure was set already at this point of time, the applicable actions have been limited to specific improvement measures, like the additional integration of Green and Blue infrastructure.

5. Conclusion

The GREENPASS® approach has been successfully proven itself in practice, based on the Case Study 'FLAIR in the City' – the worldwide first GREENPASS® Gold certified project.

Figure 15. Visualization - 'FLAIR in the City' Planning optimized (FLAIR GmbH)

It is following recommended, to use GREENPASS® as standardized tool for climate-resilient urban planning processes, in parallel to the energy pass for buildings. This international award is further proof that not only costs can be saved with the right choice of building integrated greenery and targeted green space design, but also maximizing the thermal comfort for all residents. This result shows that the consideration of green and blue infrastructure ensures climate-resilient urban planning in a simple and cost-effective manner. The thermal comfort and the quality of life for residents in urban areas can thus be significantly increased. In addition, biodiversity and habitat quality can be promoted, too.

The worldwide applicable GREENPASS® technology has been already applied for more than 35 projects in Austria and the EU [3] and is summarized, an efficient planning approach and realization tool that provides profound decision-making ground. It helps to prevent urban heat islands and other urban challenges in times of climate change and to make our cities climate-resilient and livable.

Nevertheless, it's important to consider climate adaption aspects and the integration of innovative planning tools in urban design process as early as possible, due to a strong impact of the building structure and used materials to its surrounding and on humans and to be able to optimize the building structures, if necessary. Lesson learned is following, that climate adaptation in urban design processes should be considered from the very early beginning of the detailed planning process (or even in urban planning processes before) to get the best out of the project.

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Public procurement for carbon reduction in infrastructure projects – an international overview

Kadefors A[1,2], Lingegård S[3], Alkan-Olsson J[4], Uppenberg S[5], Balian D[5]

[1]Dept. of Real Estate and Construction Management, KTH Royal Institute of Technology, Sweden

[2]Technology Management and Economics, Chalmers University of Technology, Sweden

[3]Dept. of Sustainable Development, Sustainability Science and Engineering (SEED), KTH Royal Institute of Technology, Sweden

[4]Centre for environment and climate research, Lund University, Sweden

[5]WSP Group, Sweden

sofia.lingegard@abe.kth.se

Abstract. Carbon emissions emanating from infrastructure construction projects are substantial and stem primarily from production of construction materials and use of energy for construction transport and site activities. In recent years, public infrastructure clients world-wide have begun to include carbon reduction goals in their procurement requirements. This is however a new and complex field where practices vary and are still developing. In this paper, we compare models for carbon reduction requirements in infrastructure construction projects based on case studies of large projects in Australia, USA, the Netherlands, Sweden and UK. We found that open, functional carbon reduction requirements were considered innovative but entailed costs for calculating baselines and risks for speculation. Also, high time pressure in projects limits contractors' opportunities to explore reduction opportunities. Thus, specific, prescriptive requirements may play an important role in client-led, long-term innovation processes. Organizational competence and resources on the buyer side are essential, and policies for carbon reduction should aim to increase client capacity. Further, procurement practices are developed in mutual interaction between clients and suppliers over longer periods of time, which limits possibilities to transfer procurement policies and requirements between contexts.

1. Introduction

The construction sector causes a substantial part of all carbon emissions, primarily carbon dioxide. Traditionally, the focus has been on improving the energy efficiency of buildings, while it is only recently that the considerable carbon emissions arising from the manufacturing of construction materials and components, and from construction processes and transport, have been acknowledged [1]. Consequently, the infrastructure construction sector is now recognized as a major source of carbon emissions and there is increasing awareness that these emissions need to be significantly reduced if the international and national carbon reduction targets are to be met. In the UK, the Green Construction Board has estimated that emissions from the construction, maintenance and operations of infrastructure assets account for 1/6 or 16 % of the nation's total carbon dioxide emissions.

In the European Union as well as in the OECD countries, the focus on public procurement as a policy instrument has increased in recent years [2]. In particular, ecological and social sustainability and innovation procurement have been promoted. Large public buyers are pointed out as key actors in driving development especially in sectors where they stand for a high share of total demand, such as construction [3]. This allows them to not only influence emissions stemming from their own purchasing, but also to create lead markets for new products and services.

In the infrastructure sector, large public buyers such as road and railroad administrations, state-owned companies, municipalities and county councils represent a large proportion of the total demand. Their procurement models and requirements not only define the assets constructed but also the incentives and motivation of contractors, designing engineers and material manufacturers to develop competencies and new innovative solutions [4] also in the field of sustainability [5]. In recent years initiatives have been taken world-wide to include sustainability criteria in infrastructure construction procurement. Sustainability assessment schemes (CEEQUAL, BREEAM Infrastructure, the IS rating system, Envision), sustainability frameworks (SUNRA) and carbon management frameworks (PAS 2080, CO2 Performance Ladder) have been developed. Recent guidelines such as those by UK Green Building Council [6] and IISD and i24c [7] address the role of public procurement in this field and provide best practice examples.

Still, it is not evident how to design and implement procurement models and incentives that efficiently contribute to carbon emissions reductions in infrastructure construction projects. The measures to achieve reductions in the infrastructure projects are multifaceted: they involve new construction materials, optimizing designs to use less materials and energy over the life cycle, coordinating use of masses within and between projects, minimizing emissions from transport and site operation, as well as documentation, reporting and verification of requirements [8, 9]. Thus, similar to green public procurement in the construction sector in general, a wide range of project functions and supply chain partners are affected [10].

This research project provides a cross-country overview of how public infrastructure clients use procurement requirements to support carbon reduction goals in large construction projects. This paper describes the different types of procurement requirements used and briefly discusses experiences, developments over time and policy context. The countries covered are Australia (New South Wales), The Netherlands, Sweden, the UK and the US (California).

2. Previous research

2.1. Research on green and sustainable procurement

There are few research-based studies on carbon requirements in infrastructure projects and the number of studies on green public procurement (GPP) or Sustainable Public Procurement (SPP) in construction is also limited. However, the body of literature on GPP and SPP often covers wider areas which also may include construction. More generally, Cheng, Appolloni, D'Amato and Zhu [11] showed that GPP is a growing research field with 50 % of the articles published between 2013 and 2016. Low carbon procurement emerged as a subset of GPP around 2010. Often, the ambition is to map practices, drivers and obstacles. For example, Brammer and Walker [12] report results of a survey of GPP/SPP practices in all sustainability dimensions and in all sectors in 20 countries. They found that procurement policy and practices vary significantly between regions, and that the national policy context has a high influence on the use of SPP as well as on focus areas and measures [12]. Such cross-country studies are however rare and repeatedly called for [8, 12].

Studies focusing on public procurement for innovation show that change processes are complex and dependent on mutual interaction between demand-side requirements and supply-side development over longer periods of time [12, 13]. The need for organizational awareness, competence and capacity on the buyer side to craft and implement successful policy measures is emphasized [13-17]. Collaboration between the purchasing department and environmental units is another success factor [16], and many studies find that individuals are important [18]. Front-runner suppliers play a key role since a lack of green products and services on the market is one of the main obstacles to innovation-oriented green public procurement [10, 12, 14].

2.2. Green procurement and procurement requirements in construction

Research has shown that green requirements are becoming increasingly common but there are only few studies on how criteria are formulated and developed [15, 19]. Further, there are different types of requirements. First, sustainability may be used in the tendering process, as pre-qualification or award (MEAT) criteria [5, 20]. Other requirements regard the product or asset to be built and these may be project-specific specifications or embedded in standards or rating systems. There are also requirements that specify processes, documentation and competence. In construction, award criteria and style of specifications are strongly related to the chosen delivery model. Prescriptive requirements and price-based selection are associated with traditional, or design-bid-build, models, where the client specifies the design. Design-build contracts are based on performance requirements, and place more of the design responsibility on contractors. The general trend is towards design-build contracts [21]. In many countries there is also increased use of integrated strategies where contractors are involved earlier in the process and collaborate with the client and the design consultants to jointly define the design [22].

In our case study descriptions and discussions, we classify requirements using the following four categories:

- Selection and award criteria (qualification and MEAT criteria)
- Technical specifications and other requirements pertaining to the finished asset, the production process or organizational and individual competence. An important distinction is between prescriptive/specific/closed and functional/performance/outcome specifications.
- Rating systems/Sustainability Assessment Schemes, where the infrastructure asset may receive a certification or label provided that certain product and/or process criteria are fulfilled.
- Carbon reduction requirements, which specify or reward percentage reductions of emissions in relation to a baseline. Such requirements are sometimes referred to as “functional” or “performance”, since they leave it open to contractors how to achieve the reduction goals.

3. Method

The study has been designed and conducted in collaboration between partners from academia and industry. Interviews were performed with client representatives as well as with other parties in the supply and value chains, primarily contractor and consultant representatives but also manufacturers of construction materials. Interviewees were selected with the aid of local WSP and SKANSKA connections who were involved in the projects. Depending on project phase and availability, different combinations of roles were interviewed in different projects. In general, interviews lasted for 2-3 hours. Most interviews included more than one interviewee. The Swedish case study was coordinated with a project to follow-up the experiences from a new model to incentivize carbon reduction in construction supply chains, and there was a higher number of interviews. All interviews were voice-recorded under permission of the interviewees, and transcribed.

For a summary of interviews see Table 1. The interview guideline questions were organized under six headings aiming to capture information about procurement requirements used in the case study projects as well as personal experiences and views. The headings were:

1. Sustainability procurement requirements for reduction of carbon emissions in the project
2. Basis for/origin of requirements, such as policies, standards or certifications
3. Organization and processes for implementing and following up requirements
4. Mechanisms for learning and improvement
5. Results

6. Perceived key success factors and barriers

Case summaries were developed and fed back to interviewees for fact-checking and comments. As a basis for the analysis, a description of the policy context of each case was developed based on literature and input from local representatives.

Table 1. Cases and interviewees

Country	Project	Actors interviewed (no of individuals in parenthesis)	Number of interviews
Australia	Sydney Metro Northwest	Client (3), Contractor (1), Designer (2), Steel Supplier (1)	4
Australia	Newcastle Light Rail	Client (1), Contractor (1), Designer (4)	2
The Netherlands	A6 Almere	Client (2), Contractor (1)	1
Sweden	3 projects and other interviews	3 project interviews + interviews with clients (23), consultants (16), contractors (22) and suppliers (15).	17
UK	Anglian Water, Grafham WTW Resilience and Dalton Piercy WTW	Client (2), Contractor (1), Designer (1), other (1)	1
UK	HS2	Client (3), Contractor (1)	2
USA	California High-Speed Rail	Client (4), Contractor (1), Designer (1), Supervisor (1), Steel supplier (1)	5
USA	SFO AirTrain Extension	Client (1), Contractor (2), Designer (2)	3

4. Results

This section gives an overview of policies, procurement requirements and experiences.

4.1. Policy context

The general policy structures for the procurement requirements for carbon reduction were influenced by the national culture for policy development. Fundamental differences concerned the governance structure: Australia and the US both have a state level with high power while in the Netherlands, UK and Sweden the national level is the most important. Further, some countries and organizations (Australia/NSW, NL, UK) have a longer tradition of carbon management in infrastructure construction while in others (Sweden, US/California) such ambitions are more recent.

Some clients and projects have implemented a national policy while others have taken a role to push policy and practice forward. For very large mega-projects such as CHSR in California and HS2 in the UK, the client management teams perceive an obligation to align project ambitions with higher national and international goals despite that explicit directives to clients or projects were in fact vague or lacking. In the UK, the water company Anglian Water has served as a role model for the whole industry, demonstrating that it is possible to achieve a 50% reduction in capital carbon and also that carbon reduction is often associated with cost reductions. In the CHSR project, the explicit ambition was to use its volume and drive market development. In several cases, such as Sydney Metro, CHSR and Anglian Water, individual champions have played key roles in raising ambitions. In the Netherlands, HS2 and Sweden, the development is more policy-driven. We can also see that governments, clients, projects and industry networks take different roles in driving development. In Sweden there is a relatively clear top down approach by the Swedish Transport Administration whereas in the two US cases it is more up to the clients and projects to drive development. In New South Wales in Australia, clients have been the primary change agents, while in the UK and the Netherlands industry collaborations and partnerships with active support by government have also been important. Suppliers as well may act as front runners and set more ambitious goals than those of the client. In Sweden, some large contractors have been ahead of the client in implementing carbon reduction measures.

4.2. Procurement requirements

A summary of the types of procurement requirements with relevance to carbon reduction identified in the cases is provided in Table 2.

Table 2. Types of requirements and examples in the cases

Type of requirement	Examples in cases
Selection and award criteria	Tender discount based on organizational capabilities (NL: CO2 Performance Ladder) Tender discount based on carbon footprint calculation/reduction (NL: DuboCalc, see also under reduction req. below) Organizational environmental competence based on staff CVs Organizational competence evaluated based exemplar low carbon designs (UK: HS2) (Award criterion)
Technical specifications and other specific requirements	Requirements for competence, roles and processes: - req. for carbon manager, carbon management plans - carbon footprint calculations and documentation - PAS 2080 compatible (UK), SUNRA (SW) Carbon performance and documentation requirements: - Carbon performance for selected products/material - Renewable fuels/energy - EPDs Technical requirements: - Cement clinker replacement, Recycled ballast - Steel production req. - Asphalt, LED lightning
Rating systems/Sustainability assessment schemes (SAS)	LEED, BREEAM, Green Star (buildings) BREEAM, ISCA, CEEQUAL, Envision (Infra)
Carbon reduction requirements	Reduction in embodied or capital carbon in relation to baselines calculated for reference designs (AU, NL, SW, UK) or in relation to business as usual (US).

Following the general trend in construction procurement towards performance specifications, the case studies show that there is a preference in several countries (UK, NL SW) for open requirements that do not specify in detail which measures should be employed by contractors to reduce carbon emissions. The ambitions are to provide incentives for carbon reduction and reward contractors that invest in carbon reduction competence. Two types of requirements are used for such purposes: MEAT award criteria and requirements for carbon reduction in relation to a baseline. The UK cases have set ambitious goals of 50% reduction levels and emphasize collaboration within the supply chain: Anglian Water uses a long-term alliance contract while HS2 uses a two-stage Early Contractor Involvement contract. The Swedish Transport Administration has recently begun to include carbon reduction requirements in all projects above 5 MEUR, starting with targets around 15% which are to be raised over time. In the Netherlands, the DuboCalc tool has been developed to calculate environmental impact of construction projects, including carbon. In large projects, DuboCalc is used as an award criterion in combination with the Competitive Dialogue process. In New South Wales in Australia, reduction requirements are included in the ISCA Rating System, which is compulsory for projects of a defined size and significance. Requirements for conformance with rating schemes are applied also in the UK. In the Netherlands, the certification system CO2 Performance Ladder for carbon management is used in tender evaluation.

4.2.1. Experiences

As for MEAT award criteria, several interviewees said that the main difficulty was that there are many aspects to consider when procuring a contractor and that each area will account for a small share of the total score. In several cases studied, award criteria were used not so much to produce sharp incentives but as a means to raise awareness of the importance of carbon reduction activities and ensure that contractors include staff with high carbon competence in their teams.

Regarding reduction requirements, setting a baseline was seen as a fundamental challenge. The main points were:

1. Uncertainty in defining the reference case: on what design should the baseline be based (what project stage and on worst-case or state-of-the-art design)?
2. Uncertainty as to when the baseline should be updated, as well as which changes should be counted as savings (or increases) in relation to the baseline and what should be counted as a scope change leading to adjustment of the baseline.
3. Calculating and re-calculating baselines is costly and competes for personnel resources and management attention with actual activities to reduce carbon emissions.
4. There is a risk that incentives for carbon reduction either do not influence behavior or produce speculation and a focus on creative calculation.
5. There is limited time in a construction project to involve sub-contractors and material suppliers in low carbon design activities.
6. The development and testing of new products and materials require a longer time and need to be managed with a long-term perspective that stretches over several projects.

To some extent, these uncertainties are related to inexperience: certainty as to how to set baselines is expected to increase as standard practices develop. However, setting relevant reduction levels calls for high client competence and market knowledge, and sharp incentives may increase transaction costs for both clients and contractors. More collaborative models carry a higher potential for knowledge integration and innovation [23], but the UK experiences show that strong client leadership and commitment is essential both to legitimize collaborative contracting models and to achieve more fundamental behavioral change within such schemes. Rating systems as well are only used in the more mature contexts. In general, client carbon competence and active engagement is seen as important success factors. To speed up innovation processes and reach out in the supply chain, clients in Australia and NL use specific requirements while in the UK, innovation and learning between projects is addressed by national initiatives.

5. Discussion and conclusions

There is a high belief on the policy level in procurement as a driver of change and innovation, especially in a highly government-dominated and outsourced industry such as infrastructure construction. This study points at the complexity involved in designing and implementing procurement requirements for carbon reduction in this context. In general, it is not just a question of including certain requirements and incentives in the tendering documents, but a lengthy process that includes development of industry competence and institutions as well as clients with a long-term perspective and deep understanding of how innovation may be driven in this complex, project-based industry. Goals and measures for carbon reduction are new to many actors, and both clients and industry partners need time to adjust and develop new competencies [14].

Regarding style of requirements, specific/prescriptive requirements are often associated with conservatism while performance/functional requirements and MEAT award criteria are believed to encourage innovation. In practice, however, it is more complicated. Any single award criterion will hardly achieve enough weight to be a strong driver, and both time and resources for developing and evaluating tenders are limited. Carbon emissions in construction have many sources, and all of them are not possible to consider at the tendering stage. Functional carbon reduction requirements in relation to a baseline were used in all countries except the US. However, these were found to entail numerous implementation issues, including time and costs for calculating baselines, risks to produce a work-to-rule speculative mindset and need for independent institutions. Moreover, high time pressure limits contractors' opportunities to explore reduction opportunities during the design stage, especially if suppliers need to be involved [24]. This implies that functional requirements are less useful to leverage innovation in a project-based context than in sectors with more continuous demand and production. In effect, the case studies show that specific, prescriptive requirements may play an important role in long-term innovation processes by transferring new knowledge between projects. However, such processes have to be led by competent clients and require effective collaboration between their environmental and technical experts, procurement functions and project managers. Thus, in line with previous studies [14-17], this study emphasizes the importance of organizational awareness, competence and capacity on the buyer side.

Implications for policy-makers and client top management are that policies for carbon reduction should encompass measures to increase client capacity and incentives to drive innovation, including development of transparent systems for updating standards. Further, in countries with a longer history in carbon management, development of procurement strategies and requirements has been aligned with information and training initiatives, tool kits and guidelines for the entire supply chain. Since there is a close relationship in infrastructure construction between carbon reduction and cost reduction, and because so many project processes and participants need to be involved, policies should address the general competence of public clients to procure and manage infrastructure projects, including collaborative delivery models and strategic alliances.

Altogether, the results demonstrate that opportunities to transfer procurement policies and requirements between contexts are limited. Procurement requirements are developed in mutual interaction between clients and suppliers over longer periods of time [12, 13, 16]. Thus, policy and procurement strategy taken out of context will seldom work in a new setting that differs from the original one.

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Implementing climate impacts in road infrastructure in the design phase by combining BIM with LCA

Slobodchikov R, Lohne Bakke K, Ragnar Svennevig P, O'Born R

University of Agder, Jon Lilletuns vei 9, 4879 Grimstad, Norway

reyn.oborn@uia.no

Abstract. Building information modelling (BIM) software is increasingly being used in as a visual road design tool and offers real-time information on material demands as designs change. Life cycle assessment (LCA) is a tool that is used to measure the lifetime environmental impacts of systems, materials and processes. LCA data sets are organized according to process or product, which is ideal for implementation as a parameter in BIM. This paper seeks to explore how BIM and LCA can be used together in road design by analysing existing literature, creating a Norwegian test case on a road designed in a BIM model and adding LCA data to the model before comparing to a standard LCA study of the same road. Challenges such as including machinery emissions, uncertainty, data availability, and other insights gained will be discussed. The goal of this paper is to present a path forward for road builders to combine LCA and BIM to promote simplified LCA calculations.

1. Introduction

1.1. Background

Materials extraction and their associated processes contribute up to 50% of the global greenhouse gas (GHG) emissions and new infrastructure has outsized role in this growth [1]. Construction of infrastructure, and especially road infrastructure, is estimated to be a significant contributor to global GHG emissions [2]. As a road is designed and built, the most important decisions are made in the early design phase, which can have significant impacts on the overall GHG emissions of a project [3], [4]. The use of tools, such as life cycle assessment (LCA), can help determine environmental impacts in the early design phase, but use of such tools are often hindered due to lack of data, poor interface between road designs and LCA tools, and poor understanding of LCA as methodology [5]. This has been partially addressed by simplifying LCA for use in early decision making through tools such as CO_2CONSTRUCT, LICCER, CHANGER and JOULESAVE [6]–[9]. These models still require users to input data from one model (the road design) into a separate LCA model, requiring additional time, effort and expertise [10]. As the design of road infrastructure increasingly takes place within digital design tools as they become more sophisticated, integrating LCA with tools such as Builiding Information Modelling is becoming more attractive, although the use of Building Information Modelling (BIM) in road design is not widespread [11], [12]. BIM has several advantages over traditional modelling software and paper designs, namely that changes are shown visually in real-time [13], [14]. There have been several studies that have successfully integrated BIM and LCA in the construction sector [15]–[18] but still more work needs to be done for wider use. There have been few studies on integrating BIM with LCA for road construction but there has been some work on using spatial visualization and adopting BIM for road infrastructure projects [12], [19]. As road builders are increasingly forced to consider LCA and are increasingly moving towards digital tools for road design, it will be natural to combine BIM and LCA. This paper will show how it is possible for road planners to integrate BIM and LCA together for use in road planning and design.

1.2. Case study

The Norwegian government has set targets for greenhouse gas (GHG) emissions reductions in new road transport infrastructure in accordance with the signing of Paris Climate Agreement. The Norwegian government must reduce GHG emissions in new built transport infrastructure by 50% by the year 2030 [20]. This has meant that road planners, road builders, material producers and researchers have been forced to cooperate on developing strategies for reducing emissions in order to meet these targets [21]. The Norwegian Public Roads Administration (NPRA) is slowly mandating that LCA be used in assessing road projects and have their own simplified model for calculating emissions based on basic volumetric calculations and material requirements [22]. This model, like all LCA studies and models used in road construction, is not directly connected to the design process and requires users to input data from the road design model into an additional LCA model. The University of Agder and engineering consultant firm Sweco have been developing a BIM and LCA tool for road builders in Norway so that the design process and the LCA model are directly connected. The model is currently unnamed but can be called the BIM-LCA-ROAD (BLR) model for this paper.

The BLR model was developed and tested using a real-world road design model from Sweco's design for a highway stretch on the European Highway 6 (E6) between Arnkern and Moelv in Norway as shown in Figure 1. Sweco chose this route for testing as there was an interest on determining GHG emissions in the project and because they had a design already built in a 3D BIM model. The model was designed in Trimble Novapoint according to Norwegian road standards and exported into the file format LandXML so that it be possible to import the models into Autodesk Civil 3D for further work.

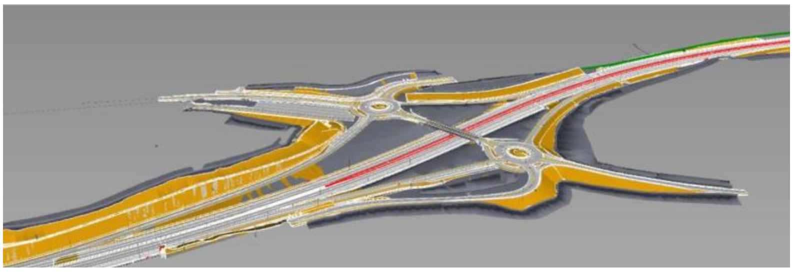

Figure 1. Sweco's Trimble Novapoint design for E6 route Arnkern-Moelv

2. Methods

2.1. Life cycle assessment

According to ISO 14040, a life cycle assessment study comprises of four main phases[23]:

1. Goal and scope definition
2. Inventory analysis
3. Impact assessment
4. Interpretation

The *goal and scope definition* phase includes the definition of the system boundaries and processes covered, the functional unit, the impact categories to be included and a declaration on who the LCA study is for. The BLR model is intended to be used by road designers and has a functional unit of one road. The BLR model is a cradle-to-gate model and has system boundaries that include the material production, construction machinery and transportation of materials to the construction site. Road operation, maintenance, traffic and end-of-life are not included in the BLR model and currently only global warming potential (GWP) and cumulative energy demand (CED) are included, although the model framework can be expanded to include costs (in Norwegian Kroner) and other LCA impact categories. The *inventory analysis* phase involves the collection of data on resource and energy demand for each process and emissions from each process within the system boundary and calculated according to the functional unit. The data collected for the testing of the BLR model comes from the material requirements calculated in the BIM model while transport distances are from real world calculations from Sweco. The test analysis used in this paper only analyzed the road base layers and driving surface and associated material production, construction and transport processes. Fuel usage in machinery comes from the Norwegian EFFEKT model version 6.6 [22]. Additional material requirements come from an additional Norwegian case study and EcoInvent 3 [21], [24]. The *impact assessment* phase uses the results from the inventory analysis phase to present the environmental impacts of the system. This is accomplished by organizing emissions into impact categories and calculating their potential impact through characterized emissions factors. The emissions factors used in this version of the model also come from the EFFEKT model version 6.6. The BLR model calculates GWP using ReCiPe 2016 midpoint indicators [25] and expresses emissions in CO_2-equivalents. Finally, the *interpretation* phase presents the results of an LCA study and recommendations. There is often also a validation process for these results, usually via comparison to other studies found in literature or through data analysis, such as a sensitivity analysis on important model parameters. This paper presents the results of the BLR model for the case and compares it to the same calculations carried out in LCA software SimaPro. This comparative analysis was also performed to determine where the most uncertainty in the model occurs and to see where model improvements need to be made.

2.2. Programming and calculation procedure in BLR model

The programming of the BLR model took place using .NET framework with C# as the programming language in Microsoft Visual Studio. This code was then implemented in Autodesk Civil 3D to carry out calculations in the form of an add-on application. Autodesk Civil 3D is one of the two main programs for digital road design used in Norway (the other being Trimble Novapoint). Autodesk 3D has an advantage over Novapoint in that add-on applications can be implemented and that external programs can easily communicate with these applications. The BLR model use Dynamic Link Library (DLL) files to import external coding into Autodesk Civil 3D to the application programming interface (API), or application. In essence, the BLR model is actually an add-on application in Autodesk Civil 3D but is designed in the same way as a conventional LCA tool. The basic inventory analysis and emissions data were imported from an Excel file into the application. The BLR model has an additional module that shows the results in real-time color coding on the actual modelled road (See Figure 6). The code used in this model is currently has not been made public. The full calculation procedures for the BLR model are shown in Figures 2 and 3.

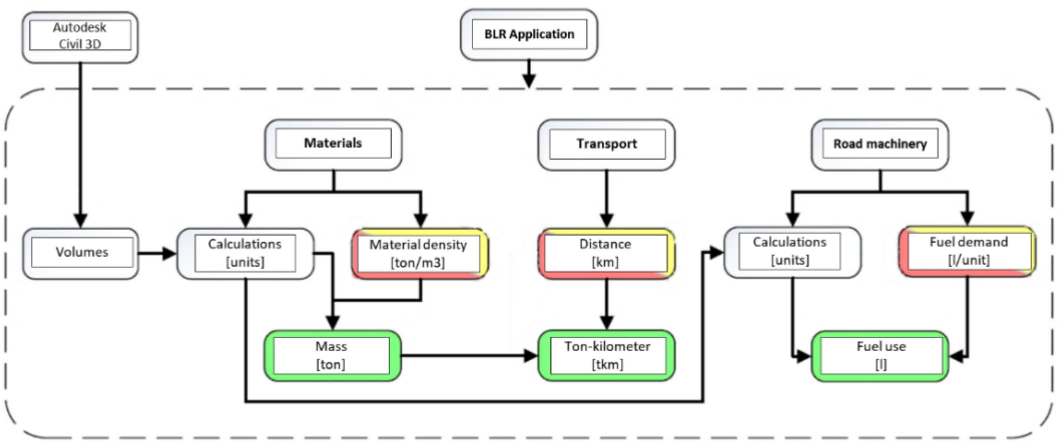

Figure 2. Calculation procedure for materials, transport and fuel in BLR model

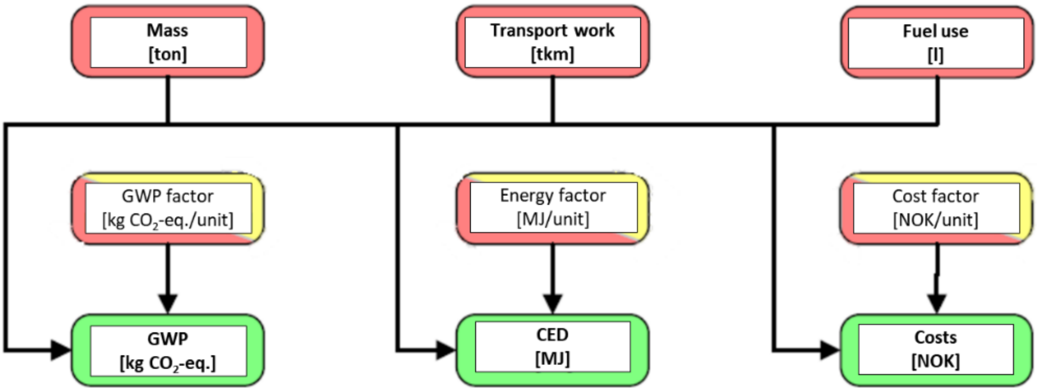

Figure 3. Calculation procedure for total GWP, CED and costs in BLR model

The BLR model calculates volumes according to the geometric volumes in the BIM model which are then converted into mass based on material density. The transport distance takes the mass calculations to calculate the overall transport work in ton-kilometers (tkm) which are used for calculating transport fuel demand. Road machinery processes also calculate based on volumetric mass calculations for earthworks and are combined with the transport fuel demand to determine the overall fuel demand in the road project. Once the fuel, mass and transport work are known, these are multiplied by GWP, Energy and Cost factors to determine the overall impact of the project. In Figures 2 and 3, the red boxes show which areas where the model does not allow for any changes in calculation parameters while the yellow boxes show where project-specific inputs can be added if the user so chooses, while the green boxes show the final calculated results.

3. Results

3.1. Life cycle inventory results

The two cases were calculated with Autodesk Civil 3D to determine the overall material requirements for each road base. Case 1 is a theoretical road crossing made in Trimble Novapoint and exported to Autodesk Civil 3D while Case 2 is a real-world example of a 4-lane highway design.

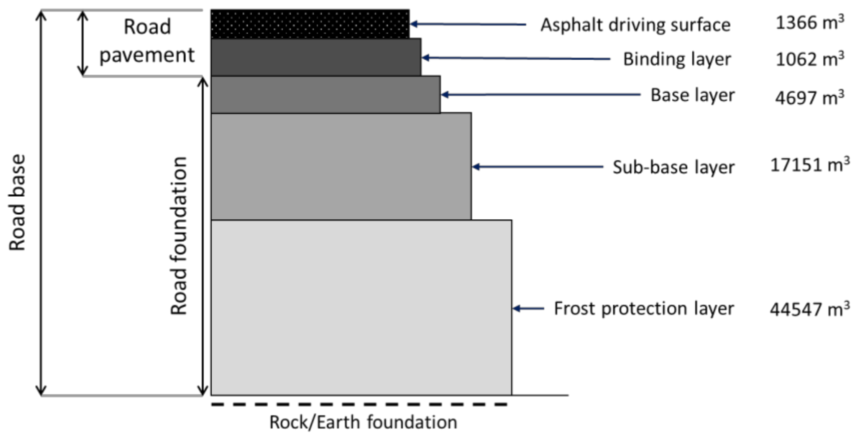

Figure 4. Material requirements for the test case

Figure 4 shows the volumetric material requirements for each component of the road base as modelled. These were calculated directly in Autodesk Civil 3D. The asphalt driving surface is a mix of gravel and bitumen while the other layers are layers of gravel and aggregates of various dimensions.

3.2. Life cycle global warming potential results

This case study is limited in that it only evaluates the GWP of the case and is used as an illustration of what is possible with a BIM model. Nevertheless, the aim of the BLR model is to calculate emissions as equally well as a standard LCA model thus the results were compared with an LCA model constructed in SimaPro. The model in SimaPro used the same impact factors and material demands as the initial BIM model. Figure 5 shows the relative emissions for each construction process and for material production for both the SimaPro LCA model and the BLR model while Table 1 shows the aggregated emissions for each of the main processes.

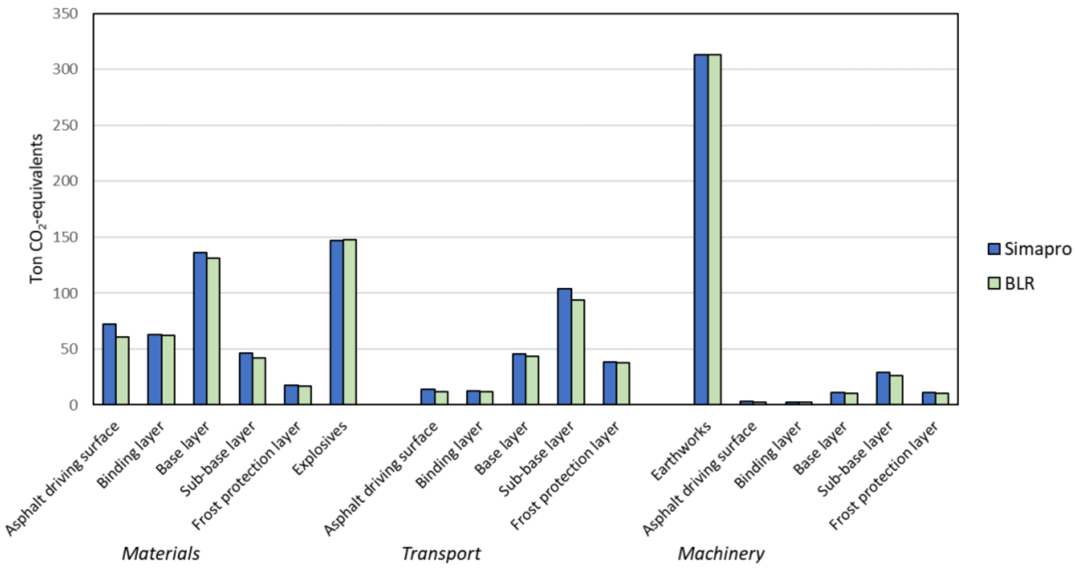

Figure 5. GWP life cycle impact assessment results (in tons CO_2-equivalents)

Figure 5 shows the emissions for each of the different road layers according to the material production, transport of materials and construction machinery. The largest single impact for both versions of the model was emissions from earthworks machinery (primarily cutting and filling, digging of trenches and drainage), which amounted 313 tons CO_2-eq. for each analysis. Other high impacts were explosives (147 to 148 tons CO_2-equivalents), material production for gravel in the base layer (which require more crushing) and transport of materials for the sub-base layer (which have the greatest total mass of all materials produced). The frost protection layer is generally lower emissions for both production and transport as emissions from the production of these materials are included in cutting and filling, which are reflected in the earthworks emissions. Overall, there is a small difference for many of the processes in the SimaPro model versus the BLR model, where the SimaPro model in general has slightly higher emissions. Table 1 summarizes the differences between the three main processes of material production, material transport and construction machinery.

Table 1. GWP results based on SimaPro and BLR analysis

Item	SimaPro	BLR	Unit	Difference
Materials	482.24	461.53	Tons CO_2-eq	4.3 %
Transport	213.93	199.15	Tons CO_2-eq	6.9 %
Machinery	370.36	366.46	Tons CO_2-eq	1.1 %
Total	1066.53	1027.14	Tons CO_2-eq	3.7 %

The BLR model underestimates emissions by 3.7% compared to the SimaPro model. Most of this is due to material production emissions being underestimated although the highest uncertainty comes from transport of materials. This is largely due to calculation differences between the original Trimble

Novapoint design and the re-imported version in Autodesk Civil 3D. This variation issue can be solved by adding coordinates directly from the LandXML file, although this has not been implemented in the BLR model at this time.

3.3. Model results and model functionality

This section outlines the functionality of the model beyond the LCA results. The BLR model was developed in this study is designed so that the user has the ability to comprehensively calculate environmental impacts in real-time during the design process. This is useful for users who are familiar with designing roads in BIM but lack the time or expertise to do a separate LCA analysis. The calculations are shown both in numerical form as tables and visually on a color-coded scalar plot as shown in Figure 6.

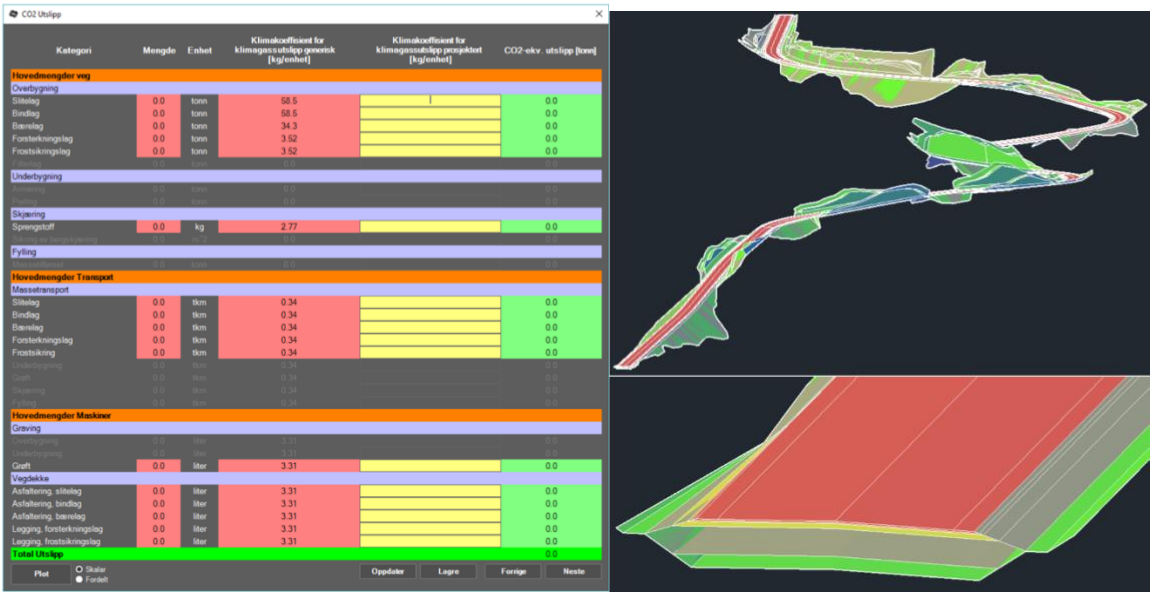

Figure 6. Example of GWP results presentation in BLR model

The table shows the calculated amounts for each material/process in the second column and the emissions factors (GWP per unit in this figure) for each material/process in the fourth column. The fifth yellow column allows for the user to add a project specific emissions factor if they choose while the sixth green column shows the total calculated emissions. The scalar plot on the right shows the overall project emissions color coded, where red has the highest emission and green has the lowest emissions. Grey colors signify elements that are not included in the current BLR model. The user can also zoom in or out on the project in the same way as any other BIM model shown Autodesk Civil 3D.

4. Discussion

Researchers have been working for many years to try and develop models that combine LCA with road project designs as customers and road authorities demand emissions reductions in new infrastructure. The overall goal of the development of BLR was to make LCA calculations as simple as possible while also being robust enough to compare well with more standard LCA road models. BLR differs from existing LCA models in that the road design and impact calculations are carried out simultaneously within the same model while other models typically require information from finished road designs as inputs. The BLR model is advantageous for road builders and designers as they can evaluate emissions and make decisions to reduce emissions in real-time. The visual aspects of the BLR model also help to easily see which sections of the road require efforts to reduce emissions.

The BLR model is a proof of concept showing that it is possible to include emissions in BIM for road designs but the model has several shortcomings in its current form and in relation to traditional

LCA models and methods. The first major shortcoming is that the scope of the model is extremely limited compared to other LCA studies as only CED and GWP are included. Other LCA studies and even Environmental Product Declarations (EPDs) have far more impact categories included. As the BLR model was only designed as a proof of concept, these impacts were not included but space for additional impact categories has been included as road authorities prioritize GHG reduction over all other impact categories [26]. Other impact categories such as eutrophication, acidification, and photochemical oxidation that are usually included in road LCA studies should be prioritized [27], [28]. The BLR model is also limited in that it does not include the full depth and breadth of materials and construction processes used in road construction in its current form. As the model continues to be developed, more information will be added to it which will improve the model quality and LCA results and could be expanded to included maintenance and end-of-life processes in the future. This will require better data inputs, which could be improved by linking up to existing LCA inventories for roads in Norway, by implementing EPDs and by using project specific data when available [29], [30].

5. Conclusion

This paper presented an integrated BIM and LCA model for road design and tested the model through the use of a case study in Norway. The results of the testing showed that it was indeed possible to combine emissions calculations in a BIM model through the use of C# to develop an Autodesk Civil 3D application. Future work should improve the robustness of the model by adding emissions factors for more construction processes and materials, by expanding the model to include more impact categories and additional life cycle phases, and by linking the BLR model to existing LCA datasets.

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Influence of cross passages temperatures on the life-cycle cost of technical equipment in a railway tunnel

Scherz M[1], Fruhwirt D[2],Bacher M[2], Steiner H[3], Passer A[1] and Kreiner H[1]

[1] Working Group Sustainable Construction - Institute of Technology and Testing of Construction Materials, Graz University of Technology (A)
[2] Working Group Traffic and Environment - Institute of Internal Combustions Engines and Thermodynamics, Graz University of Technology (A)
[3] ÖBB-Infrastruktur AG - Project Management Koralmbahn 1, Graz (A)

marco.scherz@tugraz.at, fruhwirt@ivt.tugraz.at, bacher@ivt.tugraz.at, helmut.steiner2@oebb.at, alexander.passer@tugraz.at, helmuth.kreiner@tugraz.at

Abstract. In order to achieve the climate goals, the implementation of sustainable construction is becoming more and more topical in the construction sector. Due to very long service lifes especially in railway projects, the consideration of life-cycle aspects into the early design process is of great importance. Regarding the assessment of the economic pillar of sustainability, life-cycle costing has become an established method. This study presents the application of life-cycle cost analysis (LCCA) for decision aiding in railway construction. The two tunnel tubes of the project Koralmtunnel (KAT) are connected with approximately 70 cross-passages (CPs) at intervals of around 500 m. These CPs serve as escape-ways and additionally host utility rooms for technical equipment (telecomunication, power supply and remote control). First thermal simulations revealed indoor temperatures up to 80 °C due to the heat release of the technical equipment without implementation of technical cooling systems in operation phase. This is caused by the limited heat transfer with the surrounding rock and with the adjacent running tubes. Therefore, the implementation of a cooling system is necessary. It is stated that higher indoor temperatures lead to reduced service lifes of the installed telecommunication systems. By the application of Arrhenius equation, the influence of several indoor target temperatures on the expected life time of the installed telecommunication systems has been determined. In order to meet target temperature requirements appropriate scenarios including different cooling scenarios have been designed. Finally, LCCA by application of the net-present value-method (NPV-method) was conducted in order to determine the most economical solution regarding CPs cooling systems based on selected target-temperatures.

1. Introduction

Large railway projects place manifold requirements on the design, the construction, the equipment, the commissioning as well as on the later operational management. In order to reconcile all these areas, which in some cases need to be assessed very differently, far-reaching considerations are required in advance. Long railway tunnel projects, increased demands on tunnel safety and the exploitation of existing technical possibilities are reasons why a massive increase in technical equipment can be observed. This trend needs to be monitored very carefully and critically so that it does not lead to increased maintenance cost, reductions in system availability, capacity constraints and quality of

operations management. Sustainable construction occupies a special place in the construction industry due to the centuries-long life-cycles of construction projects. Therefore, the construction sector plays a key role in this context and has enormous potential to reduce the human impact on our environment. From a economic persepective, private stakeholders often only focus on maximum profit and on short-term yielding. To implement sustainable construction, the three dimensions of sustainability (ecology, economy, sociality) must be considered throughout the lifecycle of a construction project. For the consideration of the economic pillar over the entire life span of construction projects LCCA represents a suitable instrument. Especially, public railway projects usually have very long lifetimes. Due to the long-term cost implications of operating cost and the maintenance of their technical equipment, a life-cycle-oriented approach is indispensable.
The so called southern corridor (the Austrian part) is part of the Baltic Adriatic corridor of the Trans-European Network Transport (TENT-T) [1, 2, 3, 4]. Core of this southern corridor are the Semmering Base Tunnel (SBT) with a length of 28 km and the Koralmtunnel (KAT) with a length of 33 km.

The two railway projects SBT and KAT will be operated as high-speed track. According to the distance reduction between Graz and Klagenfurt (230 km to 130 km), the travel time will be reduced for more than 2 hours [3, 4]. Today the KAT is the sixth longest railway tunnel in the world. The KAT consists of 2 tunnel tubes, which are connected with approximately 70 CPs, every 500 m. The CPs (see figure 1) serve as escape-ways and as utility rooms which contain the technical equipment for operation.

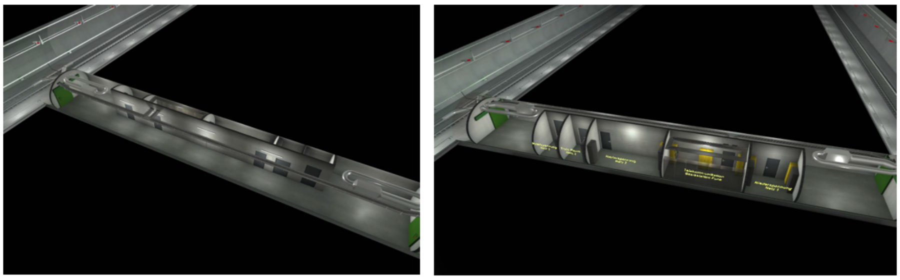

Figure 1. Schematic of a cross-passage - escape-way (left), utility rooms (right)

Thinking the entire life-cycle in the construction phase leads to different implementation scenarios due to limited service life of telecommunication systems. Due to the limited possibilities of dissipating the heat through the rock or through the adjacent running tubes, utility room temperatures of up to 80 °C occur during operation without cooling activities. These high temperatures mean that the telecommunication systems has to be replaced in shorter cycles. Based on the Arrhenius equation, the service life of the telecommunication systems can be determined as a function of the temperature. To increase the service life of the telecommunication systems, the utility room temperatures must be cooled. The cooling of the utility rooms requires additional construction cost of air- conditioning systems and/or ventilation systems in the construction phase as well as higher energy requirements for cooling in the use phase. On the other hand there are longer replacement cycles of the telecommunication systems in the use phase. In the sense of sustainable implementation, the decision-making problem arises for the investor between low initial construction cost with high usage cost or higher initial construction cost with lower usage cost.

2. Applied methodology

We illustrate how to use a NPV-method for decision-aiding in the design stage of railway projects under consideration of different thermal conditions.

2.1. Thermal conditions of long railway tunnels

The requirements for the thermal conditions inside a tunnel differ between construction phase and tunnel operation. During construction phase, the main constraint is the maximum allowable air temperature at the working areas, which must not be exceeded. While operation, the thermal conditions in the tunnel are important because tunnel air often is used for cooling technical equipment, which usually is located in utility rooms or zones within the CPs between the two tunnel tubes. To guarantee that the acceptable temperatures limits for the single utility rooms will be kept, a cooling process by the usage of tunnel air is required. Due to cost efficiency a simple mechanical ventilation system shall be installed in as many CPs as possible. In case this simple cooling process is not sufficient, air-conditioning systems are required.

As soon as outside air gets into the tunnel, the outside air temperature is one of the influencing parameters for the tunnel air temperature. For the current simulations the weather data (outside air temperature) from the region for the years 2010-2016 [5, 6] was processed. It turned out, that in 2013 summer short-term outside air temperatures, which represent the worst case for compliance with the temperature specifications, were maximum.

The rock temperature is one of the major parameters for the tunnel air temperature while construction and operation. The rock temperature curve was measured and monitored during the excavation phase and represents the start condition for the simulation of the time dependent evolution of tunnel-wall temperatures along the tunnel.

The most important heat sources during operation are the trains themselves. The impact of trains depends on the speed, the geometry of the trains as well as of the tubes. The piston effect of the trains generates an air flow in the tubes, which is essential for the thermal conditions along the tunnel. Hence the interval between the trains as well as their driving direction are further essential parameters. Depending on the slope of the track the convective heat release by breaks has to be considered too. The highpoint of the KAT is a few kilometers west from the emergency stop station. On both sides of the tunnel is a regular train station, so trains will have to stop and breaking energy will be released already in the tunnel.

In general, the fresh air-requirement is the major parameter for the tunnel air conditions. The higher the fresh air volume flow the bigger the influence of the outside air temperature.

Since tunnel air is used for cooling the utility rooms inside the CPs, the released heat from technical equipment such as the telecommunication units or the power supply units, have to be considered. In all of the 70 CPs technical equipment is installed. The released heat varies between 3 kW and 25 kW, depending on the type of equipment installed. A single CP would not have a big impact to the thermal conditions, but the sum of transported heat can lead to remarkable changes in thermal conditions within the tunnel. Due to redundancy reasons both cooling systems (ventilation and air-conditioning) are capable for re-cooling in both tubes. Depending on the tunnel air temperature in front of the CPs, re-cooling will take place in the tube with lower air temperature. If one tube is closed for maintenance, the second one is still in operation and due to the trains, an air flow and therefore a heat transport is granted. In the maintained tube the airflow depends on meteorology and if required on the maintenance ventilation. Simulations were performed, for identifying tunnel regions where tunnel air is cool enough to fulfill the thermal requirements. In figure 2 the simulation of thermal conditions within the utility rooms along the Koralmtunnel is shown.

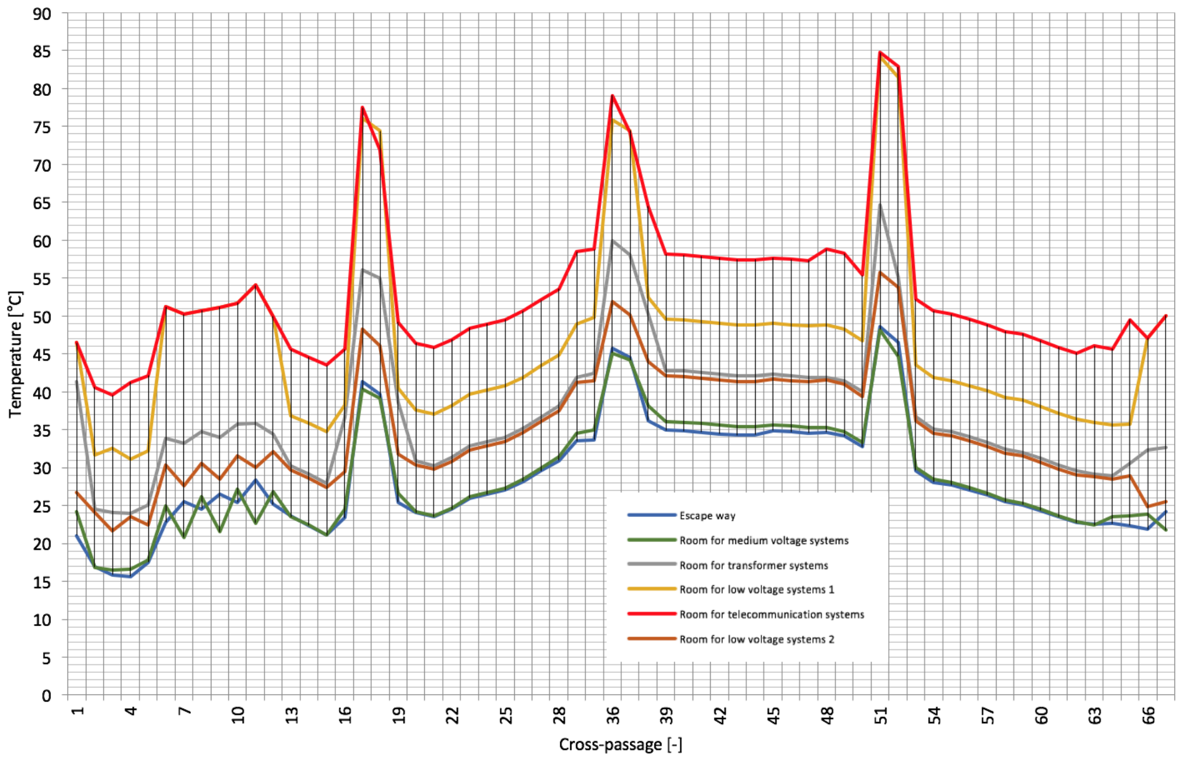

Figure 2. Simulation of thermal conditions within the utility rooms along the Koralmtunnel

The technical equipment includes power units for low voltage, medium voltage, transformer systems and telecommunication systems. Due to the high temperature sensitivity of the telecommunication systems and its effects on their service lifes, only utility rooms with located telecommuncation systems are considered. The increased room temperature in the CPs in figure 2 is the result of the installed telecommunications systems with base stations, which produce increased waste heat.

2.2. Service life of telecommunication systems - Arrhenius equation

The Arrhenius equation, named after Svante Arrhenius (1859 - 1927), describes approximately a quantitative temperature dependence in physical and chemical processes in which an activation energy has to be overcome at the molecular level [7, 8]. The Arrhenius equation is related to the Eyring equation, which represents a connection of the microscopic interpretation.

$$t_E = t_Q * e^{\frac{E_A}{R} * \left(\frac{1}{T_E} - \frac{1}{T_Q}\right)} \qquad (1)$$

where:

t_E = qualified life at absolute operating temperature T_E
t_Q = test or qualification duration at absolute test or qualification temperature T_Q
E_A = activation energy (the aging reaction)
R = gas constant

Based on the Arrhenius equation, the service life of the telecommunication systems were calculated as a function of the utility room temperatures. Table 1 shows the service life and the replacement cycles of the telecommunication systems over a 50 year period.

Table 1. Service life of telecommunication systems at different utility room temperatures

Utility room temperature	Service life	Replacement cycle
22°C	16 years	3
25°C	13 years	3
30°C	9 years	5
35°C	6 years	8
40°C	4 years	12
45°C	3 years	16

2.3. Life-cycle cost analysis

The framework for assessing the economic performance of construction projects is defined on international level in ISO 15686-5 [9]. In the course of a life-cycle cost analysis, different cost types that occur during the life-cycle of a construction project can be taken into account. In addition to different cost types, different calculation methods can be used. In general, a distinction is made between static and dynamic methods [10]. This study uses the NPV-method for the life-cycle cost analysis. With the NPV method it is possible to estimate the difference between the present value of cash inflows and the present value of cash outflows over a period of time [11].

$$NPV = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t} \tag{2}$$

where:

R_t = net cash inflow-outflows during a single period t
i = discount rate or return that could be earned in alternative investments
t = number of time periods

In particular, the usage cost and the assumed calculation parameters are of great importance for the results of LCCA [10]. In addition due to the uncertainties in assumed calculation parameters, the uncertainty of LCCA results is increased with increasing reference study period. Dominance analyzes, sensitivity analyzes and risk analyzes were performed to estimate the uncertainty of results. Dominance analysis is an appropriate analytic technique to identify the relative importance of predictors of an outcome [13, 14].

According to the ISO 15686-5 sensitivity analysis is defined as the test of the outcome of an analysis by altering one or more paramaters from initial value(s). A sensitivity analysis can reveal how precise the calculation is, and how it affects the calculation if the inputs were different. Sensitivity analysis helps to identify input data with the highest impact on the LCCA results and the robustness of the final decision. Finally, for evaluating the opportunity and risk potential of the results Monte-Carlo simulations are applied. Monte-Carlo simulation is a numerical method that runs simulation with random numbers. Within the Monte-Carlo simulation, it is possible to determine probability distribution functions based on defined calculation rules [15].

3. Case study - Koralmtunnel

In the course of LCCA, two calculation runs were carried out. In the first calculation run, the classification of CPs made at the beginning was compared with an extreme value scenario (cooling of all CPs with air-conditioning systems). It turned out that the high energy requirement for cooling to low target temperatures with air-conditioning systems was the driving cost factor. Based on the first results the extreme value variant was excluded after the first calculation run. Furthermore, scenarios with target temperatures in the utility rooms above 35 °C were excluded for reasons of occupational safety during maintenance and repair. The adapted classification of CPs (four scenarios) is shown in figure 3.

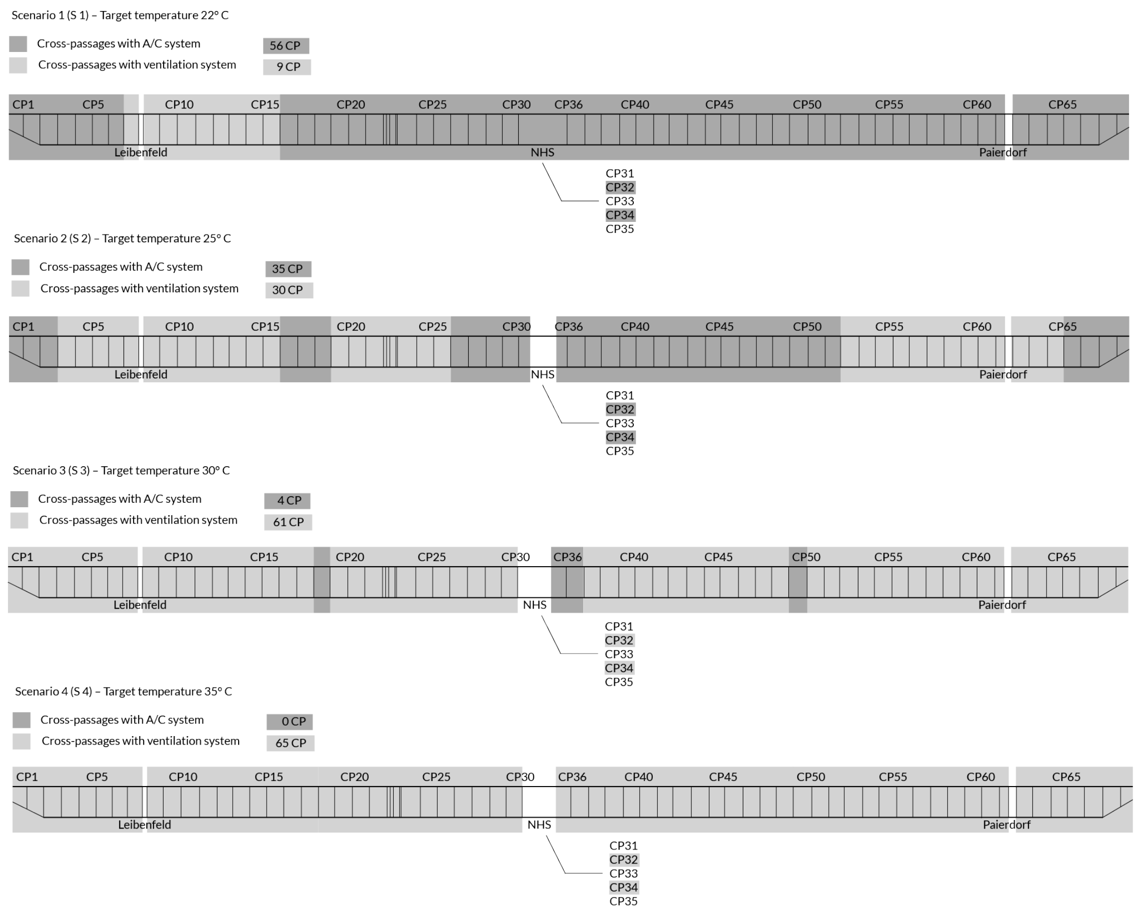

Figure 3. Classification of CPs depending on different target temperatures

The darkgray areas represent the CPs with air-conditioning systems and the lightgray areas the CPs with ventilation system. In all target temperature scenarios the CPs without utility rooms for technical equipment (CP 31, CP 33, bypasses and fire brigade accesses) are not considered.

The required input parameter for the application of the LCCA is shown in table 2. The values were given on the basis of literature research and from the experience of the project partners.

Table 2. Initial input parameter LCCA - Scenario 3 (target temperature 30 °C)

Input parameter	Value
Reference year	2025
Interest rate	4.0 %
Rate of price increase	2.5 %
Rate of energy price increase	2.75 %
Energy price	0.125 €
Initial construction cost air-conditioning systems	211377 €
Initial construction cost ventilation system	89094 €
Initial construction cost telecommunication systems for standard CPs	178265 €
Initial construction cost telecommunication systems for CPs with base station	385516 €
Adaption, refurbishment and repair cost air-conditioning systems	3 % of CC/year
Adaption, refurbishment and repair cost ventilation system	6 % of CC/year
Adaption, refurbishment and repair cost telecommunication systems for standard CPs	11.3 % of CC/year
Adaption, refurbishment and repair cost telecommunication systems for CPs with base station	11.3 % of CC/year
service life air-conditioning systems	10 years
service life ventilation systems	20 years
service life telecommunication systems for standard CPs	9 years
service life telecommunication systems for base station CPs	9 years
Operating hours air-conditioning systems	8760 h/a
Operating load scenario air-conditioning systems (Year 1 to 4)	25 %
Operating load scenario air-conditioning systems (Year 5 to 9)	28 %
Operating load scenario air-conditioning systems (Year 10 to 24)	29 %
Operating load scenario air-conditioning systems (Year 25)	31 %
Operating load scenario air-conditioning systems (Year 26 to 44)	31 %
Operating load scenario air-conditioning systems (Year 45 to 50)	33 %
Operating hours ventilation systems (Year 1 to 4)	2600 h/a
Operating hours ventilation systems (Year 5 to 9)	2700 h/a
Operating hours ventilation systems (Year 10 to 24)	2750 h/a
Operating hours vventilation systems (Year 25)	3200 h/a
Operating hours ventilation systems (Year 26 to 44)	3256 h/a
Operating hours ventilation systems (Year 45 to 50)	3500 h/a
CPs with air-conditioning systems	4
CPs with CS	61
Standard CPs	57
Base station CPs	8

For the NPV-method, all input parameters were compounded to the reference year 2025. Dynamic energy consumptions were determined for a realistic picture of the temperature development due to climate change. This is why an increasing energy consumption is emerging in the cooling of the utility rooms over the years. As a result, higher operating hours of the ventilation systems and higher operting load scenarios of the air-conditioning systems are required.

4. Results

This section presents the decision aiding process based on the results of the LCCA. To deal with the uncertainties in the assumptions, the results of dominance analysis, sensitivity analysis and risk analysis are also presented.

4.1. Comparison of scenarios

In figure 4 the results of the four CPs classifications (S1, S2, S3 and S4) are shown.

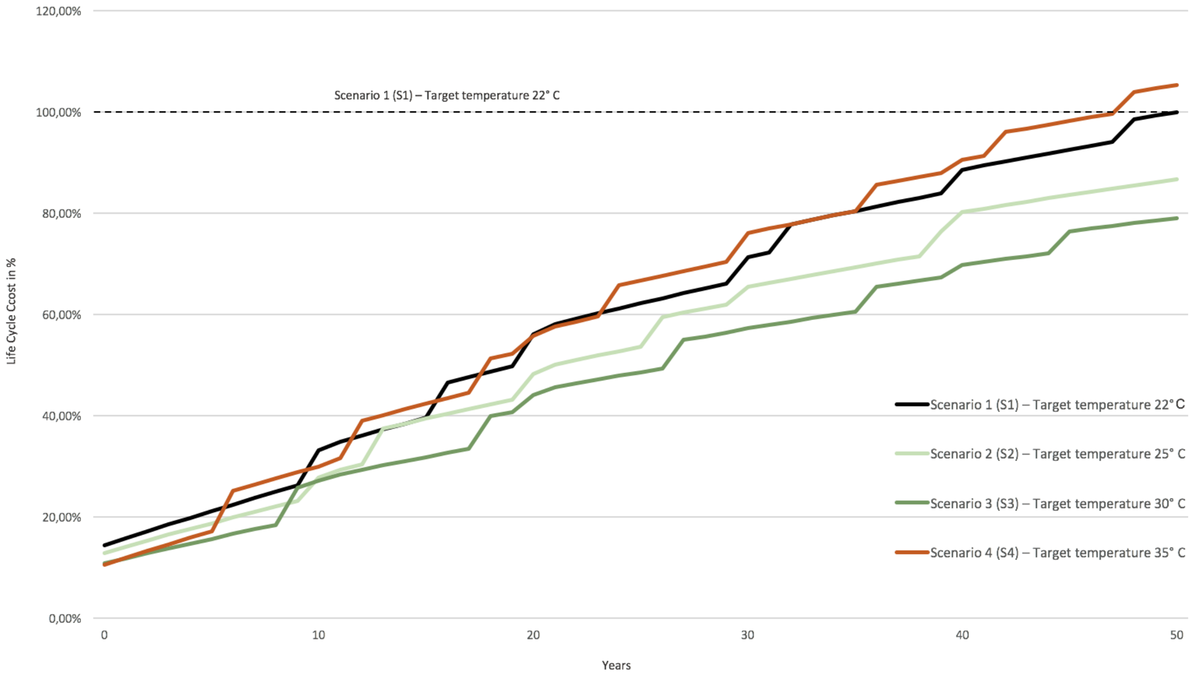

Figure 4. LCCA comparision of scenarios

As shown in the illustration, scenario 3 (darkgreen line) has the lowest life-cycle cost after 50 years. Based on this scenario, the course of jumps and slopes over the considered life-cycle are explained.

In the construction phase, the initial construction cost of air-conditioning systems, ventilation systems and telecommunication systems are incurred. The initial construction cost for scenario 3 involves the cost of 4 air-conditioned CPs and 61 ventilated CPs. All 65 CPs will be equipped with telecommunication systems (8 of them with telecommunication systems for base stations). The slope up to the year 9 results from the annual cost for the energy consumption for the cooling as well as from the annual adaption, refurbishment and replair cost for air-conditioning systems , ventilation systems and telecommunication systems. The jump in year 9 results from the first replacement cycle of telecommunication systems. The next jump in year 10 results from the first replacement cycle of the air-conditioning systems. Based on dynamic energy consumption, the slope between jumps is always a bit steeper over the years. Further jumps occur in the years 18 (second replacement cycle of telecommunication systems), in the year 20 (second replacement cycle of the air-conditioning systems and first replacement cycle of ventilation systems), in the year 27 (third replacement cycle of telecommunication systems), in the year 30 (third replacement cycle of the air-conditioning systems), in year 36 (fourth replacement cycle of telecommunication systems), in year 40 (fourth replacement cycle of the air-conditioning systems and second replacement cycle of ventilation systems) and in year 45 (fifth replacement cycle of the telecommunication systems).

Compared with sceantio 1 (black line in figure 4), which was adopted as a reference scenario (100 % after 50 years), scneario 3 reduces life-cycle cost by up to 20 %.

4.2. Dominance analysis

In the course of the dominance analysis, the most influencing factors on the overall result. were identified. Figure 5 shows the influence of the different cost categories in a sankey diagram. The considered cost categories are assigned to the technical systems (air-conditioning systems, ventilation systems and telecommunication systems) on the right side of the sankey diagram. Telecommunication systems of standard CPs and telecommunication systems of CPs with base stations were merged in this illustration.

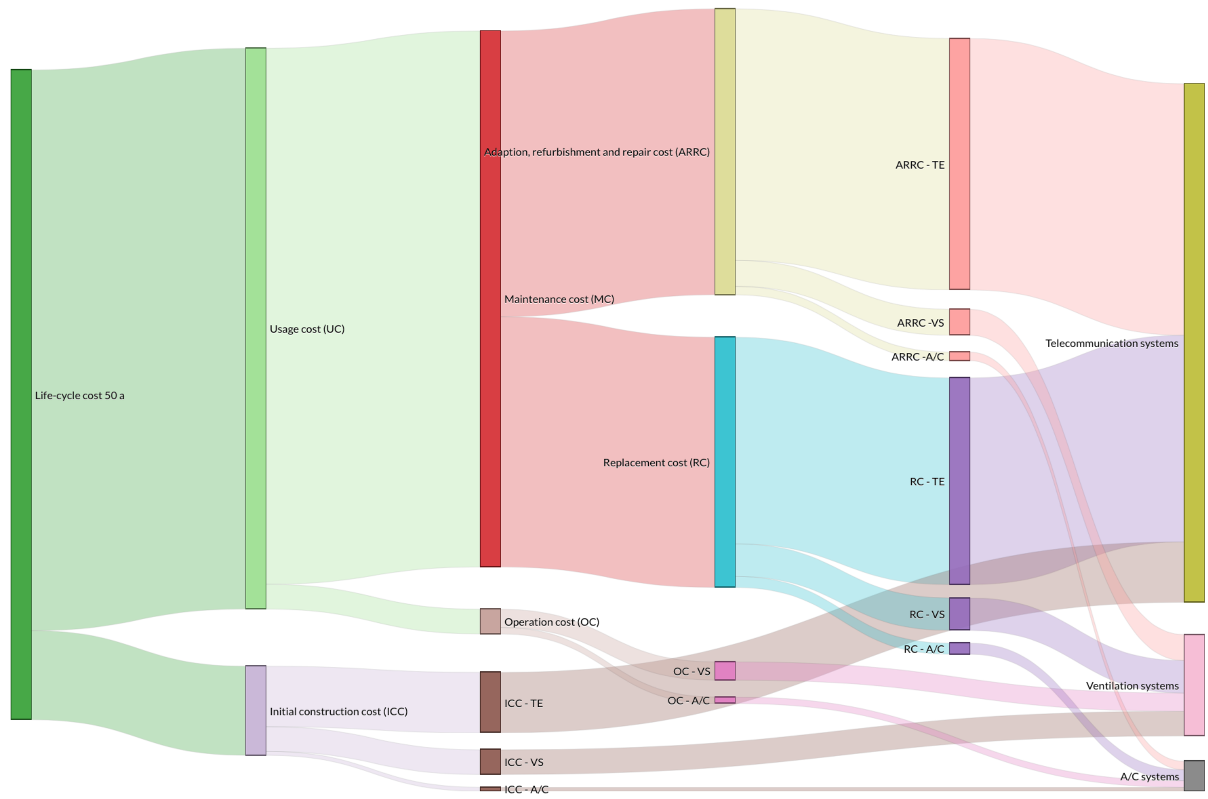

Figure 5. Sankey diagram for scenario 3 (target temperature 30 °C)

The life-cycle cost after 50 years are initially divided into approx. 86 % on usage cost and approx. 14 % on initial construction cost. A closer look at initial construction cost shows that the air-conditioning systems have a very small influence on the initial construction cost, followed by the initial construction cost of ventilation systems and telecommunication systems. The usage cost are divided into maintanencance cost and operation cost. 73% of operation cost come from the energy consumption of the ventilation systems and 27 % from the energy consumption of the air-conditioning systems. The maintanencance cost are divided according to ISO 15686-5 in adaption, refurbishment and repair cost and replacement cost. The adaption, refurbishment and repair cost has a share of 53 % and the replacement cost a share of 47 %. Most of the adaption, refurbishment and repair cost comes from the telecommunication systems. These make up the decisive contribution with a share of 88 %. The second largest share is the adaption, refurbishment and repair cost of ventilation systems with 9 %. The remaining 3 % is provided by adaption, refurbishment and repair cost of air-conditioning systems. Even in the replacement cost the decisive stem from replacements of the telecommunication systems (replacement cycle every 9 years) with 83 %. Followed by the replacements of the ventilation systems with 13 % and the replacements of the air-conditioning systems with 4 %. In the right part of the sankey diagram, all cost categories are transferred to the technical systems. It can be clearly seen that the telecommunication systems account for the largest share of life-cycle cost (80 %.). The contribution of the ventilation system to the overall life-cycle cost is 17 %. Due to the low active cooled cross-passages (only 4 CPs with air-conditioning systems), the share of air-conditioning systems is only 3 %.

4.3. Sensitivity analysis

In the first step of the sensitivity analysis, based on the assumed initial input parameters (table 2), the parameters are changed individually and the effect on the life-cycle cost after 50 years was analysed. This procedure identifies the most sensitive parameters for influencing the overall life-cycle cost after 50 years.

Table 3. Sensitivity analysis for scenario 3 (target temperature 30 °C)

Initial input parameter	Minimum threshold	Input parameter	Maximum threshold
Interest rate	3.0 %	4.0 %	5.0 %
Rate of price incease	1.5 %	2.5 %	3.5 %
Rate of energy price increase	1.75 %	2.75 %	3.75%
Energy price	0.0625 €	0.125 €	0.1875 €
ARRC[1] ventilation systems	0 % of ICC[2] /year	3 % of ICC/year	8 % of ICC/year
ARRC air-conditioning systems	1 % of ICC/year	6 % of ICC/year	11 % of ICC/year
ARRC telecommunication systems	6.3 % of ICC/year	11.3 % of ICC/year	16.3 % of ICC/year
Service life ventilation systems	15 years	20 years	25 years
Service life air-conditioning systems	5 years	10 years	15 years
Service life telecommunication systems	4 years	9 years	14 years
Operating hours air-conditioning systems	3760 h/a	8760 h/a	13760 h/a
Operating load scenario air-conditioning systems	11 %	31 %	51 %
Operating hours ventilation systems	1200 h/a	3200 h/a	5200 h/a

1 Adaption, refurbishment and repair cost

2 Initial construction cost

In figure 6 the fluctuation of the considered input parameters after 50 years is shown. Accordingly, the economically positive effects are shown with the dark gray bars (below 100 %) and the negative effects are shown with the light gray bars (more than 100 %). The 100 % line represents the life-cycle cost after 50 years with unchanged input parameters (initial input parameters in table 2). The most sensitive screw within the life-cycle cost analysis is the service life of the telecommunication systems. If this information differs by 5 years (from 9 years to 14 years), the total life-cycle cost would increase by more than 45 %. The second and third most important parameters are the interest rate and the rate of price increase. With a fluctuation of the interest rate and the rate of price increase by plus/minus 1 % the life-cycle cost would increase by more than 20 %.

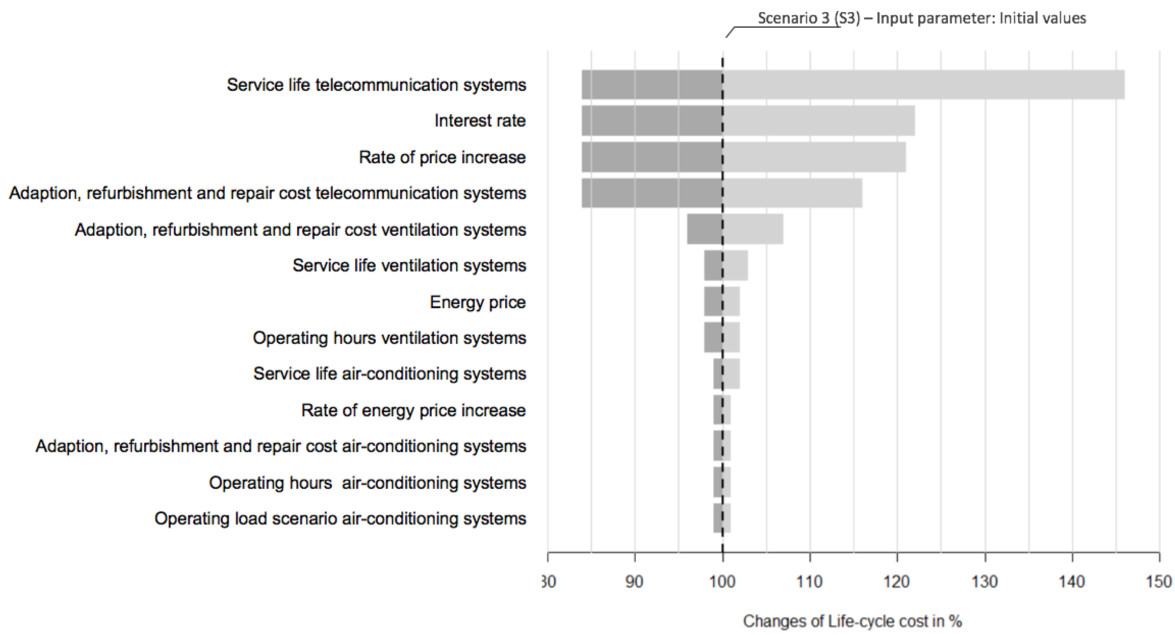

Figure 6. Sensitivity analysis of input parameters of scenario 3 based on the minimum and maximum thresholds (see table 3)

As shown in figure 6, the adaption, refurbishment and repair cost of the telecommunication systems - increasing life-cycle cost by more than 15 % at 5 % higher adaption, refurbishment and repair cost of the telecommunication systems - and the adaption, refurbishment and repair cost of the ventilation systems - increasing life-cycle costs by more than 6 % at 5 % higher adaption, refurbishment and repair cost of the ventilation systems - are also decisive parameters.

4.4. Risk analysis

In the course of the risk analysis it is examined with which probability the economically best scenario (S3 - target temperature 30°C) with fluctuating input parameters also remains the best scenario. For this purpose, the input parameters (interest rate, rate of price increase, rate of energy price increase and energy price) are stored within their bandwidths (see table 3) with a probability of occurrence. For the calculations, it was assumed for the parameters considered that the probability of occurrence between the lower and upper thresholds was 68.27 % (which corresponds to a standard deviation of sigma). Within these bandwidths random numbers were determined by Monte-Carlo simulation.

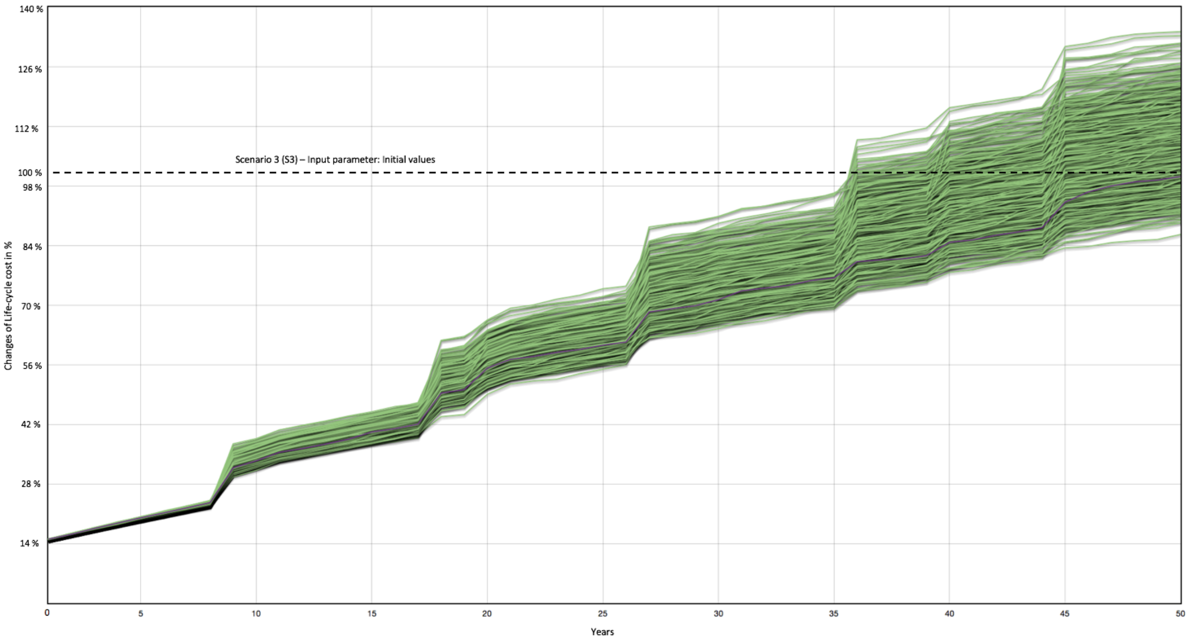

Figure 7. Risk analysis scenario 3

Figure 7 shows the range of life-cycle cost for scenario 3. As already mentioned, a large amount of uncertainty arises as the reference study period increases. In the year 50, due to fluctuations in the parameters, in best case up to 15 % lower and, in worst case, up to 30 % higher life-cycle cost could occur. A comparison of all 4 scenarios in a risk analysis is not required. A different fluctuation of the input parameters in different scenarios can not occur.

5. Discussion

The first calculation run has shown that the decisive input parameters are the required cooling energy for air-conditioning systems and ventilation systems. This required energy input is significantly influenced by the classification of the cross-passages (cooling with air-conditioning systems or ventilation systems). From these findings, the extreme value scenario (all CPs equipped with air-conditioning systems) was discarded after the first calculation run and the focus was placed on the reduction of the required energy demands. The most obvious optimization measure with regard to the reduction of the life-cycle cost was the change of the cross-passages classification. With higher target temperatures, it is possible to equip less cross-passages with air-conditioning systems and thus reduce the energy consumption.

After completion of the second calculation run, it was found that, the cross-passage classification for the target temperature 30 °C (scenario 3) is the most economical scenario over a period of 50 years,.

Allowed target temperatures of 35 °C (scenario 4) exceed the life-cycle cost of scenario 3. The reason for this is that at 35 °C target temperatures the decisive parameter is the replacement cycle of the telecommunication systems (every 3 years). This huge cost factor can not be compensated with the reduced energy demand in scenario 4 (no CPs equipped with air-conditioning systems).

In the dominance analysis, it can be seen that the cost drivers for the most economic scenario are the maintenance cost of the telecommunication systems. This finding is also confirmed by the sensitivity analysis carried out. The uncertainties in the service life of the telecommunication systems would most affect the overall life-cycle cost. The final risk analysis repeatedly emphasizes that life-cycle cost analyzes are always subject to uncertainties. Future developments of interest rates or price increase rates can not be predicted and can therefore only be taken into account with scenario analyses.

6. Conclusion

In the course of the study, it has emerged that an accompanying life-cycle cost analysis has a medium to long-term economic advantage in the construction of railway projects. The life-cycle cost can be considerably reduced, if the results of the LCCA are incorporated into the planning of cross-passage classification iteratively. Due to the great influence of energy consumption, the location of technical equipment (power units for low voltage, medium voltage, transformer systems and telecommunication systems) should be determined early in order to calculate the resulting waste heat in detail. Therefore, the design of the utility rooms should be tailored to the technical equipment in an early design stage.

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Integrated evaluation of energy and emission reduction potential and management strategies for urban road systems

Anastasio S[1], Wu S[2], Bohne R A [1], Passer A[3], Spaun S[4], Kristensen T[5], Li J[6], Xie J[2], Kreiner H [3], Hoff I[1], Barbieri D M[1], Vignisdottir H R[5], Lau A[1], Amirkhanian S[1], Hoxha E[3]

[1] Department of Civil and Environmental Engineering, Norwegian University of Science and Technology, 7491 Trondheim, Norway
[2] State Key Laboratory of Silicate Materials for Architectures, Wuhan University of Technology, 122# Luoshi Road, Wuhan, Hubei 430070, P. R. China
[3] Institute of Technology and Testing of Construction Materials, Graz University of Technology, 8010, Inffeldgasse 24 Graz, Austria
[4] Zement+Beton Handels- und W. GmbH, Franz-Grill-Straße 9, 1030 Vienna, Austria
[5] SINTEF AS, SINTEF, P.O. Box 4760 Torgarden, NO-7465 Trondheim, Norway
[6] Institute of Blue and Green Development, Shangdong University, Shanda South Road No. 27, P.R. China

sara.anastasio@ntnu.no

Abstract. Solving the problems of high energy consumption and high emissions generated by the urban road systems is of great importance for the construction of low-carbon cities. Several tools have been developed to establish a method to evaluate the carbon emission related to the life cycle of road pavements. However, the lack of key basic data such as energy consumption, pollutants and carbon emissions, and accurate management policies have hindered the transition of urban roads to clean, low-carbon systems. The HERMES project aims to compile long-term dynamic inventory of urban road energy consumption and environmental emissions and build a life cycle model. The Data Envelopment Analysis model will be used to predict the energy saving and emission reduction potential of urban roads depending on the technological solution, establish a multi-criteria evaluation system that includes energy, environment, and economic parameters, identify the best available technological solution in different cities, and propose a more targeted and effective clean low-carbon management policies. The study will provide an accurate understanding of the environmental impact of urban roads in China and Europe, evaluate the potential for energy saving and emission reduction, and provide theoretical data and decision-making reference for a clean, low-carbon transition.

1. Introduction

More than 275 million tons of asphalt are produced every year in Europe alone for maintenance and rehabilitation of roads (1). This consumes large amounts of resources and contributes to the emission of greenhouse gases (GHG). This equals approximately 30 million tons of CO_{2eq} emissions from the production of asphalt for maintenance and rehabilitation alone (EPD Norway). However, roads are heterogeneous in their design and construction; the global warming potential (GWP) associated to these operations shows a large variation, depending on the material composition, procedures and maintenance. Typical values vary from almost neglectable to 60 000 tons of CO_{2eq} per lane km over a 50 year time

period (2). In order to reduce the negative impact related to maintenance and rehabilitation of urban roads, the goal of HERMES project is to provide a methodology enabling the selection of the best available technology and strategy with the lowest cost for the environment and society.
The final output of the project would therefore be a matrix usable by road owners and contractors to define, based on the local conditions, regulations, restrictions and technology availability the best solution for the construction or maintenance of the road in terms of environmental factors, financial investment and local boundary conditions.

2. Objectives and targets

Targets for a greener future are being set worldwide. To achieve these goals, a shift towards more sustainable technologies is required in all fields including road construction, maintenance and rehabilitation. Better asphalt mixtures and technologies have a great potential to contribute to the reduction of greenhouse gases, pollution and energy consumption (3). The introduction of a procurement system based on sustainability criteria could encourage the development of more efficient and durable solutions. Several methodologies (LICCER, CEREAL, EDGAR (4, 5)) have already been developed and EPDs are becoming a standard procedure: the general trend highlights the shift towards more environmentally friendly technologies. The limited success, in terms of direct use by others, of the previous projects was due to several factors such as the extend of the life cycle considered, the flexibility in considering additional new technologies, the possibility to adapt the tool to local conditions and requirements and most important user friendliness and practicality. It has therefore been of crucial importance to consider all those factors already from the conception of the project.

A suitable tool to analyse the operations connected to road construction, maintenance and dismantlement thoroughly is represented by Life Cycle Assessment (LCA) . Previous researches have highlighted the most important inputs, system boundaries, functional units and limitations connected to the LCA of pavement infrastructure (6, 7); furthermore, LCA is a holistic tool that can be used to assess the impact of using both traditional and alternative materials (8). LCA is a data-intensive methodology strongly dependent a variety of inputs connected to various scientific fields; acknowledging the deficiencies of the LCA conducted so far can allow HERMES study to define a more transparent assessment framework, thus contributing in synergistic fashion the literature and previous researches (9, 10).

The overall objective of the HERMES project is to establish a long-term dynamic inventory of carbon emissions deriving from the analysis of a variety of urban roads, based on best practices is Europe and China. The main research tasks are connected to the following areas:

1. Energy consumption and emission patterns throughout the life cycle,
2. Best available technologies for road pavements,
3. Clean and low-carbon construction and maintenance operations.

The project aims to improve emission reduction management policies that can be adopted to promote the sustainable development of urban road systems in China and Europe. Currently there is no cross-national comprehensive comparison regarding the different road design methods and their environmental impacts on the service-life in different urban settings and climate zones.

The development of HERMES project will be based on the following criteria:

- User-friendly and global
- Comprehensive
- Sustainability oriented
- Performance oriented
- Tested in collaboration third parties.

To achieve the main objective, the following targets have been identified (refer to figure 1 for short work package (WP) description):

1. Review of the available methodologies and technologies for the assessment of green asphalt (and other construction materials) (WP3)

2. Analyse the procurement processes including a sustainability assessment (WP3)
3. Broaden and improve the data inventory by including information about pavement life time prediction (WP3 and 4).
4. Assess the effects of maintenance schedule on emissions (WP5).
5. Test the validity and usability of the HERMES tool (WP6)
6. Establish the bases for further implementation and cooperation (WP2, 3 and 6).

In order to avoid a strictly national approach, the project acknowledges that road construction operations are influenced by climate mitigation policies that contribute to different SDGs (Sustainable Development Goals). Thus, a more integrated approach can allow for a broader understanding of mutual dependencies in the development of road construction. This will provide a more detailed insight into the actual design and operating of road constructions.

Moreover, the project is especially aimed at creating a management system able to take into account the pavement life cycle, environmental, social and economic issues. Special emphasis is put on how the management and monitoring operations are performed when it comes to evaluate climate change policies. For a better mutual understanding and implementation, the methodologies will be applied in trial road sections in both Europe and China.

The project involves trans-national cooperation between Norway, Austria and China, and is meaningful for both research institutes and stakeholders of road construction projects. The collaboration also addresses how road constructions in Norway, Austria and China approach sustainability assessment in their strategies. Therefore, HERMES project entails the exchange of knowledge, analysis of policy making strategies and identification of differences in planning frameworks at an international level.

The LCAs connected to HERMES project take the first steps considering the limited amount of literature currently available regarding pavement infrastructure. These investigations have been carried out on countries that are geographically close to the nations involved in the HERMES project: Sweden (11), Finland (12), Switzerland (13), South Korea (14) and Taiwan (15).

The project contributes to ongoing scientific discussion by adopting different interdisciplinary insights. On one hand, the project provides a more practice-oriented research perspective to sustainability assessments, at road constructions which enables to discuss how the context of urban processes and subsystems is conceptualized in these assessment methodologies. Rather, this project aims at developing ways to contextualize assessment methodologies from the perspective of stakeholders' practices. On the other hand, the project provides a more assessment-oriented research perspective to practice and transition studies in relation to sustainable development.

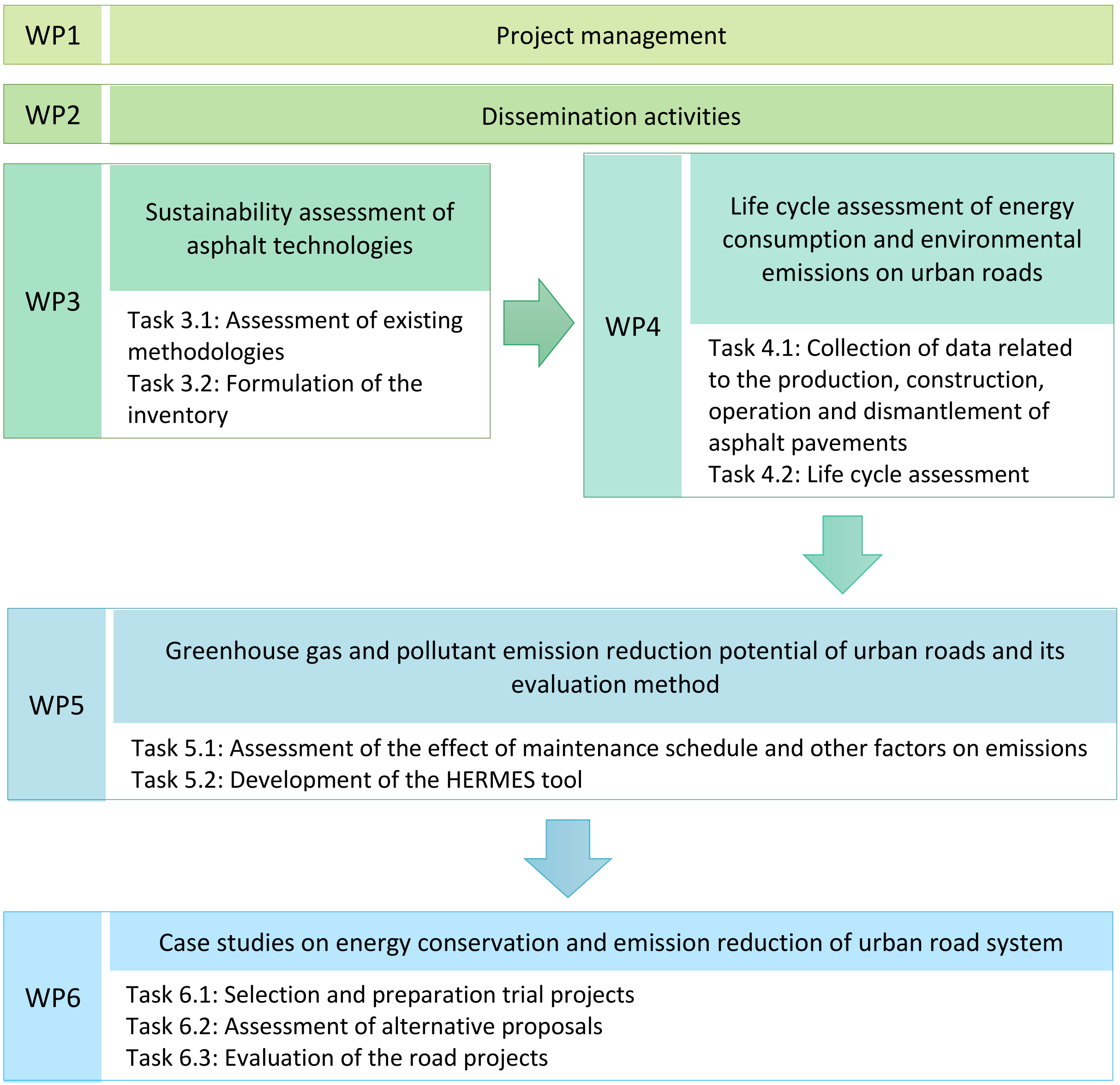

Figure 1: Work package description

3. Key activities

The overall objective of the project is to create a tool able to help both stakeholders and contractors reducing the impact of pavement maintenance and rehabilitation on the urban environment in terms of both energy consumption, emission and pollution production, efficiency and cost-effectiveness through a more efficient and effective planning. At the end of the project, the existing gaps will be filled, and a functional methodology will be available, rising the technology readiness level from 5 to 8. Therefore, the project will start from an analysis of previously developed tools and procurement processes based on sustainability criteria leading to the formulation on the basic framework of the HERMES project (WP3). At the same time a high resolution dynamic inventory of emissions from urban roads construction and maintenance will be created (WP3).

Once the energy consumption and emission sources have been identified and analysed, an appropriate life cycle analysis method (Simapro and Ecobalance) will be used to quantify the effects of urban road systems on resources, energy and environment in both the Chinese and European case (WP4). Great importance will be put in the uncertainty/variability assessment of the different indices used in the analysis.

The next step (WP5) is focused on the development on the HERMES tool based on considerations on how other factors, such as pavement service life, maintenance schedule, and innovative technologies influence the computation of the technical indices. In this step it will be important to emphasize user-friendliness and flexibility of the tool. The tool shall be able to integrate the evolution of energy saving and emission reduction potential with management strategies for the urban road systems. Collaboration and cooperation between the partners and dialogue between the work-packages will be central enabling factors to facilitate and make the success of the project possible.

While the other work packages will progress towards the development of the HERMES tool, the WP6, centred on its utilization, will start its activities in large advance to guarantee a smooth cooperation with the local stakeholders and contractors during the preparation of the procurement tender and contract documents. The extended period of time will also allow the contractors to gather data and information to calculate the technical indices to be considered in the procurement process. Once the alternative proposals will be assessed, the partners will evaluate the case studies and how stakeholder and contractors interacted with the HERMES tool.

4. Expected impacts

The expected outcome of the HERMES project is to analyse effective ways of assessing environmental impact of both present and future urban road systems. The project interdisciplinary approach enables a meaningful connection between stakeholders of road construction projects, policy maker practices and sustainability assessments.

A major challenge of the project is to ensure a proper holistic integration of the many perspectives and interests of the involved parties. The non-hierarchical structure of management should facilitate the execution of such an interdisciplinary project.

The potential users of research project are mainly stakeholders of road construction projects, policy makers in municipalities and similar organizations that are responsible for developing strategic plans and project concerning climate mitigation solutions. The project is also intended to challenge the national and international policy making systems (like that of the European Union), since these often play an important role in defining the planning framework for the development and access to strategic plans. There is a general need to recognize the difficulty of bridging between the local complexity of specific plans and projects, and the abstract methodological complexity of sustainability assessments. This challenge can only be addressed through a more thorough understanding how these issues intersect in the practices of policy makers.

Since the project entails a tight Sino-European collaboration, the differences in creating policies are important to be taken into account. Generally, when a study is carried out at a purely national level, the specific social, technical, geographical and organizational norms of the country are often neglected or overlooked. A trans-national project will ensure that these critical differences between different countries involved in the project are surfaced and addressed. Such a trans-national perspective will also contribute to help to address the scaling challenges more specifically, since it will become clear that the three countries operate within similar global contexts, but within different national and local conditions.

5. Expertise of the consortium

The project brings together a unique combination of research knowledge and expertise to underpin the development of the HERMES tool at international level. The consortium is formed by five research institutions (SINTEF, Graz University of Technology – TUG, Norwegian University of Science and Technology – NTNU, Wuhan University of Technology – WUT and Shangdong University) with key knowledge in the project's topics and an enterprise (Zement+Beton Handels- und W. GmbH (Z+B)) who has already widely contributed to the development of sustainable solutions for concrete roads with the implementation of tools and regulation for their construction and maintenance.

This consortium combines environmental, technical and social research competences, hereby representing a truly interdisciplinary consortium that analyses quantitative sustainability assessments and social dynamics of change and practices in relation to technical infrastructures and networks in an urban context. This provides a more holistic basis for developing assessments tools and methods to be more effectively adopted to achieve reductions in GHG emissions through climate mitigation policy making. The partners have a well-recognized leadership, expertise and skill in the following crucial areas for the project:

- Management and coordination: SINTEF
- Greenhouse gas and pollutant emission: NTNU, TUG, Shangdong University and WUT, Z+B
- Energy consumption: TUG, Shangdong University
- Life cycle analysis: NTNU, TUG, Shangdong University, Z+B
- Road materials: SINTEF, NTNU, WUT
- Life cycle cost assessment: SINTEF, NTNU, Shangdong University, Z+B
- Road pavement construction, maintenance and rehabilitation: SINTEF, NTNU, WUT,
- Z+B
- Communication, dissemination and exploitation of results: SINTEF, NTNU, TUG,
- WUT, Shangdong University, Z+B

For the assessment of existing methodologies, a large effort is expected by all partners. The internationality of the group allows to gather information about projects and procurement processes using sustainability indicators to evaluate road pavements around the globe, giving the opportunity to finally extend the analysis to the Asian context that because of language and cultural barriers has always been difficult to approach. The involvement of other research groups and local stakeholders will be necessary.

Shangdong University and WUT, together with TUG, Z+B and NTNU will also have an extremely important role in the assessment of both emissions (including greenhouse gas and VOCs) and energy consumption due to pavement construction and maintenance. During this phase the partners will gather information also through direct contact with local contractors.

SINTEF, NTNU and WUT are nationally and internationally known for their expertise in pavement design, maintenance and rehabilitation. Their knowledge, previous research projects and local contacts will be used to assess the service life of different pavement technologies. Their impact on emissions and energy consumption will then be assessed by TUG, Shangdong University and Z+B.

A common effort will be put in the development of the HERMES tool and in the case studies.

Acknowledgments

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Life Cycle Assessment of Alternative Road Base Materials: the Case of Phosphogypsum

Saadé-Sbeih M[1], Feraille A[2], Alaoui Soulimani A[2,3]

[1] EIVP, 80, rue Rébeval, 75019, Paris, France
[2] ENPC, NAVIER, 6-8 avenue Blaise-Pascal, 77455 Champs-sur-Marne, France
[3] OCP group, 19 rue Hamelin, 75016 PARIS, France

myriam.saade@eivp-paris.fr

Abstract. Phosphogypsum (PG) is the most abundant by-product generated by the phosphate fertilizer industry. Formed during the production of phosphoric acid from natural phosphate rock, PG is mostly disposed in stacks or released into coastal regions' waters. Due to the expected increase in the world PG production – currently estimated to be around 250 Mt per year – and the environmental impacts of actual waste management scenarios, there is a call for a paradigm shift, by considering PG not as a waste but as a resource. About 15% of the total PG production is nowadays used as fertilizer, retarder, road base material or building material. The load of radionucleids and heavy metals contained in PG however questions the sustainability of such valorization routes. This paper aims to compare the environmental impacts of different PG valorization scenarios through life cycle assessment. Based on Moroccan conditions for phosphoric acid production, it discusses the key parameters influencing the assessment as well as assumptions regarding the allocation of emissions and resource use over PG and phosphoric acid.

1. Introduction: Phosphogypsum: waste or resource?

Phosphogypsum (PG) is the most abundant by-product generated by the phosphate fertilizer industry. It is formed during the wet production process of phosphoric acid, after digestion of natural phosphate rock with sulpuric acid (eq. 1). On average, the production of 1 ton of phosphoric acid (as P_2O_5) generates 5 tons of dry PG [13].

$$Ca_5F(PO_4)_3 + 5H_2SO_4 + 10H_2O \rightarrow 3H_3PO_4 + 5CaSO_4{\cdot}2H_2O + HF \qquad \text{(eq. 1)}$$

PG is mainly composed of gypsum but also contains impurities such heavy metals (Pb, Cd, As...) and radionucleids (Uranium-238, Thorium-232 and their daughter elements such as Ra-226), naturally occuring in the phosphate ore [3],[7]. Because of its low radioactivity, PG has been considered as a waste and is mostly stored indefinitely in open stacks (Florida, China) or discharged into the sea close to coastal regions (Morocco, Tunisia, South Africa...). Both PG disposal routes have environmental impacts and costs [20]; [4];[10];[17].

In 2013, the International Atomic Energy Agency concluded that "[a]ll evidence suggests that the doses received as a result of the use of PG in agriculture, road construction, marine application and in landfill are sufficiently low that no restrictions on such uses are necessary.” [11]. As a consequence, there is a call for a paradigm shift, by considering PG not as a waste but as a resource [12],[5].

Due to the increasing demand in phosphate fertilizers at global scale, PG production – currently estimated to be around 250 Mt per year [19] – is expected to increase, as well as the environmental impacts of actual waste management scenarios. About 15% of the total PG production is nowadays used as fertilizer, retarder, road base or building material [6]. The sustainability and environmental suitability of such valorization routes are however to be investigated.

The objective of this paper is to assess the environmental impacts of PG valorization as road base material throughout its life cycle. It aims at 1) comparing environmental burdens of “conventional” versus alternative road base materials, respectively granulate and PG mixtures; 2) assessing the potential displacement of environmental impacts from a life cycle stage to another; and 3) discussing the influence of allocation approaches on the assessment. It presents preliminary results of a study conducted at the Ecole des Ponts ParisTech in collaboration with the OCP group. Based on Moroccan conditions for phosphoric acid production, it discusses the key parameters influencing the assessment, and assumptions regarding the allocation of emissions and resource use among PG and phosphoric acid.

2. Goal and scope definition

2.1 Goal

The main objective of this study is to compare the potential environmental impacts of formulations used as base layer containing different proportions of PG.

2.2. Functional unit (FU)

The functional unit (FU) considered in this case study is an experimental road pavement structure of 200 m length, with a width of 7 m. The PAP is 25 years. The average annual daily traffic (AADT) is considered to be equal to 15 heavy duty vehicles (HDV)/day. The FU is defined as a “unit of pavement that can safely and efficiently carry the same traffic over the same PAP” [15].

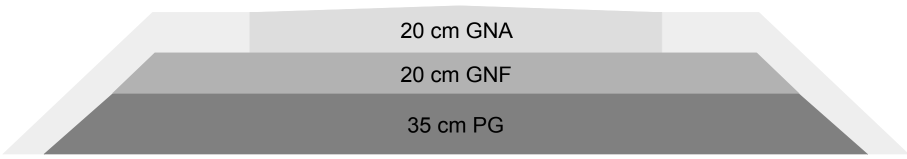


Figure 1 – Experimental road pavement cross section, modified from [14]

The pavement structure (Figure 1) is composed of 20 cm bank-run gravel type A (GNA), 20 cm bank-run gravel type B (GNB), and 35 cm phosphogypsum mixture (PG) as base layer, the latter being under scrutiny. Table 1 presents the formulations of the PG mixture used for the base layer, as described in [14]. The baseline scenario is a base layer composed of 100% granulate. The 4 phosphogypsum mixture scenarios have different proportions of PG and waste rock, and a constant 7% dry mass binder material, as cement 42.5. All materials are produced in Morroco, in less than 100 km radius from the road pavement construction site. As a first approach, it is assumed that the total dry weight of material required for the FU is equivalent for all scenarios (1200 t/UF). This assumption should be further discussed.

Table 1 – Formulation of the phosphogypsum mixture used for the base layer (%dry mass equivalent)

	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Granulate	100	0	0	28	0
Cement	0	7	7	7	7

Phosphogypsum	0	57	65	65	93
Waste rock	0	36	28	0	0

2.3 System boundaries

The system boundaries of this study (Figure 2) include the extraction and production of road base material such as granulate, cement and PG; the material transportation from the production site to the road pavement construction site; the on-site laying of the base layer; and its use over the PAP. The PG formulation is assumed to have no influence on the lifespan and maintenance of the road structure. Therefore, extraction and manufacturing of materials for upper layers GNA and GNB are not accounted for, as well as road maintenance processes and the end-of-life (see below). Waste rock generation during phosphate rock washing (see below) is also excluded from the system.

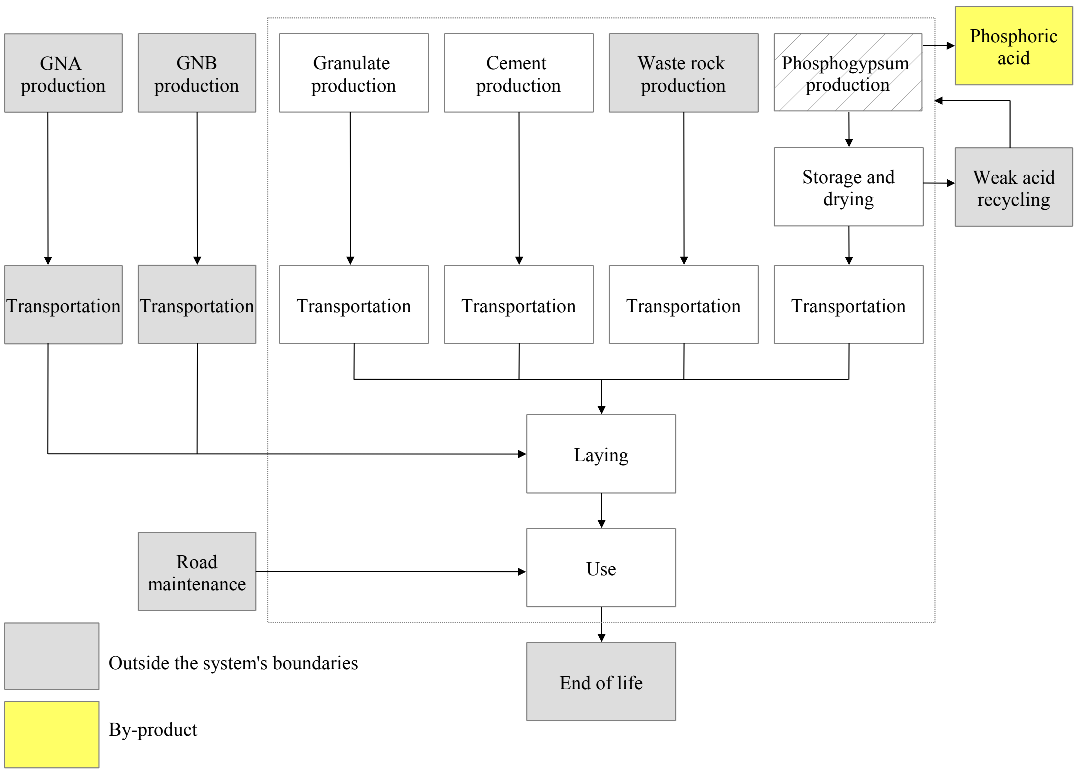


Figure 2 – Flowchart of major processes in the life cycle of a road pavement structure

In order to match Morrocan conditions, manufacturing of virgin materials (granulate and cement 42.5) are adapted from French processes, described respectively in [18] and [2]. Since no electricity mix exists for Morroco, Greek electricity mix from ecoinvent, "*electricity, medium voltage | market for electricity, medium voltage – GR*" is chosen for its proximity with the Morrocan mix (23% coal, 61% oil, 5% gas, 7% biomass, 2% renewable, 2% import, no nuclear energy, ref). It replaces the French electricity mix used in the processes where nuclear energy predominates.

PG production is adapted from the ecoinvent process for phosphoric acid production in Morroco, "*phosphoric acid production, dihydrate process | phosphoric acid, fertiliser grade, without water, in 70% solution state, MA*", described in [1]. After extraction, phosphate rock is beneficiated through screening, washing and flotation. The beneficiation process does not involve adjunction of chemicals. Reaction between beneficiated phosphate rock and sulphuric acid produces phosphoric acid and PG. Substances reported in the original ecoinvent process and emitted during disposal of PG into the ocean are allocated among the use and end-of-life stages, where 100% of heavy metals and radionuclides are leached into groundwater. Emissions, raw material extraction and environmental impacts generated by this multifunctional system are partitioned between the two co-products based on the “cut-off” approach, meaning that environmental burdens are attributed to phosphoric acid alone [16], as a first step. The influence of allocation methods is discussed below.

After attack of phosphate rock with sulphuric acid, the generated PG slurry (30% water content) is conveyed, stored in open tailings ponds and air-dried. Acidic pond water is partially recovered (about 15% of the total volume) and reinjected in the phosphoric acid production process, before adjunction of sulphuric acid [8]. Although this is common practice for Morrocan conditions, the recycling of weak phosphoric acid and the benefits associated with avoided sulphuric acid production are not included in the system. Air-dried PG (15% water content) is recovered for further use. PG recovery thus avoids waste management where PG slurry is diluted in the Atlantic ocean (see above).

Distances and vehicle types for road base materials transportation are taken from [14].

The on-site laying process is assumed to be the same for all formulations, i.e 30 minutes mixing, except for the baseline scenario where no mixing is required [14].

During the use phase, only direct leaching to groundwater of water soluble substances contained in PG is taken into account. While all substances particularly trace elements and radionuclides contained in PG are directly emitted into sea water when disposed into the ocean (avoided waste management scenario), addition of cement to the PG mixture has an inerting effect [9]. Contaminants are trapped in a solidified matrix and only a part is leached with precipitation water. The crucial point is to determine the flows of pollutant potentially tranfered into groundwater. Since no data are currently satisfactory to estimate transfer coefficients, assumptions about the inerting effect of cement are made. It is assumed that 100% of the impurities are emitted into groundwater (no interting effect: worst case scenario), based on the transfer coefficients into sea water estimated in ecoinvent [1]. This assumption will not be discussed in this paper.

Exposure to radioactive substances resulting from airborne particle emissions are usually carefully considered [1]. In our case, phosphogypsum mixtures are used for road subgrade layer construction, the emission of airborne particules from abrasion during the use phase is considered inexistant.

For the end-of-life, it is assumed that the road pavement structure is rehabilitated after the end of the PAP, i.e. after 25 years. Rehabilitation of the road pavement implies scraping the surface course, excavating the base layers GNA, GNB and PG which are mixed together, compacting the road foundation, applying the mixture as base layer and renewing upper layers. As a consequence, the rehabilitated road pavement structure is raised 10-15 cm. The effective lifespan of the road is not known. Since it is assumed that the PG mixture does not influence the rehabilitation frequency and lifespan of the pavement structure, the only discussion is about the long term fate of contaminants and how to allocate pollutants release between the use and the end-of-life. Too many uncertainties are attached with the fate of such structure, the end-of-life is then excluded from the system.

3. Results and discussion

The OpenLCA software version 1.7.4 is used for the modelling of the scenarios and calculation of environmental impacts scores. The chosen impact assessment method is RECIPE (H), at midpoint level.

3.1 Impact assessment

The LCIA scores for the road pavement scenarios are calculated by applying the RECIPE midpoint (H) method. Environmental impact scores are calculated considering that first burdens related to phosphate rock processing is totally attributed to phosphoric production (cut-off approach: Schrivers et al (2016)), second no substitution related to the avoided waste management of PG (disposal into the ocean) is taken into account and third 100% of the heavy metals and radionucleids contained in PG are released into groundwater during the use stage of the road (worst case scenario).

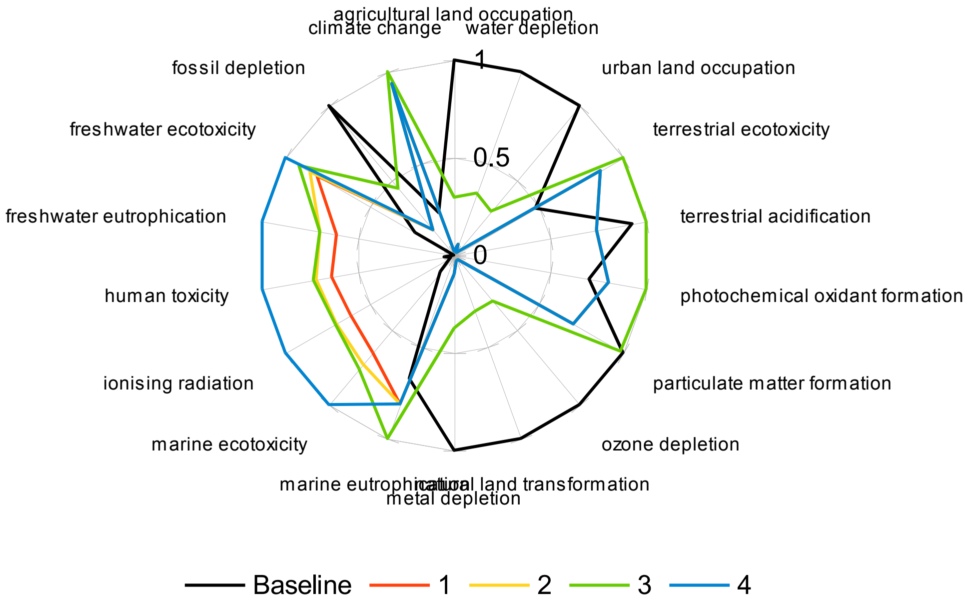
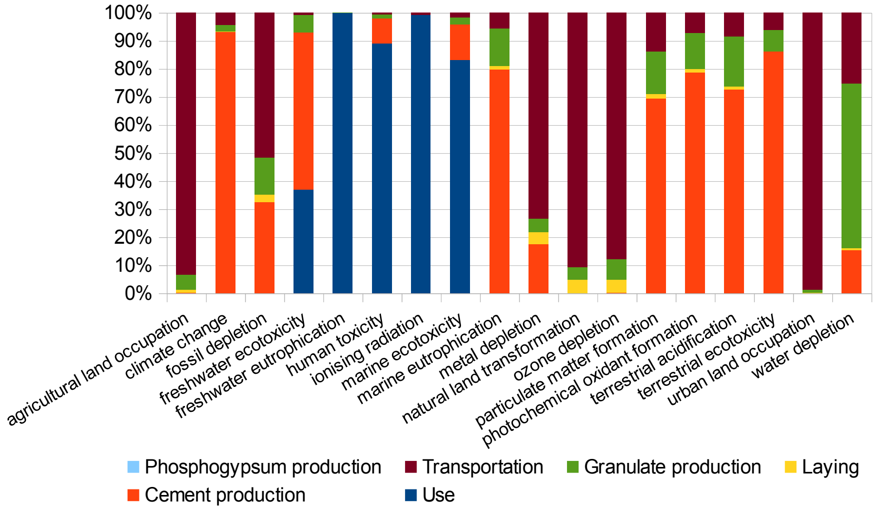


Figure 3 – Relative LCIA results for the road pavement scenarios, calculated with RECIPE midpoint (H), cut-off approach, 100% transfer to groundwater, without substitution

The results presented in Figure 3 show that phosphogypsum mixtures scenarios are improving the environmental performance of the road pavement for impact categories such as ozone depletion, metal depletion and fossil depletion, compared with the baseline scenario (hight impact related to transportation).



(a)

(b)

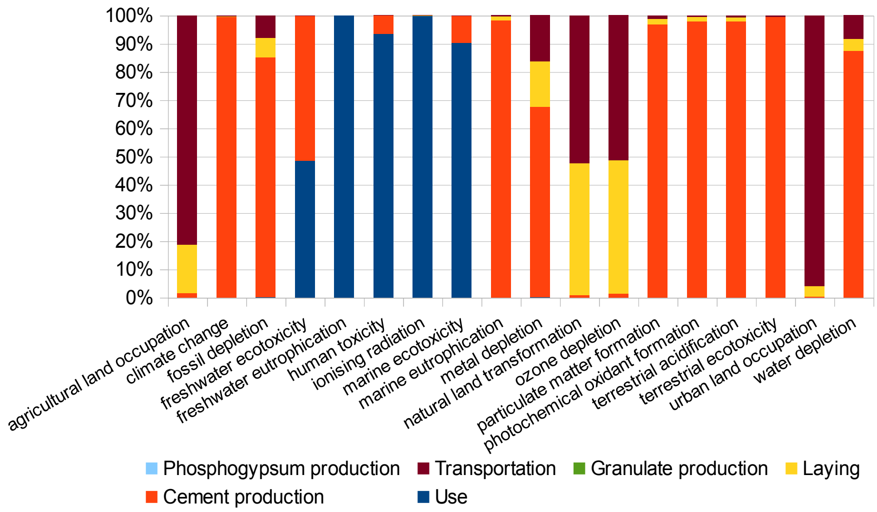


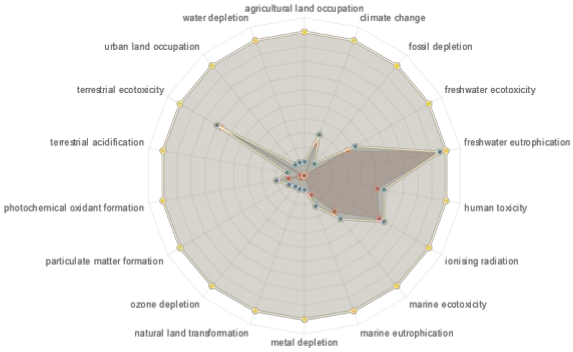
Figure 4 - Relative impacts for a) road pavement scenario 3 and b) road pavement scenario 4, life cycle stages, cut-off approach, 100% transfer to groundwater, without substitution, ReCiPe Midpoint (H)

Scenario 4 presents the highest impact scores for freshwater ecotoxicity, freshwater eutrophication, human toxicity, ionising radiation and marine ecotoxicity because of heavy metals and radionuclides transfered to groundwater (Figure 4). Scenario 3 shows the higher scores for impact categories such as terrestrial ecotoxicity, terrestrial acidification, photochemical oxidant formation and climate change. Effects on climate change are related to the production of cement as binder in the phosphogypsum mixtures, as production of cement induces decarbonation.

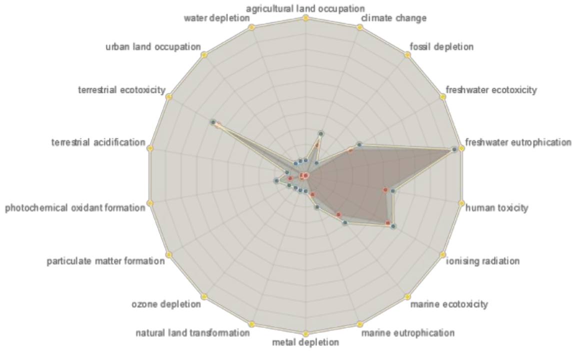
3.2 Sensitivity analysis: influence of allocation methods

PG is generated during the production of phosphoric acid. Previously, emissions, extractions and related impacts have been allocated between the two co-products based on the cut-off approach (Schrivers et al 2016). According to this approach, environmental impacts of phosphate rock extraction and processing are attributed to phosphoric acid alone. The choice of allocation methods however influences significantly the impact scores. Figure 5 compares the relative impacts of scenario 1 to 4 calculated based on the cut-off approach and two other partitioning methods (based on mass and market price of substituted material). With mass allocation, since 1 kg P2O5 in acid and 4.83 kg PG are produced during the processing of phosphate rock, 82.8% of the environmental burdens are attributed to PG. With economic partitioning, it is assumed that 1 t of PG substitutes 1 t of granulate (30 €/t); and 1 t P2O5 in acid worths 350 €/t. Therefore, about 8% of total impacts are attributed to PG.

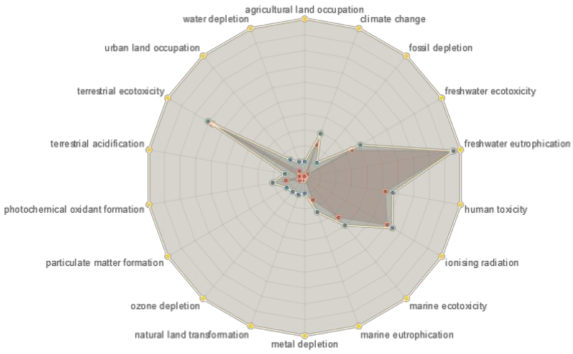
Considering that 100% of the environmental burdens associated with the extraction and processing of phosphate rock are attributed to PG has a significant influence on the calculated impact scores. According to the mass allocation approach, the PG production stage generates the greater impact for almost all categories.



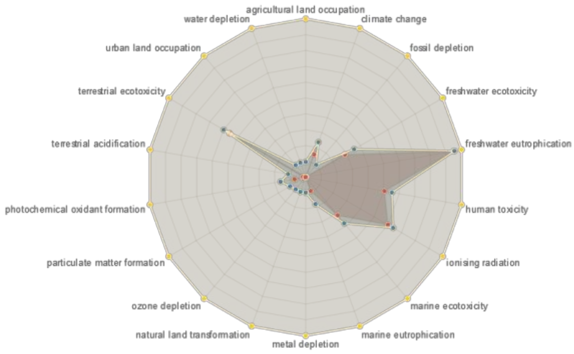
(Scenario 1)



(Scenario 2)



(Scenario 3)



(Scenario 4)

Figure 5 – Relative impacts for road pavement scenarios, according to different allocation approaches (orange: mass allocation; red: cut-off; blue: economic partitioning). 100% transfer to groundwater, without substitution, ReCiPe Midpoint (H)

4. Conclusion

Preliminary results show that, with 100% transfer of heavy metals and radionuclides into groundwater, direct emissions during the use stage of the road pavement structure are responsible for major impacts on human health and ecosystem quality. This assumption however ignores the inerting effect of cement. It is then necessary to specify transfer coefficients from phosphogypsum mixture to groundwater and to take into account the temporality of such transfer. Allocating the effects of heavy metals and radionuclides leaching between the PAP and the long term (end-of-life) has to be discussed as well.

The impact of cement consumption in the PG mixtures predominates for climate change, particulate matter formation and photochemical oxidant formation. Decreasing the proportion of cement in the PG mixture should be investigated parallel to its inerting effect.

Preliminary results are based on the hypothesis of no abrasion during the use phase, because PG is used in the base layer mixture and not in upper layers. Scenarios taking into account abrasion processes and particulate dissemination in different environments (with low to high population density, for example rural and urban areas) are to be discussed for longer PAP.

The impact assessment shows the influence of several parameters. The choice of the electricity mix is important, especially regarding ionizing radiations. There is no ecoinvent electrictity mix for Morocco and the available African electricity mix is not suitable. The allocation method has a great influence on the results. By allocating emissions and extractions based on mass, PG production is the life cycle stage with the higher impact score for most categories.

Finally, substitutions related to the replacement of virgin material (granulate) by phosphogypsum mixtures and the avoided waste management scenario (PG disposal into the ocean) are not taken into account. This should be further investigated.

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Towards housing sustainability: a framework for the decision-making process of tenants

Pagani A, Binder C R

Laboratory for Human-Environment Relations in Urban Systems (HERUS), École Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland

anna.pagani@epfl.ch

Abstract. The mismatch between the supply and demand of rental apartments in Switzerland represents an obstacle to the transition towards a more sustainable society. The difficulty for the housing providers to accommodate the fast societal change of the demand brings about an increase in vacancies and, to minimize investment risks, a resistance to innovation in the building sector. In this context, understanding the determinants of tenants' residential mobility and location choice becomes key to designing and promoting sustainable housing. In this paper we present a new interdisciplinary framework for the decision-making process of tenants. To do so, we elucidate the main parameters of the decisions to move and where to move, based on literature review and a group discussion in the Swiss canton of Vaud with the tenants of the two housing providers SCHL and Swiss Mobiliar. We find that the desired housing *function* determines the tenants' housing selection. We observe that this desired function changes according to the type of trigger that pushes tenants to move. Additionally, we elicit the potential sustainability implications of the housing functions in the Swiss context. We conclude that the framework can serve as a starting point for rethinking sustainable interventions in the housing sector.

1. Introduction

Considering that nearly a third of the global final energy use and CO_2 emissions comes from buildings, and that 75% of these are residential [1], the transition towards sustainable housing is crucial. The ways to implement this transition are, however, still unclear. In fact, housing is a central and interconnected part of an urban system, whose complexity makes both the system understanding and its sustainability assessment a difficult endeavor [2]. As a consequence, and despite the many attempts to conceptualize it, housing 'sustainability' remains an ambiguous notion that is rarely regarded – as proposed by the 2015 UN Geneva Charter on Sustainable Housing [3] – in its environmental, economic, social and cultural components. Furthermore, each of these components is often weighted very differently [4] by each of the actors in the housing value chain, whose requirements and expectations do not always coincide [5]. This mismatch manifests itself in the rental housing market, where discrepancies occur between the needs and strategies of the housing providers (e.g., apartments layout, location, features) and the ones of the increasingly fast changing demand (e.g., ageing population, high divorce rate, trend towards single living).

Currently, in Switzerland, the mismatch between the residential preferences of the tenants and the offer of the housing providers is resulting in increasing vacancies [6], which often involve new constructions: in June 2017, 1 in 6 vacant apartments (ownership and rent) was newly-built [6,7].

Therefore, an increase in the number of new low-carbon and zero-energy housing solutions cannot support alone the transition towards sustainability: for these solutions to be effective, dwellings need to be rented. However, this is not possible if buildings and related measures negatively impact users' quality of life e.g., by layout restrictions, occupancy rules, or the need to move to a different home if their circumstances change [8]. In fact, when the buildings cannot accommodate users' needs, these move to adjust their housing disequilibrium [9]. On these premises it becomes clear that ensuring *acceptability* and *acceptance* of housing sustainable solutions is crucial for determining their success, and overcoming the 'innovation resistance' of the building sector.

To understand the factors governing the success of sustainable housing solutions, the identification of the driving factors determining people's decisions has been proven to be key [10]. In the context of residential mobility and location choices, these factors have been studied by a multitude of disciplines [9,11,12]. They can be grouped into the two following categories:

- *The triggers: the determinants of the decision to move*. Triggers are situational or 'push' factors'[11] – such as opportunities (e.g., new job), problems (e.g., noise), changes in family structure – that affect the stress threshold of the household. When this threshold is overcome, the household moves to adjust its housing disequilibrium [9].
- *The determinants for the selection of a new dwelling*. The household perceives its housing environment in terms of characteristics [9], defining both the dwelling (balcony, view, materials) and its context (the location and neighborhood). The characteristics that play a role in the selection of a new dwelling are divided in 'non-substitutable' (must be there) and 'substitutable' (interchangeable) [11].

Concerning the triggers, previous research shows (1) that the determinants of the decision to move are not equally influential and effective in exceeding the household's stress threshold and (2) that these determinants have unequal correlations with the level of satisfaction of the household [9]. Therefore, greater study of the interrelationships between the triggers, the level of satisfaction of households with their dwelling, and the final decision to move is needed. With regard to the determinants for the selection of a new dwelling, studies have prioritized the role played in the decision by the characteristics of dwelling, location and neighborhood, which, grouped in categories, have long defined the building *typologies* used by practitioners (e.g., 'Multi-family residential'), or researchers (e.g. for the sustainability assessment in the construction sector [13]). However, households may not necessarily group the characteristics into categories as theorized by economic publications [9].

Therefore, it becomes clear that, in the context of rental housing, the study of the decision-making process of tenants needs a systemic understanding. To acquire system knowledge and explore the interrelationships between the decision components, we address the following research questions (RQ):

- **RQ1:** Which determinants prevail in the decision for the selection of a new dwelling?
- **RQ2:** How do the triggers influence the decision to move?
- **RQ3:** Is there a relationship between the triggers and the determinants for the selection of a new dwelling?

In this paper we propose an interdisciplinary framework, which links the elements playing a role in the decision-making process of tenants. The framework displays the interaction between supply and demand, advancing the hypothesis that, being the determinant of the system's dynamics, the *function* of housing plays a central role in the housing decisions of tenants. Furthermore, investigating how this desired housing functions can hinder sustainable housing strategies allows us to question how sustainable interventions are currently designed or promoted.

We structure the paper as follows. First, we introduce the methods for identifying the determinants of the decisions to move and to choose a new dwelling. Subsequently, we display the framework obtained, the functions and their validation, and explore the determinants of the decision to move based on the analysis of the qualitative group discussion in the Swiss canton of Vaud. Lastly, we critically review the methods adopted, the results, and our contribution to the practice, and conclude with an overview of the next steps of the research.

2. Methods

2.1. Project Partners

This research was carried out in collaboration with two of the largest housing cooperatives in Switzerland, ABZ and SCHL, and a large insurance company and institutional property owner, Swiss Mobiliar. SCHL (Société Coopérative d'Habitation Lausanne) owns over 2'100 dwellings in and near Lausanne and ABZ (Allgemeine Baugenossenschaft Zürich) about 5'000 in or near Zurich. Swiss Mobiliar, an institutional property owner, owns 3'500 dwellings located all around Switzerland.

2.2. Framework Development

To acquire system knowledge, we first developed a systematic conceptual framework by conducting interdisciplinary literature review. Theoretical frameworks are fundamental in interdisciplinary contexts, where their use allows for the integration of disciplines [14]. To develop the framework, we scanned literature by discipline and subject and defined the boundaries of the system studied. Following this step, theories were identified and combined in a first conceptual representation displaying the relationship between variables. Furthermore, literature review supported the identification of the different functions fulfilled by housing, which were then represented in a table structured in line with the system elements (Table 1).

2.3. Qualitative Group Discussion

To assess whether the theories and assumptions of the framework were *credible* (or to ensure the *internal validity*) [15], we organized a group discussion. The group discussion allowed us to validate the functions, and to further explore their relationship with the trigger. The structure of the group discussion was based on the *Pilot Study* proposed by Ajzen [16], where behavioral outcomes, normative referents and control factors are elicited from a small sample of individuals.

2.3.1. Sampling. The group discussion took place in November 2018 in the École Polytechnique Fédérale de Lausanne, Switzerland. The location made it possible to gather the tenants of two project partners, SCHL and Mobiliar. After defining the sample universe, we adopted two different sampling strategies: the purposeful sampling first, followed by convenience sampling [17]. We then sourced the samples accordingly [18]. To contact the tenants, agreement on the data to collect was established with our partners, their technical administrations, and the Human Research Ethics Committee of EPFL (HREC). The final sampling resembled the original structure of the stratified purposeful sampling, involving 10 participants: 5 tenants of the SCHL and 5 of Swiss Mobiliar, among which 5 women and 5 men, 4 living alone and 6 in larger households. The total duration of the group discussion was about 2h, and the language used in the session was French.

2.3.2. Analysis. The group discussion was organized in 5 different phases. It investigated the tenants' reasons for moving as presented in the framework (*Phase 1*), the relevance of each housing function in the decision process (*Phase 2*), the 'non-substitutable' characteristics of their former and present dwelling (*Phase 3*), the determinants for the selection of a new apartment (*Phase 4*), and the lessons learnt during the discussion (*Phase 5*).

The material collected at the end of the group discussion was in form of drawings, post-its, questionnaires, and recordings. Data were then extracted, condensed and summarized. Code construction was followed by the design of qualitative tables for the analysis. The systematic presentation of information in the data displays allowed for comparisons and pattern recognition, and was used to draw descriptive conclusions [19]. Two matrices were found to be useful for data display: the checklist matrix and the thematic conceptual matrix. The first was used to display the diversity of determinants of the decisions to move and to choose a new dwelling; the second (Table 2) resulted from blending inferences drawn from the first and was used to analyze and display the relationship between the determinants of the decisions (to move, to select), the housing function and the level of satisfaction.

Furthermore, to validate the functions proposed, word counting was performed. Finally, from the data display, a summary set of analytic comments was laid down.

3. Results

3.1. The framework

Nested in the system of interactions between the social structure, with its rules and resources, and the natural and technical environment, the housing system is defined by supply and demand constraints [9]. The supply is the dwelling itself, with its characteristics (design, location, neighborhood) and the values, standards, regulations shaping it, while the demand is the result of the tenants' decisions. In order to investigate these interrelationships, we propose a conceptual framework for tenants' residential choices (Figure 1). The framework combines Binder's work [20], which is based on the Structuration Theory of Giddens [21], and the Theory of Planned Behavior [22].

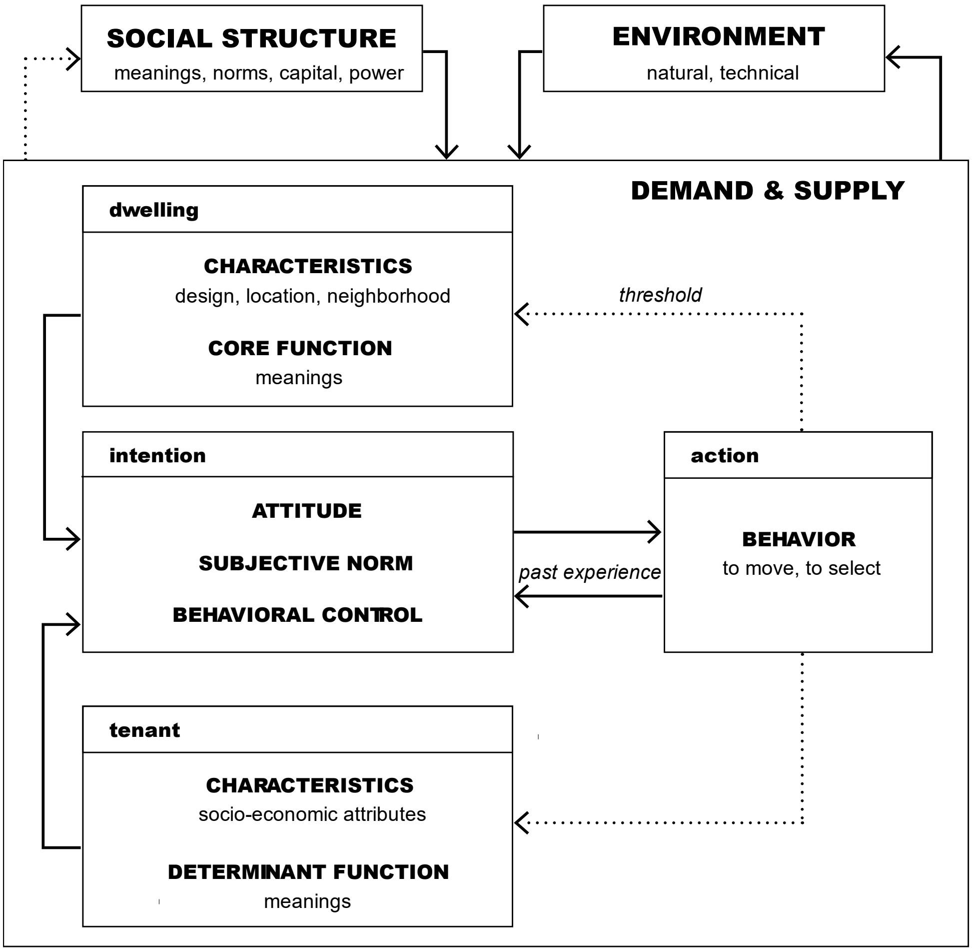

Figure 1. A new framework for tenants' residential mobility and location choice. The interaction between environment, social structure, and action is from Binder [20]; the intention and related factors are from Ajzen [22].

Binder's framework displays the interaction and feedback between social structure (e.g., legislation, culture, and economic system), human action (agent) and the environment [20]. More specifically, it displays that, when making decisions, agents consider external factors (i.e. the existing social structure conditions) as well as internal factors (i.e. their personal motivations and individual environmental awareness). At the scale of the agents, the work of Ajzen [22] provides insights for predicting and understanding tenants' decisions, determined jointly by the *perceived behavioral control* (or the ease or difficulty of performing the behavior of interest), the *attitude towards the behavior* (the favorable or unfavorable evaluation or appraisal of the behavior in question) and the *subjective norms* (the perceived social pressure to perform or not to perform the behavior). The framework considers the housing *function* as the determinant of the residential mobility and location choice of tenants. According to Meadows [23], the *function* of a system is the most crucial determinant of the system's behavior. Applied to the housing system, the housing function can be considered as determining the system's dynamics. Therefore, being nested in the larger housing system, the decision-making process of tenants is also affected by the housing function, which determines tenants' intention and final behavior. More precisely, this function originates in the social structure, which manifests itself through the sociocultural values [24] and collective meanings, later translated into material forms. The core function of the dwelling has to match the function that the tenant desires the dwelling to have, in line with the individual meaning it attributes to housing. This hypothesis makes it possible to overcome the heterogeneity and incompatibility of the research outcomes that have focused on housing characteristics as determinants of the household's decisions. Additionally, in the framework it can be seen how actions (to select a dwelling) provide diachronic (dotted lines) and synchronic (full lines) feedbacks to tenants, dwellings, the environment and the social structure (e.g., if a dwelling is often vacant, after a certain time threshold and according to the owners' strategies, its rent can decrease, or it can be demolished).

The *credibility* (i.e., internal *validity*) of the framework was assessed positively by the tenants during the group discussion. Firstly, preliminary results confirmed the applicability of the Theory of Planned Behavior to the housing case: the tenants considered the questions asked during the group discussion as pertinent, and were able to describe each intention component (e.g., *subjective norm*) that had played a role in their decision to move and select their current dwelling. Secondly, concerning the role played by the social structure in the decision, we recorded differences in the intention components between e.g., the tenants from the housing cooperative SCHL and the private investor Swiss Mobiliar, and tenants moving from foreign countries (undergoing a political transition e.g., Brexit). Lastly, we also proved the environment to play a role in the decision, in terms of awareness of the *natural* and *technical* possibilities in Switzerland (e.g., importance of view, green spaces, housing quality).

3.2. The role of the function

Dwellings are not only physical structures, but also social ones. The functions that these structures have to fulfill range from the basic provision of shelter and protection [25], to ensuring domestic activities [26], permanence, security, control, status, sense of belonging [27]. These functions vary among social groups and across history [28].

Table 1. Extract of the functions ranked by the tenants among the three most and three least important in the group discussion.

STRUCTURE	PURPOSE	BEHAVIOR	BEHAVIOR	BEHAVIOR	SOURCE
Changing factors	**Functions**	**Physical implications**	**Social implications**	**Potential implications (CH)**	
Location S-E status	**SHELTER** *refuge, protection*	-Basic house providing shelter	-Dream of the suburban house	-Obstacle to shared living	[25–27]
Location S-E status	**SECURITY** *for family and very restricted friends*	-Undifferentiated homes -Specific room function	-Desire for privacy -Recreation outside of the house	-Obstacle to flexibility and adaptability	[5,25,27–29]
Place of the individual in the culture	**IMPERMANENCE** *liberation from tradition and history*	-Comfort as negotiable social construct	-Different ideal solutions for household groups	-Increase in housing mobility and redistribution	[11,26,27,30]
Place of the individual in the culture	**PERMANENCE** *continuity, belongingness*	-Universal archetype of house -Long-lasting structures	-Rigid customs, codes and regulations -Attachment, identity	-Unsophisticated building technologies -Resistance to innovation	[5,11,24,27,30]

Table 1 displays an extract of the 9 functions derived from literature, organized according to the components of a system such as the structure, purpose and behavior. Each of the 9 functions proposed was ranked by the tenants at least once among the three most important functions of their dwellings. The function *Shelter,* followed by *Security*, occupied in the largest amount of cases the first, second and third ranking. The function ranked the most often among the least important, instead, was housing as a 'permanent' place. This can be explained by the fact that participants were tenants (and renting is not a long term investment). It must also be taken into account that international work migrants represent 1 in 3 persons in employment working in Switzerland [31] and frequently do not plan to stay permanently [32]. *Impermanence* was also a function often ranked amongst the least important. In fact, *Permanence* and *Impermanence* are not mutually exclusive: an impermanent dwelling might reflect the tenant's life-stage, needs and desires regardless of the future ones, while encompassing a desire for permanence, and an attachment to tradition.

Lastly, in the table, we introduce the 'potential implications' of each function specific to the Swiss context (CH), as discerned by the authors. Together with the physical and social implications, potential implications are relevant when considering the role played by each function in determining the behavior of the larger housing system. For example, the function *Shelter* can represent an obstacle to the use of shared spaces, and therefore hinder, in a sustainability setting, the goal of reducing the floor area per person.

3.3. The trigger

From the literature, we know that some triggers (1) are more effective than others, and (2) have unequal correlations with the level of satisfaction of the household with their dwelling [9]. Furthermore, triggers are difficult to represent in the framework, since they can influence all its components, and originate in each of them (e.g., a new child changes the household's characteristics and can result in the search for a new dwelling function and characteristics: larger, closer to school).

Table 2 displays the relationship between the levels of satisfaction, the situational factors (triggers), and the determinants for the selection of a new dwelling (functions, characteristics), resulting from the qualitative analysis of the group discussion. It is important to underline that this analysis does not lead to the design of a bidirectional link: the matrix displays only the trigger *needed* for tenants to move as observed in the data, or the link leading from the satisfaction to the trigger and function, and not the opposite (e.g., if the people with high satisfaction need an imposed trigger to move, it does not mean that all the people moving because of an imposed trigger have a high level of satisfaction).

Table 2. Thematic Conceptual Matrix: Relationship between levels of satisfaction and the mobility and location choices of tenants.

Satisfaction	**Low**	**Medium**	**High**	**High**
Trigger type	Trigger needed: Any trigger (AT)	Trigger needed: Opportunity (OP)	Trigger imposed 1: Radical Change (RC)	Trigger imposed 2: Problem solving (PS)
Trigger	Work opportunity	Opening of a bar, construction of a new building	Household formation (divorce, new family), retirement	End of contract, new job location
Characteristics	Correspond to what was missing	Some same others improved	New	Same plus problem solving
Function change	No change	No change	Change	No change
Function	Shelter	Asset; Impermanence	Production / Consumption; Property; Self-representation	Shelter

Four main observations can be made. Firstly, there is a relationship between the level of satisfaction of tenants with their dwelling *prior to the trigger* and the type of trigger pushing them to move. Secondly, the level of satisfaction determines the function and characteristics needed in the new dwelling. Thirdly, according to the different triggers, the function of housing is more, or less, prone to change; conversely, the function of housing suggests whether the tenants will be more keen to move or not. Lastly, there is a relationship between the change in function and the change in characteristics.

In fact, data show that when the level of satisfaction is low any trigger (AT) can push the tenants to move. In this case, the desired characteristics for the new dwelling correspond to the ones missing in the former location, and the desired function, which was not fulfilled, doesn't change. When the level of satisfaction is 'medium', instead, specific triggers are needed for people to move: opportunities (OP) (e.g., the opening of a bar, the construction of a new building in front of the current one) easily become triggers, presenting themselves to the tenants as favorable circumstances to improve some of the housing characteristics, and get closer to the desired housing function. Tenants belonging to this group display desired functions such as *'Asset'* and *'Impermanence'*, which suggest a greater propensity to move. When the level of satisfaction is high, an imposed trigger is the only push factor that can lead to the move. A radical change (RC) in the current life cycle stage (e.g., household formation, retirement) results in a change of the desired function: e.g., when retiring, the dwelling is not used for activities in after-work hours anymore, but rather for inviting friends and spending the day. The functions the most common in this category are the '*Property*' and the '*Self representation*'. Furthermore, tenants with high satisfaction are often forced to move because of another type of imposed trigger: problem-solving (PS). Examples of problem-solving are the end of the contract, or a change in job. In this case, tenants look for a dwelling with the same characteristics, of which one necessarily has to change to solve the problem. However, we must take into account that housing choices are often compromises between the desires of each household component. Therefore, despite having high levels of satisfaction, small improvements in the characteristics can be recorded. This category of movers has been found to be related to the function '*Shelter*', whose inhabitants tend to move only when conditions are not met (low satisfaction), or when triggers are imposed.

4. Discussion

The goal of this paper was to provide a systemic understanding to the study of tenants' decision-making process, in order to inform the actors in the housing value chain about housing dynamics and eventually mitigate the current discrepancies in the Swiss rental housing market, which prevent the promotion of innovative and acceptable housing solutions. We therefore answered the questions concerning the determinants for the selection of a new dwelling (RQ1), the role played by the trigger in influencing the move (RQ2), and the interrelationship between the determinants of the decisions to move and to choose (RQ3). We found that the housing *function* is the key determinant of the decisions to move and select the new dwelling: on the one hand it influences the level of satisfaction with the current dwelling (function is or is not fulfilled), on the other hand it changes – together with the dwelling characteristics – according to the type of trigger leading to the move and the level of satisfaction prior to the move. Other studies have previously explored the type of trigger, level of satisfaction and housing characteristics [9,11,12]. We go beyond these studies by integrating each of these components in the housing system, by means of an interdisciplinary approach.

It is also relevant to state the limits of this study. We acknowledge that, in the process of validation, the risk of *accumulating positive cases,* or gaining further evidence for the pre-defined hypotheses [33] can occur. Furthermore, *illustrative display formats* can lead to 'superficially comparable' but 'intrinsically different' data [19].

This research also provides relevant contributions to the practice. Practitioners can benefit from the housing functions as *reading keys* or *design tools*. More specifically, to ensure the success of the project in the long term, dwellings should be designed in such a way that they integrate more than one function, and therefore accommodate the new needs deriving from different types of triggers (e.g., change in family size). Furthermore, the implications of each function (Table 1) would also need to be (i) acknowledged (for a better understanding of a project's failure), (ii) overcome (as the starting point for a design e.g., *shelter,* but *permeable*; *permanent*, but *innovative*), and (iii) adapted to specific locations (e.g., Switzerland).

Based on these considerations, this paper was a first step towards a greater knowledge on the strategies for housing sustainability transition. Additional research in this direction should firstly assess the degree of dependence to the context of the results obtained, which can be done by implementing a second group discussion with the tenants of ABZ and Swiss Mobiliar in the canton of Zurich. Secondly, it should explore the correlations between the type (and not only change in) housing characteristics and the function. Thirdly, it should quantify the relationship between trigger, satisfaction and function. Thereby we consider that a survey, conducted with 10'000 dwellings from our partners, will allow for the methodological triangulation and quantification of the conceptual elements and links of the framework.

5. Conclusion

In this paper we proposed an interdisciplinary framework representing the elements playing a role in the decision-making process of tenants, with the goal to increase the knowledge on the housing system and support the transition towards housing sustainability. More specifically, we focused on the housing function as the determinant of the system's behavior. By combining the theories of Giddens [21] and Ajzen [22], we identified the determinants prevailing in the decisions to move and select a new dwelling as subordinated to the intention, and influenced by the social structure and the environment. In a group discussion with the tenants of our project partners, we further explored these components and their links, and validated the housing functions proposed. We found that the trigger influences the choice of moving according to its type (e.g., radical change) and the level of satisfaction prior to it. Additionally, we found that the determinants for the selection of a new dwelling (the function, and the dwelling characteristics) depend on the type of trigger leading to the move.

The housing functions are a new design challenge. We recommend practitioners from the housing sector, such as architects, urban planners and housing providers, to use them as a starting point to design or promote sustainable housing strategies that meet the needs of the tenants in the long term.

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Sustainable cities and communities – Best practices for structuring a SDG model

Neumann K
Scharbeutz, Germany

info@ilsa.de

Abstract. The UN's SDGs are powerful beacons to a better world yet some of their targets remain vague for the sake of special interest groups. They are sometimes synergetic and quite often ambivalent. On a concrete operative level it is therefore a challenge to plan for them fostering synergetic measures and minimizing trade-offs. Since many concrete projects that go for the SDGs are rather unique and need to consider many stakeholders, the systemic approach of a participatory explorative cause and effect modeling should be applied in order to tackle the underlying complexity of these projects. On the example of SDG 11 and with the use of the software iMODELER the approach is presented offering some best practice for structuring a SDG model, facilitating participatory stakeholder workshops, identifying levers for successful action, and establishing a culture of reflection. Although this approach has been applied successfully in Africa as well as in Germany it is also crucial to prevent typical hindrances. A kind of template for a model structure will be presented for both, a town in a developing country and a town in an industrialized country.

1. Sustainable cities and communities (SDG 11) – a complex challenge

Aiming for sustainable cities and communities should imply all three dimensions of sustainability – the social, the economic and the environmental. The United Nation's 17 Sustainable Development Goals (SDG) and their 169 targets represent these three dimensions of sustainability and only looking at their interconnections [14] reveals that some of them in practice could be contradictive resulting in necessary trade-offs while others might be synergetic at least in the long run.

Any strategic planning for sustainable cities and communities in general and following the SDGs in particular thus needs to consider this interplay of economic, social and environmental aspects. However, the prevailing practice seems to be economic aspects first followed by either social or environmental ones when regions seek for investors who aim for short term return on investment which often contradicts the provision of living space for low income families as well as the investment into green technology, better insulation, and the use of more expensive renewable materials. Environmental criteria could be set by regulation or demand. Social criteria are set only by regulation, or the lack of demand for the same space from higher income target groups that allow for higher margins for those who sell or lend space as well as for a higher tax income for the local government and higher revenues for local businesses.

All too often, thus, new buildings serve some short-term demand often in so-called pork cycles when many projects try to serve the same target group resulting in a delayed oversupply. Neither demographic change of more, less, or aging people, nor variations from demand driven prices and their long-term financing are considered. Also, if each plot seeks to maximize the utilized area and go for individual designs the region will lack green spaces and an attractive look from a common design denominator. So each region seeks to attract businesses and residents in order to provide jobs and tax income and its seems odd to argue for less short term economic gains for a greater benefit of society and long term economic opportunities as well.

The strategic planning becomes even more complex if we consider social aspects like the integration of different social milieus living in the same area (SDG target 11.A), visiting the same schools, and sharing leisure activities in order to increase variety for the greater benefit of society [9]. Adding to that a planning for intelligent mobility, public transportation, short distances, infrastructure for decentralized energy supply and optimized waste management for the long run becomes even more of a challenge since many planners are used to basing their assumptions on rather linear thinking and some sort of sovereignty of interpretation qua position.

This paper provides a tool - not a case study - to overcome this linear thinking and develop strategies that best fit the many SDG targets by revealing trade-offs and synergies. Therefore the aspects or examples mentioned are rather general, often trivial.

2. Reflecting on projects through explorative qualitative stakeholder modeling

Complex challenges in general are characterized by a large number of factors that need to be considered, by a large number of interconnections that form dynamics from so called feedback loops [18], [19], or by unpredictable behavior from elements in a system [7], [2], e.g. humans or the environment.

That means that unlike complicated challenges complex ones can never be fully predicted, yet there are tools for modeling that help us to overcome the limitations of our mind [6] to grasp the range of possible consequences from our decisions.

Modeling in general [19] means that we consider our challenge being a system that is defined by the interplay of its elements and that we need to define so-called system boundaries (time, space, detail), find a way to consider the crucial elements, and describe their interplay either qualitatively [12], [17] or quantitatively (through either System Dynamics, Agent Based Modeling or Neural Networks).

The next paragraphs will show a powerful way of qualitative modeling of a strategic plan to achieve the SDGs.

2.1. General approaches on modeling the SDGs

The number of approaches [1] to model the interplay of the SDGs is constantly rising. There are for example applications [8] of the iSDG by the Millennium Institute (www.millennium-institute.org) or the qualitative approach by the Stockholm Environment Institute [15]. And there is even an approach deriving causation from correlation of data from the target's indicators [16]. These approaches are obviously quite sophisticated and not easily applicable for concrete regions since only more or less predefined but no individual, potentially crucial aspects are included, and since the math and the use of the tools are typically expert's but not stakeholder's work.

2.2. Explorative modeling

As mentioned before it is crucial to consider the decisive elements – also called factors - of a system in order to grasp the underlying complexity. One way, of course, would be to already know what they are. In that case a model of their interplay would be descriptive. However, that seems very unlikely and therefore these kinds of challenges require what can be called explorative modeling.

Though there will never be a guarantee to have included the decisive factors there are ways to increase the likelihood of it. One way is to ask the stakeholders as described in the next sub-chapter. Another is to systematically ask the right questions for each factor within the model until the concrete measures and their dependencies are found. Established are the so-called four know-why questions from the know-why method [13].

They simply ask:

- What leads directly to more of a factor?
- What leads directly to less of a factor?
- What might lead directly to more in the future?
- What might lead directly to less in the future?

A facilitator of a workshop for example should then vary these questions and ask for organizational, financial, psychological, legal, etc. factors. The result is the visualization of arguments through factors that are connected with arrows either labeled with a "+" or a "-" meaning that more of one factor leads directly to more/less of the other factor. This way of presenting arguments can be seen as a kind of lingua franca that works in interdisciplinary professional settings as well as with kids in elementary school. Any project, strategy, paper, newspaper article or discussion can be visualized in this way [12].

2.3. Stakeholder modeling

There are two reasons for so called stakeholder modeling and some requirements to get it working. First, as already mentioned, we need to include the decisive factors and often there is information that isn't known to the decision makers or it gets underestimated in its potential consequences since it is not properly put into perspective.

The other reason is when you present your model containing hundreds of factors and the conclusion you draw from its analysis many people will reject what they don't take the time for to look into the details and of which they were no part of.

The requirements to get it working next to the ease of a lingua franca as described in the sub-chapter before are rather technical. The tool iMODELER (available as freeware, www.imodeler.info) that that was applied for this paper is constantly being improved for this kind of modeling, offering:

- a change of perspective from which one is looking at the model so that different groups can work on selected factors without getting overwhelmed by the spaghetti look of hundreds of other factors and connections.
- a collaborative modeling feature so that not just the facilitator is typing input but anyone from a group that brings a computer or smartphone. That way they grow ownership and navigate through the model by themselves looking for further crucial arguments.
- a repository of existing models to get proposals for further relevant factors from other cases, as given with www.know-why.net and the possibility to intelligently search all its factors right from a factor of one's own model. Stakeholder can then easily evaluate the need to include these proposals.
- a link directly to the model so it can be read and discussed beyond a stakeholder workshop.

The iMODELER has been applied for stakeholder - also called 'participatory' - modeling in various projects on SDGs [14] and regional development [10].

2.4. Qualitative modeling

The major reason to apply so called qualitative modeling probably lies in the effort it takes to build quantitative models and use data and formulas. Another often-named [11] reason for its use is its potential to translate fuzzy and qualitative arguments directly into a model, which is particularly important for participatory stakeholder modeling.

'Qualitative' means that an interconnection is defined simply by the already described arrows in iMODELER, and the modelers then later, once all influencing factors are connected, are able to decide whether this influence is weak, medium, or strong compared to other influences on the same factor. Also to be decided is whether these influences change from short- to medium- to long-term (figure 1).

From this rough, fuzzy differentiations as shown with the next subchapter some powerful conclusions can be drawn. It is important to note that stakeholders can easily agree on these rough weightings.

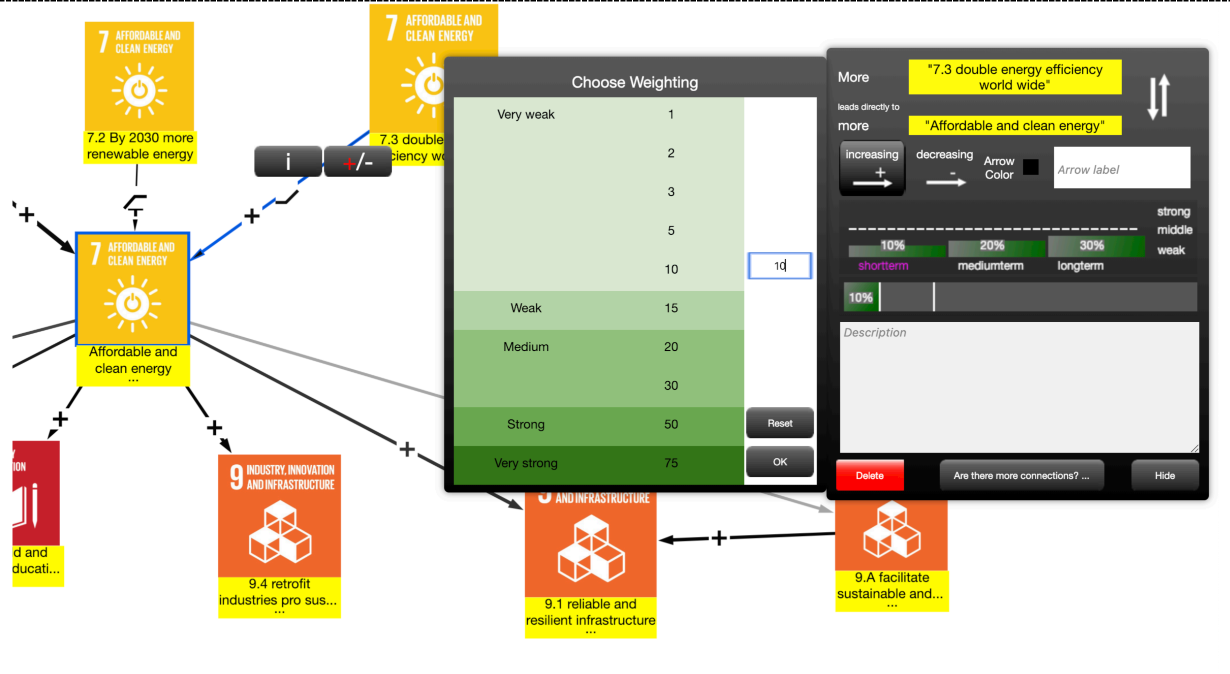

Figure 1. Weighting of connections within qualitative models.

2.5. Qualitative analysis featuring the Insight Matrix

Simulations of quantitative models show how, and with what likelihood something develops over time. A qualitative model can only compare impacts of factors within a system of interconnections, e.g. showing the potentially biggest risks or most promising action short-term, medium-term, and long-term with regard to a target factor of a model. Since these impacts stem from potentially various impact chains and interfering feedback loops that can be reinforcing or balancing it takes a computer to process the resulting effects [6]. The iMODELER offers an Insight Matrix [12] to compare the influences (horizontal x-axis) of factors and their change of impact over time (vertical y-axis) as shown in figure 2.

Reinforcing feedback loops could be both, virtuous or vicious cycles. For example more tax income from businesses could allow for more investments into public spaces that attract better-educated residents, thereby attracting more businesses. This dynamic can lead to both, an increasingly better region or an increasingly less attractive region.

An example of a balancing feedback loop could be that a dire situation causes pressure for political action and, once that action is taken and takes effect, leads to less pressure.

Modeling the SDG 11, Sustainable Cities and Communities, for a concrete region means that at least one factor is representing this goal. From its Insight Matrix the most important risks or hindrances as well as concrete actions should be derived. If one then continues to look at the Insight Matrices of these hindrances and actions, synergies and ambivalences or trade-offs can be identified that reveal crucial otherwise hidden aspects for successful strategies and projects [20].

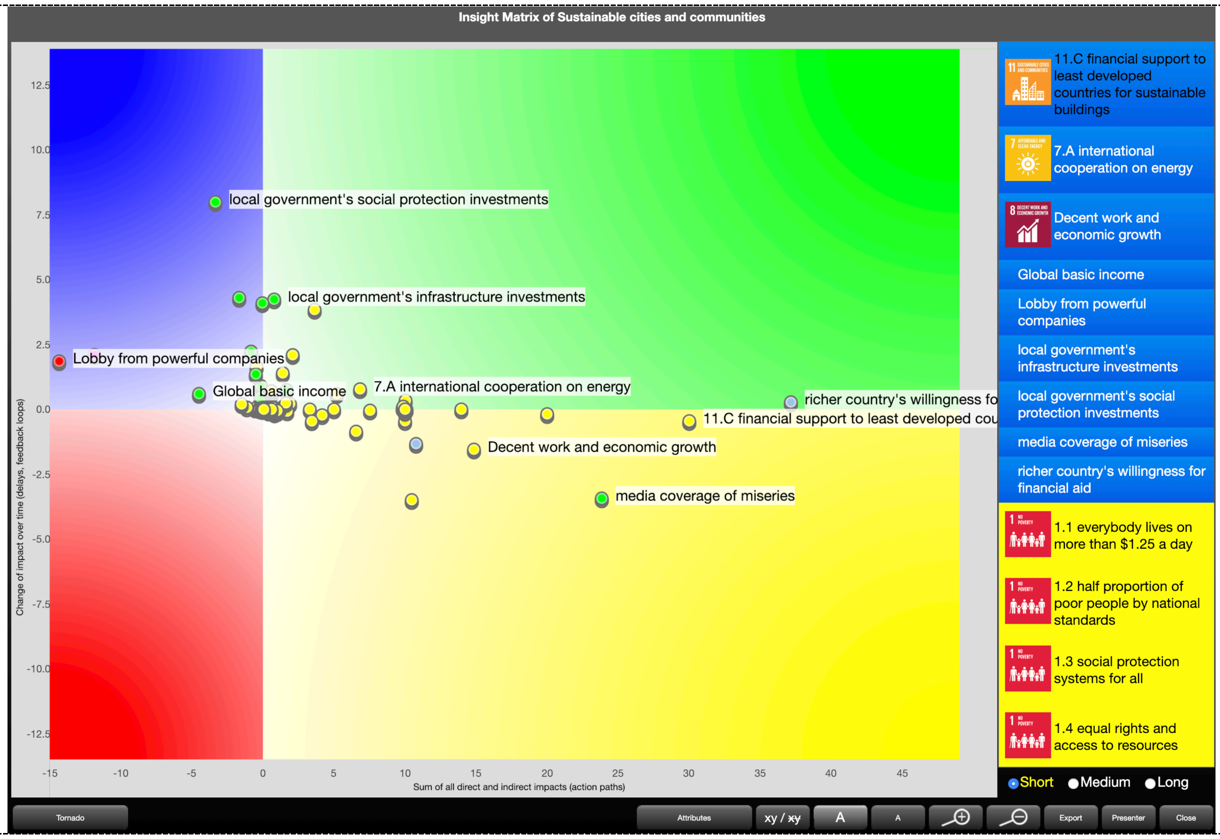

Figure 2. Insight Matrix to compare the influence of factors over time.

3. Templates to reflect on the creation of sustainable cities and communities

In principal one can start a model on the development of sustainable cities and communities from scratch by starting with that as a target factor and asking the aforementioned four know-why questions to explore the possible action and hindrances and their dynamics. But since the SDGs already feature sub targets for each goal and since they are meant to not been followed as isolated targets but rather synergetic it makes perfect sense to look at templates that have already connected the cause and effect relations between the targets and hence the goals.

One example that is publicly available and already featured in a published paper is the SDG model on know-why.net (https://www.know-why.net/model/CaLIsTKbVf7Yg5bm8yRXGyg) here shown with figure 3. It has more than 200 factors, more than 450 connections, and more than 13 million feedback loops.

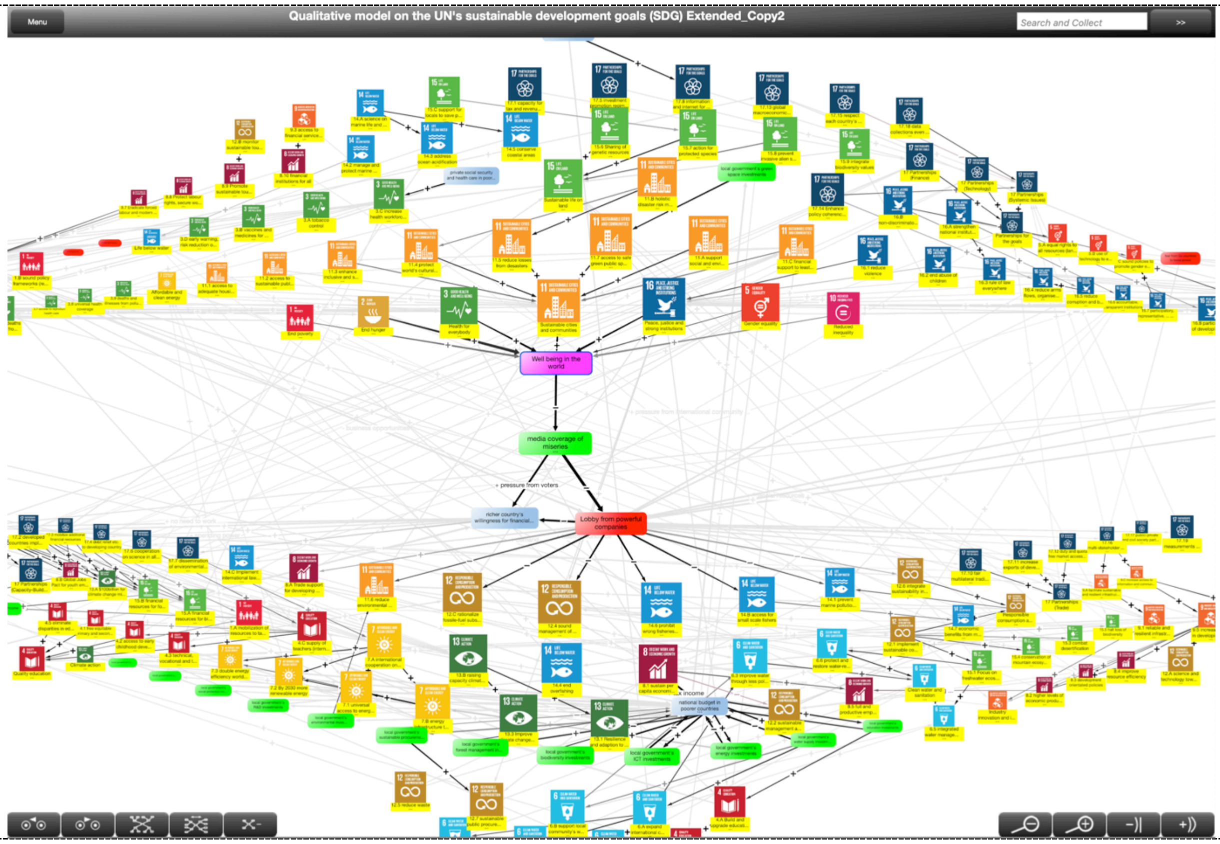

Figure 3. Screenshot of the general SDG cause and effect model from know-why.net.

Though it is a rather general model not focusing on a concrete region, it should be helpful to look for potential connections of each target with other targets. The model does not just connect the targets of the SDGs, it uses additional factors in order to explore and explain their interconnections.

Right at the beginning of the model an overall target called "well being in the world" was inserted and only 7 of the 17 SDGs directly influence this overall target while the rest are supporting these factors in some way.

Also between some of the targets the model features additional factors to show the interconnections. For example between SDG 8, Decent Work and Economic Growth, and many targets of SDG 17 on financing there are two factors, the "national budget in richer countries" and "richer countries' willingness for financial help", both influenced by further factors. This adds the possibility to explore the levers and hindrances for making a change actually happen.

It is crucial not to directly connect factors, for example each of the 169 targets with the overall target of well being in the world, if they are actually to be connected indirectly via other factors. The differentiated look at indirect connections, the so called cause chains and the feedback loops, is the added value of modeling. Drawing redundant direct connections [17] would make it impossible to draw conclusions from the model and its analysis.

Figure 4 shows the general model from the perspective of SDG 11:

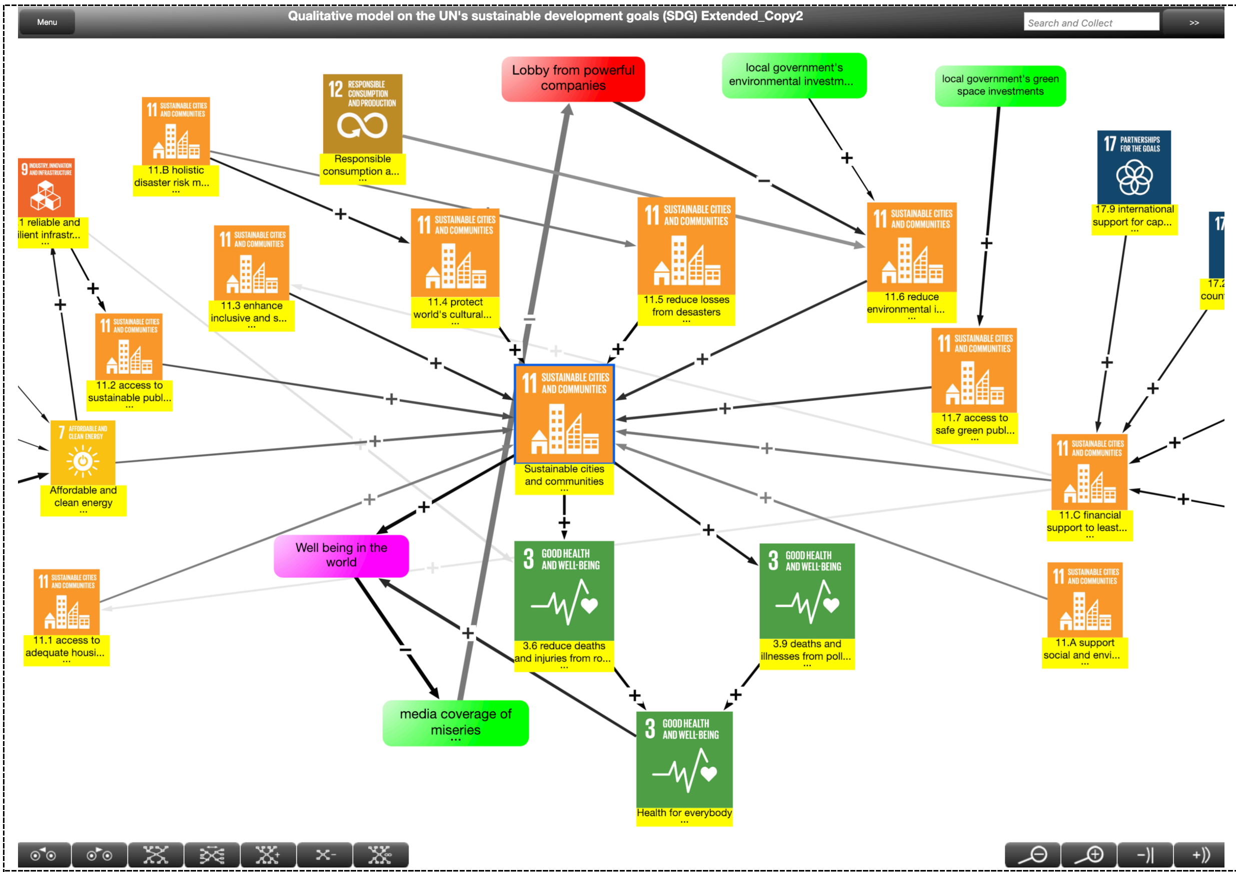

Figure 4. Screenshot from the general SDG model from the perspective of SDG 11.

Figure 5 shows the model from the perspective of SDG 7 and how this is connected to other sub targets and SDG 11 itself:

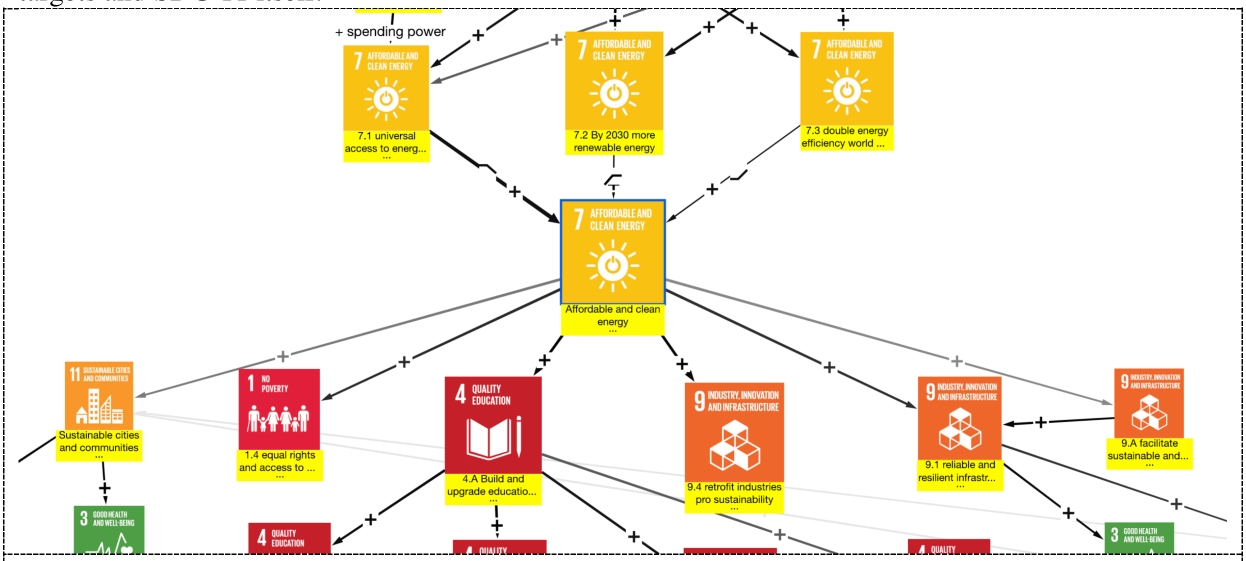

Figure 5. The general SDG model from the perspective of a sub target

Already the general model on SDGs reveals with its Insight Matrix of SDG 11 (figure 2) which targets from other SDGs are synergetic and which ones have the potential to be ambivalent. However, for a concrete region a facilitator can prepare a more concrete template.

3.1. Application for the "industrialized world"

The so-called industrialized world's population is not growing as fast as it is aging. Therefore younger people do not inherit property from their elders and need their own place to live in, which is why despite sometimes even shrinking populations there is a need for more housing. However, this implies a foreseeable decrease of need in the long run unless migration compensates for the low birth rates in those countries. A logical consequence is also the growing need for smaller and disabled friendly units. Some regions still face a rural exodus though this might change with growing numbers of home office workers and decentralized businesses [3].

Its infrastructure (e.g. SDG targets 9.1 and 11.2) features public transportation though road traffic from private cars dominates the need for space for roads and parking areas. Only recently some cities seek to provide more space for bicycle traffic. The trend to use cars to drive to outlet centers and to go for online shopping causes cities to lose businesses. The cities and their quarters thus need to plan for attractive, decentralized services that are accessible via public transportation.

Green spaces (SDG target 11.7), however, become rare since there is still a need for more housing coupled with an increase of real estate prices that could be derived from the low interest rates in the wake of the last financial crisis. And since the interest rates are low and prices are high there are widespread investment booms into new housing anywhere resulting in the pork cycle that was mentioned in the introduction. One challenge here is that today's standard will define the anthropogenic stock of resources (SDG target 8.4) and the need for energy (SDG target 7.3) for many decades to come.

Waste-water management (SDG 11.6), power supply (SDG 7), even communication cables are mostly established, yet infrastructure for the rise of e-mobility requires additional power lines and charging stations. As areas for photovoltaic panels rooftops and walls as well as pathways could be used. Rooftops also may serve as areas for urban gardening.

Active housing, that which supplies more power than it consumes, intergenerational living, short distances, access to public transportation and a lot more necessary for becoming more sustainable remains quite a challenge that requires reflection of its cause and impact relations. A model should always start defining the questions that it should help to answer! If it is the question "How to plan for a sustainable city and community?" the existing SDG model could be used as a starting point. Some targets, like '11.1 access to adequate housing and basic services', need to be either marginalized with a low weighing of their impact for a rich industrialized country, or they need to be differently interpreted e.g. as housing for all ages and income classes. Otherwise, they need to be referred to a partner city in a less developed country.

A factor like target '7.3 double energy efficiency world wide' is also interesting in its interpretation whether it means that the already high standards in industrialized countries should be increased or that they are allowed to point at higher possible margins of improvement in other areas of the world.

Starting from the given factors in the template one should continue with the four know-why questions until finally coming up with some concrete action and its required reflection. So, if for example, 'street lamps serving as charging station for e-cars' is the concrete action, one should ask how to finance it, what might cause problems, what might be a legal aspect, what is technically necessary, what might be the technology of the future, and so forth.

If it is a more detailed question that the model should answer, the model could start from scratch and use the SDG template only as a reference for inspiration. The four know-why questions should help develop a powerful explorative cause and effect model. In the context of buildings and infrastructure the questions should be varied and ask for financial, legal, organizational, social/cultural and technical levers and hindrances.

3.2. Application for the "developing world"

The so-called developing world has many more dynamics to consider when planning for its sustainable cities and communities. The worst way to develop would be the uncontrolled urbanization with all its problems of water supply, wastewater management, air pollution from road traffic, lack of standards to mitigate the effects from potential disasters (SDG target 11.4), and so forth. The second best way would be to copy the development of the industrialized world with its dominance of road traffic and the separation (neglecting SDG target 11. A) of privileged living areas from housing blocks or even slums for socially disadvantaged people. The best way would be to consider some leapfrogging to plan for cities that are more modern and sustainable than that of the industrialized world since many parts of them can almost be built from scratch.

In any case the developing parts of the world need investments. They could come from SDG target '11.C financial support to least developed countries for sustainable buildings', from investors that seek to profit from the domestic economy, from investors that seek to support the location of their business, or from investors that want to attract tourism. And, of course, there is still the possibility that a region does not strive for the typical western lifestyle with cars, petrochemical products and loads of luxury goods but instead embraces a more resilient, community centered way of living that could be based on a local bio-economy or sustainable tourism.

As for the template for a model for the industrialized world the questions that the model should answer are crucial. For rather general strategies and projects one could use the existing general SDG model. For more specific questions one might develop a completely new model using the explorative know-why questions again. One difference might be an increased emphasis on the questions what might lead to more or less in the future. For example, arguing for wider and more streets because of the increase of traffic jams that are bad for local business and investments, knowing that the future is emission free public transportation and even that of electric commercial vehicles, would be a typical shifting the burden archetype [18].

4. Beyond the tool – a culture of reflection

This paper shows no concrete application with conclusions from a model's analyses nor a step-by-step guidance. Rather it recommends, together with the provision of some tips and tricks from other projects, to use participatory explorative cause and effect modeling to reflect on concrete challenges in order to make progress achieving SDG 11. The fact that a concrete example would not imply a best practice for elsewhere is the very reason one should refer to this methodology: the challenges this world faces need individual solutions that consider the unique circumstances of every region.

Yet, trying to apply this approach quite often faces typical resistance. People doubt the benefits from these models since they consider them to be based just on assumptions. Well, that is correct. But any other approach, even that of a mere copying of 'fact based' best practice from elsewhere, would be based on assumptions as well, with the only difference that a model visualizes these assumptions, allows for their discussion, fosters creativity, and reveals logical conclusions from abductive logic [4].

Best practices are helpful but for a better future we need to add well-reflected ideas. The following photos (figure 7) show two paintings from unknown artists from an international Degrowth conference 2014 in Leipzig, Germany. One depicts for a better future a good life for all "Gutes Leben für alle" next to best practice solutions a group of people standing around a cause and effect model developing a shared idea. The other picture shows the unhealthy automatisms of more growth "Mehr Wachstum" by mere copying of lifestyles.

Figure 6. Drawings comparing the current and alternative paths for society.

This kind of collaborative problem solving (CPS) is subject to a psychological science [5]. It is considered a crucial skill for the future that can be trained and measured. Politicians, consultants, actors for media and other organizations, and indeed all of us need to learn to ask for the interplay of many factors and discuss this with others instead of restraining ourselves to best practice or gut feeling just because knowing feels better than taking the effort of exploration.

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Towards a sustainable district: a streamlined Life cycle assessment applied to an Italian urban district

Palumbo E[1], Traverso M[2], Antonini E[3], Boeri A[4]
[1] Senior Researcher, Institute of Sustainability in Civil Engineering (INaB), RWTH Aachen University
[2] Head of Institute, Institute of Sustainability in Civil Engineering (INaB), RWTH Aachen University
[3] Full Professor, Department of Architecture (DA), University of Bologna
[4] Head of Department, Department of Architecture (DA), University of Bologna

elisabetta.palumbo@inab.rwth-aachen.de

Abstract. The literature shows a lack of environmental indicators able to support the transition from a sustainable to a smart city framework, since the priority area "built environment" is indeed more comprehensively addressed by urban sustainability assessment systems (13%), than by smart city frameworks (4%) [12].

As "smaller cities inside a larger agglomerate" [19], urban districts play a key role in defining effective and innovative paths toward a smarter city, but defining a sustainable urban district is not straightforward, and even less is capturing the induced impacts due to interactions between individual buildings and their surround urban setting [23]. The adoption of a quantitative method for evaluation, such as Life Cycle Assessment (LCA), emerges as an essential step for this purpose [24].

This article explores the application of a streamlined LCA on the urban district main issues (buildings, energy, water and waste), referring to an urban retrofitting intervention of Bolognina neighbourhood.

A set of mitigation strategies developed by an interdisciplinary research group (joining researcher team from the Department of Architecture of the University of Bologna and Institute of Sustainability in Civil Engineering of the RWTH Aachen University) provides the reference framework for the application deepened within the article. This work is a first application of LCA to a case study but it not includes a comprehensive sustainability framework yet, further activities are planned to finalize the analysis, e.g. taking account of social dimension by applying Social Life Cycle Assessment.

1. Introduction

Cities Climate Leadership Group (C40) emphasize that despite occupying just 2% of the world's landmass, Cities are responsible for over two-thirds of the energy consumption and account for more than 70% of global CO_2 emissions.

As a significant contributor to climate change issues, cities represent a key challenge in curbing greenhouse gas emissions and in taking adaptation and mitigation strategies.

Therefore, the consolidation of the common approach launched by the Paris Agreement, which focuses on transition to climate change, is encouraging cities, regions and businesses to take important steps in this direction, in order to contribute reduce global temperature rise to less than 2 Celsius degrees [1].

In parallel, an interdisciplinary group of academic experts who provided independent insights to COP21 French presidency and negotiation team, underlines that strategies foreseen in the Paris Agreement, on response to greenhouse gas rise, whilst being a laudable first step, requires scientific community to make further interdisciplinary efforts, as those regarding a broader use of Integrated Assessment Models [2].

According to several literature sources, the three interconnecting pillars: economic growth, societal development and natural resource conservation should be the reference to adopt in shifting towards sustainable urban development [3-5].

Life Cycle Sustainability Assessment (LCSA) is the life cycle-based approach built on the 'triple bottom line' or 'three-pillar' model of sustainability: environmental (LCA), social (SLCA) and economic (LCC) [6-7].

Since it is an accepted methodology for quantitative assessment of buildings over their whole life cycle, LCA has been increasingly used to assess the environmental impacts of construction products and buildings in the last 25 years, while it is still difficult to apply at urban level.

Despite the application at district level highlights the difficulties in shifting LCA to a wider scale [8], the methodology could provide a robust framework for an effective tool, suitable to assess environmental issues of urban blocks or neighborhoods. Which is a very promising issue within the actual debate on the lack of environmental indicators capable in providing guidance in the transition from a sustainable to a smart city framework.

This study applies a streamlined life cycle assessment to evaluate the mitigation strategies adopted by local authorities to enhance the environmental features of an Italian urban neighbourhood within its path to became a sustainable district.

2. Background

2.1 Towards a sustainability framework for new district urban concepts integrated in smart cities

The large variety of smart city definitions converge in European Union's view, under which the aim of the smart city is reducing greenhouse gas emissions in urban areas through the deployment of new intelligent technologies [12]. In fact, a large gap exists between a sustainable city and a smart one.

Recent scientific literature on the assessment of smart city performance suggests that there is a need to further integrating sustainability indicators in existing frameworks, or totally re-defining them. In particular, it recommends that not only output indicators should used that measure the efficiency of smart solutions deployment, but also impact indicators assessing the contributions provided to ultimate goals, such as environmental, economic and social sustainability.

A shift there has been in recent years by city policies striving for smart city targets instead of sustainability goals [9]. However, those two topics are interconnected and smart cities often share several goals with sustainable cities., despite the relation to sustainability targets is often lost within the large variety of definitions that exists of smart city [10]. Hence, there is a need to better understand the relation between smart and sustainable city concepts [11].

Built environment is an important aspect underlying the notions of both smart and sustainable cities. Comparing sustainable and smart city frameworks [12], the priority area "built environment" is more comprehensively addressed by urban sustainability assessment systems (13%), than by smart city frameworks (4%). It further highlights an additional lack of environmental indicators able to provide guidance in implementing the transition from a sustainable to a smart city framework.

However, these studies do not adopt the life cycle approach and can therefore only be assumed as a starting point, since impacts along the life cycle phases may have been neglected, e.g. energy embodied into buildings and infrastructure components to manufacture, ship, maintain and eventually demolish & dispose them [13]. Conversely, adopting a life cycle perspective will help understanding the up and downstream impacts of different technologies and concepts. This will also enable the identification of hotspots along the supply chains, providing a mean by which optimization potentials can be identified, while avoiding trade-offs.

2.2 LCA at urban level

A shift to sustainable districts has become urgent nowadays. This needs having tools to assess and measure the sustainability of Urban District, and especially their Retrofitting process. LCA is considered a valid scientific methodology for the purpose, but it could lead to uncertain outcomes and be highly time consuming, due to its specific nature which strictly relies on accurate and detailed input data. Many studies highlighted the need of removing this obstacle by adopting simpler methods or switching to other approaches (e.g. material flow analysis) [14]. Lotteau et al. [8] provides recommendations and guidance on applying LCA at this scale, based on the review of 21 case studies. In particular, the study suggests two good practice to adopt: a) declaring in detail the key features of the neighbourhood (i.e. number of inhabitants, number of non-resident users, neighbourhood area, total floor area and duration of study), in order to allow a better interpretation of results and data comparison; b) aligning LCA to the data as defined at master planning stage of the neighbourhood development, specifying key factors such as urban morphology, presence of vegetation, choice of materials and their influence on buildings energy consumption.

Figure 1. Analysis of site at Urban scale (redesigned by authors [17])

3. Case study

3.1 Bolognina district

The area under study is the Bolognina Neighbourhood, one of the 6 neighbourhoods which constitute the Italian city of Bologna. Located in the northern part of the city, this neighbourhood came into being as a result of urban expansion to provide residence for the working class at the end of 19^{th} century. It has a strategic location, close to the new stop for high-speed trains, the recent main City Hall building and the new residential area in the former fruit and vegetable market. Situated west of the trade fairground and east of the parallel Adriatica Motorway A14 and Tangenziale Nord Highway, it represents an important pivot between the historical city centre and the surrounding outskirts (Figure 2).

The Urban Plan of 1899 conferred to the area its peculiar chessboard pattern, made up of plots alternating homes, open yards, public services and shops. The most common buildings types are terraced houses aligned along the boundaries of the lots, and standalone often higher buildings in between. Some of the buildings are submitted to conservation plans as they are deemed of testimonial interest by city regulations. However, there is need for actions to address some critical issues, especially those due to the aging of the building stock and socio-economic conditions, as well as to improve the urban quality and to raise environmental and energy-related standards.

3.2 Critical issues

3.2.1 Heat island effect
A simulation was performed using ENVI.met software, in order to better understand the physical and micro-climatic behaviour of the urban area under study as wells as interactions among the elements present therein. This allowed us to identify heat island effect, air flow dynamics and vegetation related benefits. The simulation was carried out on three different levels: a large portion of the built environment including part of both historic city centre and surrounding area; the northern section of Bolognina neighbourhood; a single Bolognina block. This "zoom" sequence has highlighted significant heat island effects especially in no-shade unconstructed paved areas; low relative humidity (rarely higher than 40%); critical wind speeds often affecting zones without physical barriers such as vegetation and/or buildings (Figure 3).

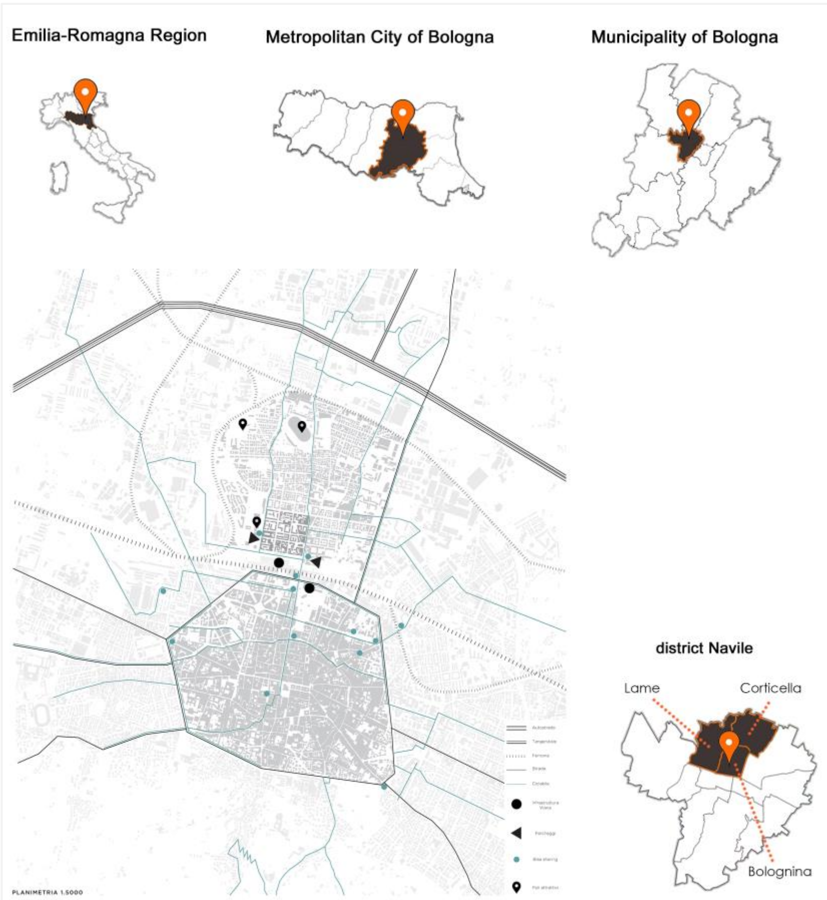

Figure 2. Territorial location of Bolognina neighbourhood

3.2.2 Open spaces
A more detailed study was also carried out on unbuilt areas, showing that green zones, parking lots, paths, home entrances (Figure 4) are left in abandoned and degraded situation due to the lack of a

hierarchical organization of the common spaces and their ordinary specific use, resulting in an inefficient use of the urban area.

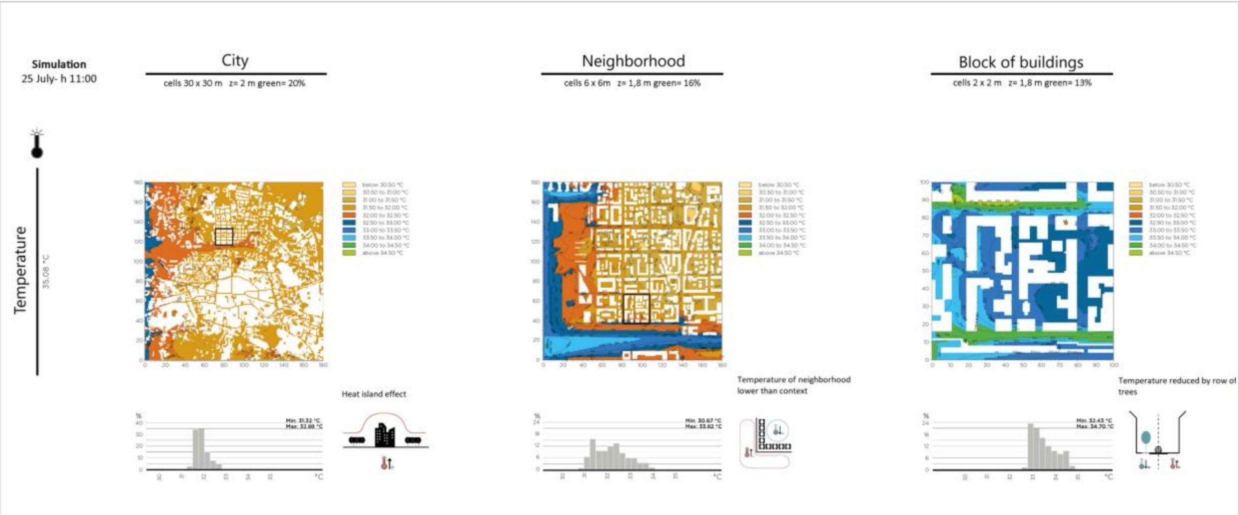

Figure 3. Head island effect on Neighbourhood (redesigned by authors [17]

3.2.3 Buildings

Residential buildings have inadequate performance levels: 70% of the rooms have lower surface areas compared to existing legal limits, 20% are under-sized by more than 70%. The type of lodgings, which today are mainly made up of 2-3 components, do not meet demands. The indoor comfort levels (exposure to sunlight and ventilation) are at critical levels; energy consumptions are very high (total energy performance Ep values range from 130kWh/m^2 corresponding to energy class E, to 230 kWh/m^2 corresponding to energy class G), mainly due to heat loss of the building envelopes, in particular windows, and to a high number of heat bridges.

4. Methods

4.1 Mitigation strategy of Bolognina and relevant environmental aspects

The opportunities and criticalities highlighted in previous analyses have been grouped in 4 categories: city, utilities, insulation and comfort. The strategic interventions were defined taking into consideration their repeatability at a higher scale, which means extending to other neighbouring blocks in order to involve the whole district. These interventions address 8 aspects of the built environment as illustrated in Figure 4.

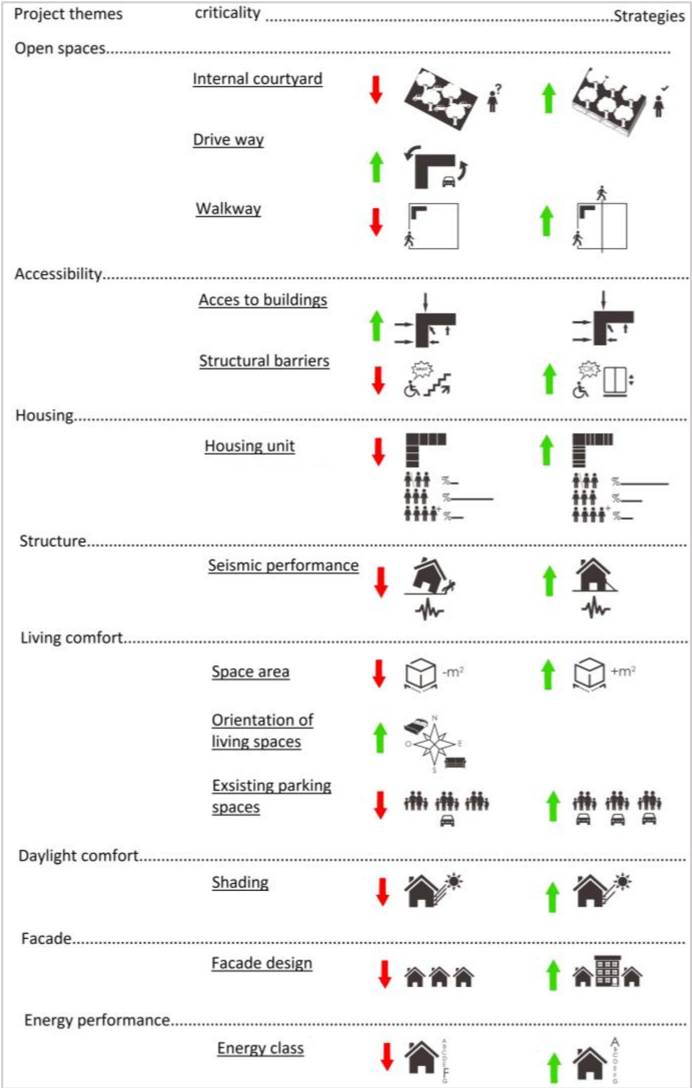

Figure 4. Mitigation strategies adopted

4.1.1 Urban district scale

The area defined by the courtyards and squares, as highlighted in the analysis in section 3.2.1 occupy a key function in the composition of the neighbourhood and shows serious functional deficiencies. The objective at the urban block scale, is to reorganize and requalify the open spaces in the internal courtyards, with the aim to re-establish a balance between built volume and open areas, reducing as much as possible the transit and parking of vehicles and extending the green surfaces.

4.1.2 Building level

The existing building stock plays a significant role in energy consumption and CO_2 emissions, accounting respectively for 40% and 36% of EU related amounts [15].

This occurs at district level too: there is therefore need to implement energy efficient and low carbon retrofit solutions which must be also affordable and designed for a long lifespan, since buildings are made to last for several decades (60 years, in accordance with the European Framework Level(s) [25].

By adopting pertinent solutions (building envelope insulation, window replacement, energy saving technical installations, etc), energy efficiency labelling could improve from class G (230 kWh/m2 year) to Class A2 (37,2 kWh/m2 year) and from Class F (160 kWh/m2 year) to class A4 (16,96 kWh/m2 year).

4.2 LCA of the Italian urban district

The LCA study was applied on the block bordered to the west by Via Nicoló Dall'Arca, via Fioravanti to east, Via Tibaldi to south and Via Albani to north, which is affected by intense traffic flows also due to daily local market here hosted and the proximity of City Hall.

These roads have uniform three-ways section: driveways are in the middle, two lines of public metered parking are located on both sideways which are lined with trees and sidewalks. Table 1 shows in detail the situation of the block under study.

Table 1. Dimensional characteristics related to the block under study

Characteristics	**UM**	**Value**
Height of the building (average)	m	16
Built volume	m^3	80,78
Open area	m^2	8910
Open/built area ratio		0.46
Green/pavement area ratio		0.75
Lodging area	m^2	1648,5
Lodging n. (+/- 5%)	n.	190
	m^2	10879,9
Green surfaces	m^2	3862
Pavement surfaces	m^2	5108
Block total area	m^2	13036
Built area	m^2	4111
Lodging average surface	m^2	65
Inhabitant/lodging average index	n.	2,5

The study firstly aims at exploring the application of a streamlined LCA on an urban retrofitting intervention of Bolognina neighbourhood. For this purpose and focusing on urban district main issues (buildings, energy, water and waste), a set of mitigation strategies has developed by an interdisciplinary research group (joining researchers of the Department of Architecture of the University of Bologna and Institute of Sustainability in Civil Engineering of the RWTH Aachen University).

The additional scope is to respond to some questions emerging in literature about the selection of functional unit suitable to allow effective interpretability of LCA results at neighboured scale, thus the studies comparability.

In order to reduce the number of variables involved and thus simplify the application model, LCA analysis focuses on some mitigation measures only, among those adopted in the retrofit intervention, as well as on two main life stages only, which are those defined in 4.2.2.

4.2.1 Functional unit

LCA standards define the functional unit (FU) as the quantified performance of a product or system that is used as the reference unit for the LCA and for comparability among assertions (ISO 14040-14044:2006). The standard EN 15978 (2011) on LCA calculation methodologies at building level relates the FU to the quantification of product identified functions or performance. For example, FU can be defined at building element level as $1m^2$ of insulation with sufficient thickness to provide a thermal resistance value of 3 m^2K/W, while at whole building scale it can be a unit of living area (1 m^2).

Given that an urban district - as the neighbourhoods it is composed of - are ecosystems, which characteristics are related to a considerable number of aspects (geographical location, space area, open spaces, building, culture and wealth of local residents to cite a few examples), the definition of a functional unit for these systems is extremely challenging [14].

As a matter of fact, state of the art on LCA studies applied at neighborhood level shows huge differences in FU choice However, we found an interesting reference in Norman et al. [15] and Stephan et al. [16] adopting a per capita FU (m2 of living space/inhabitant) but unfortunately it is cannot be used as a reference for our study, because is not clear how the amount of the open spaces is considered. This assessment is referred to dimensional characteristic of the block of Bolognina urban district, namely 8910 m2 of open area, about 190 housing units with 10879 m2 of living spaces and 475 inhabitants (see Table in Figure 2).

4.2.2 Boundaries and Life Cycle stages

Within the present study, the envisaged mitigation actions related to the built environment have been at first clustered by three main fields: buildings, open spaces and networks. This is in line with the model introduced by Popovici [18] and broadly taken over by the framework developed by Lotteau et al. [8], which allows to identifying the factors acting as major contributors within the LCA of an urban district (Figure 5).

In accordance with the boundaries defined by EN 15804 standard, the stages involved in the analysis are:

i) Product stage (raw materials extraction, manufacturing);
ii) Construction phase (Transport, building and infrastructures construction);
iii) Use phase (operation and maintenance) and vi) the Deconstruction phase (End of Life).

Therefore, in line with the goals defined in 4.2, the analysis is focused on the issues highlighted in the colored box in table 2, taking into consideration only 2 main lifecycle stages: process and use.

Table 2. Physical elements for the different fields of the built environment (readapted by authors from [8])

	PHYSICAL ELEMENTS		
	BUILDINGS	**OPEN SPACES**	**NETWORKS**
MITIGATION MEASURE	Insulation of the building's envelope	Reduce the heat island effect	District heating
	Replacement of windows	Green areas	Photovoltaic electricity in place of fossil fuels
	Reduced use of water	Parking lot	Waste collection and management services
	Reduced lighting consumption		Replace I-bulb sales with LEDs/CFLs
	Reduced energy consumption		

Elements assessed in the LCA

4.2.3 Assumption in the case study related the Life Cycle Inventory

The foreground flows are principally represented by real data collected during site visits, interviews and re-calculations based on appropriate software (e.g. energy related retrofit of buildings). Whenever primary data were not available, regional and national references sources were considered as shown in table 3.

Table3. Foreground flows output and waste

	Foreground flows Output and Waste			
	Electricity	**Natural gas**	**Water**	**Waste**
Reference unit	m^2 of living space	m^2 of living space	m^3/ inhabitant	m^3/ inhabitant
Typology of data	Primary data	Primary data	Secondary data (source: Hera*)	Secondary data (source: ISPRA**)

*Multi-utility company that provides water and energetic services in the Bologna municipality) Italian **Institute for Environmental Protection and Research)

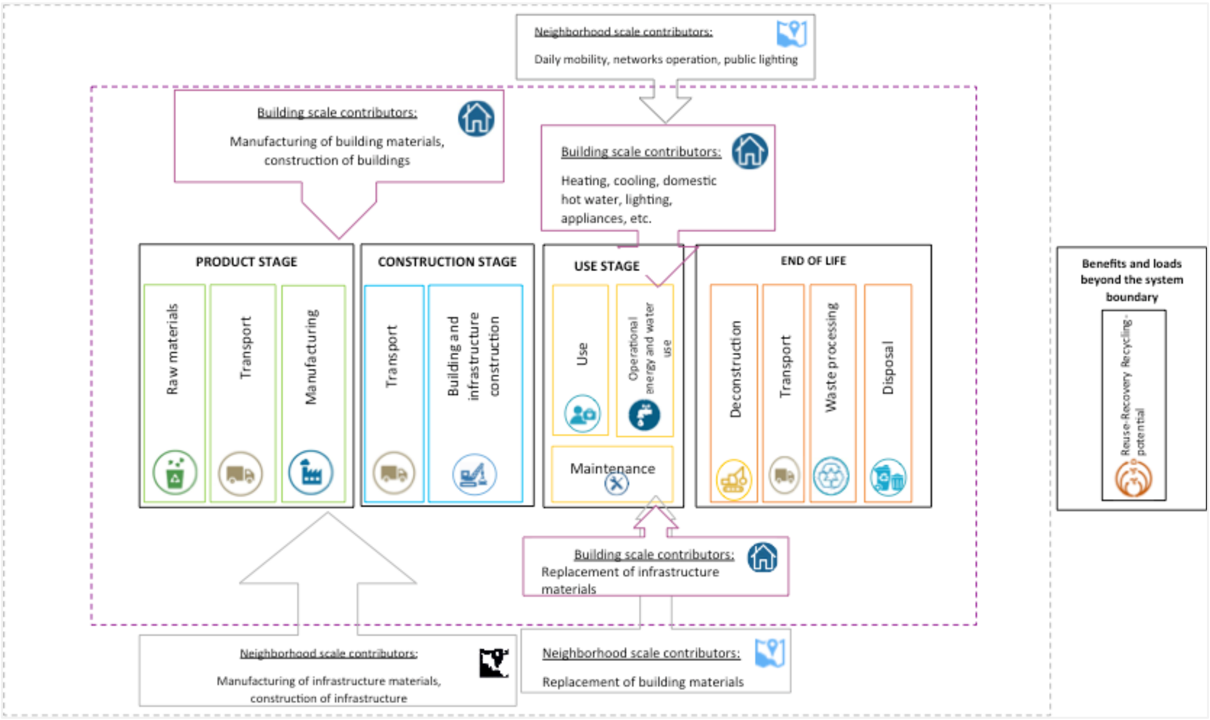

Figure 5. Neighbourhood life cycle steps and associated contributors at both building and neighbourhood scale (readapted by authors from [8])

The Life Cycle Assessment of almost all physical elements was performed using the Simapro© software [20] and the Ecoinvent database v.3.5 (2019). While Environmental Performance Evaluation for replace the windows in the building and to reduce the heat island effect in the open space was carried out adopting the impact indicators avowed by the related manufacturers in the Environmental Product Declarations (EPDs) [21-22]. Results showed in this paper are focused on only one impact indicator (Global Warming Potential, measured in kgCO_2-eq).

5. Streamlined LCA of retrofitting the block of Bolognina urban district

Outcomes provided in Figures 6 and 7 are related to only one of all the assessed LCA indicators. More specifically, Figure 6 provides the Global Warming Potential [kg CO_2 equivalent] related to the environmental impacts of the LCA applied to retrofitting the block of Bolognina neighbourhood associated to the two life cycle stages (product and use stage) in 1 year, while Figure 7 is referring to the entire Building's life cycle (reference service life value from [25]).

Although limited to the GWP indicator and restricted to two life´s stages only, the improvement due to the mitigation strategies is evident. The decrease of kg CO_2 equivalent is about 59% of the total value. It can be further appreciate if you consider the entire life cycle as it is highlighted in the Figure 7, in which is showed the increase of CO_2 value (vertical axis) in the years (horizontal axis).

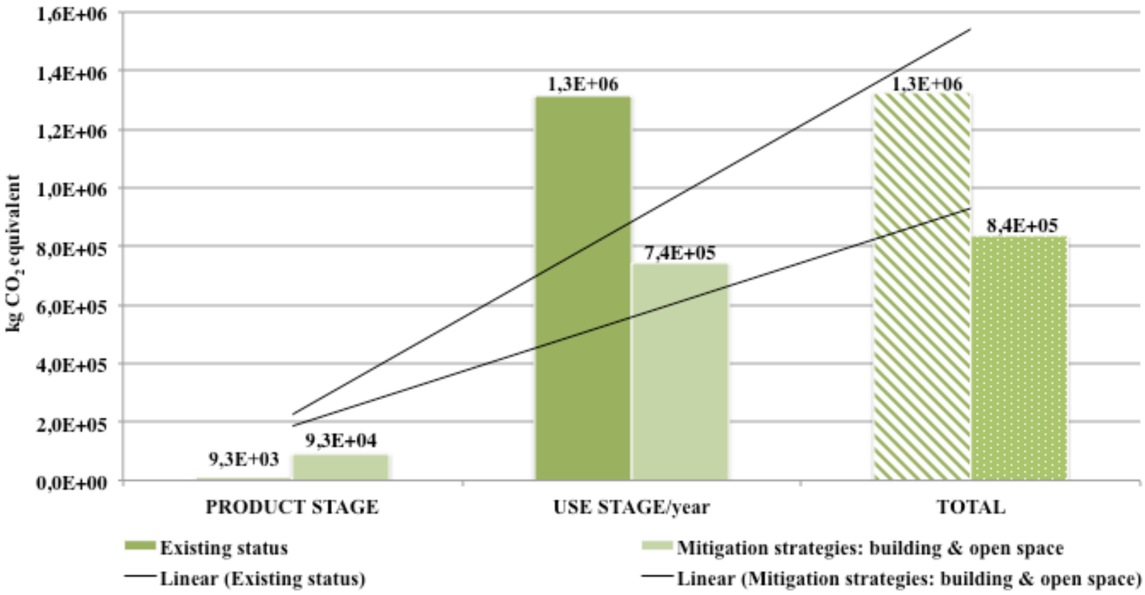

Figure 6. Comparative assessment related to Global Warming Potential (kg CO_2 equivalent) between existing status and mitigation strategies of the block of Bolognina neighbourhood in 1 year

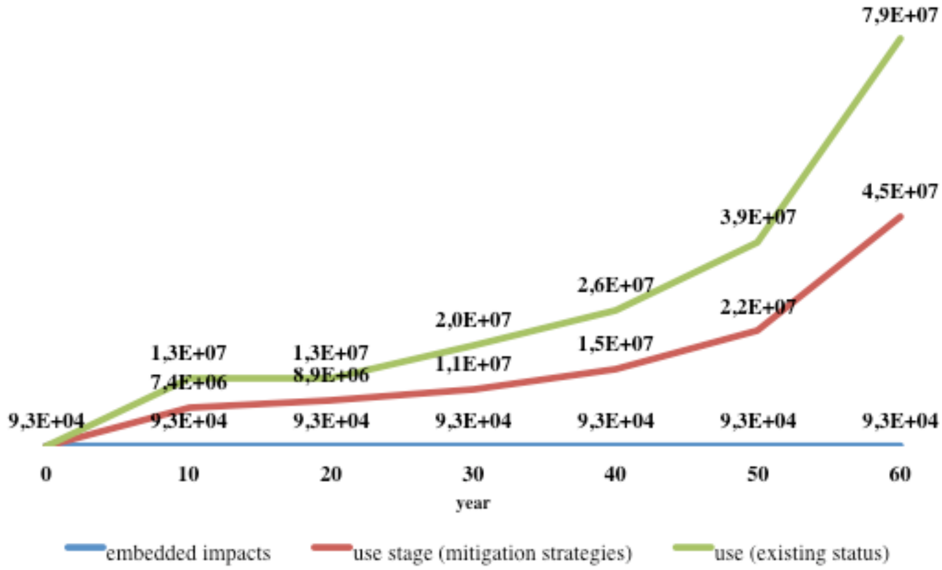

Figure 7. Comparative assessment related to Global Warming Potential (kg CO_2 equivalent) between existing status and mitigation strategies of the block of Bolognina neighbourhood during entire Life Cycle of Building (60 years)

More specifically, at building level the applied mitigation strategies have led to the reduction of energy consumptions in the building's use phase -heating, cooling, tap water and hot water- (i.e. 43,4% kg CO_2 equiv.), but increasing the embedded carbon generated in manufacturing of the materials used. However, total GHG emissions from mitigation strategies remains below the level of the existing status (37,8%). Likewise, actions on the open space (reduction of the heat island effect and drop of electricity consumption for public lighting) decreased GWP by ca. 41% (-52,1% in the use phase and + 90% in the product stage). As a first application, of a simplified application of LCA on an urban block, this study shows the potentiality of this methodology in the evaluation of the environmental performance of the built environment at urban scale. Next step will extend the evaluation to cover all other life cycle stages, but further researches are needed to complete the evaluation and to assess the three pillar of sustainability throughout a life cycle sustainability assessment.

6. Conclusions

Environmental assessments and, in general, the sustainability are nowadays relevant of most thematic areas, and particularly cities. Despite the evident irreversibility of environmental impacts like global warming, biodiversity and resource depletion, the environmental accounting in the building and urban sectors is presently based on subjective approaches and less precise [26].

Limited and simplified assumptions have been used in the present study focused chiefly on the methodologic implementation, but greater variation in context conditions would be useful to support a comparison of alternatives, notably in the design phase.

In terms of method the comparability among the case studies above all requires harmonization of the functional unit considered.

At the neighbourhood level, this is huge and complex, since that include elements different both as size that like typologies: buildings, infrastructure, public space.

Necessary gaps and implementations to build a complete and harmonized framework are presently showed from a recent study on the current state of the art [27].

Yet for application method improvement and to bridge the existing gap considerable efforts have still to be made.

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Considering the dynamics of electricity demand and production for the environmental benchmark of Swiss residential buildings that exclusively use electricity

Beloin-Saint-Pierre D*, Padey P†, Périsset B†, Medici V‡

* Empa, Lerchenfeldstrasse 5, 9014 St. Gallen, Switzerland
† HEIG-VD, Avenue des sports 20, 1401 Yverdon-les-Bains, Switzerland
‡ SUPSI, Campus Trevano, 6952 Canobbio, Switzerland

dib@empa.ch

Abstract. The environmental impacts of buildings can significantly vary with the dynamics of their energy demand and production. Significant variations have been modelled for buildings in the U.S., France, Denmark and Switzerland but the levels of variation are different between these countries. This difference can be explained by factors like the existing energy sources, the availability of renewable energy and the importation of electricity from nearby countries. With its high share of renewable energy and significant electricity exchanges with neighbouring countries, Switzerland presents a specific case where benchmark values from dynamic life cycle assessment should be well understood. The project's goal is to provide results from a dynamic life cycle assessment with a detailed study of the influence from temporal fluctuations in the national electricity production, electricity imports, decentralised generation and electricity demand from buildings. Additionally, consequences of changing the temporal precision (i.e. hourly, daily, monthly and annual) of energy dynamics are analysed. This assessment is conducted with demand and production estimations for the design of a residential building in Switzerland. Disparities of results are assessed for all temporal precision levels with a comparison to the values that are obtained with the current national methodology which operates with values based on average annual electricity production. Results thus suggest some methodological recommendations to develop the temporal aspects of the environmental impact assessment methodology for the Swiss building sector.

1. Introduction

Numerous life cycle assessment (LCA) studies of buildings have shown that energy demand, during their use phase, is often a key source of environmental impacts over their full life cycles. When combined with the inherent temporal variability of energy sources (e.g. gas, coal, photovoltaics), this observation raises the question of considering the energy dynamics to improve the representativeness of environmental impact assessment in LCA studies. Models of energy dynamics in recent LCA studies have mapped prospective scenarios of the future [1, 2], replicated the intra-annual electricity production variations [3-11] or simulated impact changes over time [12, 13].

When looking more specifically at the question of intra-annual variations of energy demand and production, the importance of such dynamics on LCA results have been investigated since 2013 mainly in the US [3-5], France [6-8], Denmark [9] and Switzerland [10, 11]. These studies have evaluated the impacts of rather recent residential [6-8, 10, 11], commercial [9] and institutional [3-5] buildings. The level of temporal precision on energy models varies between studies with hourly [5-11], daily [9] and monthly [3-5] averages and the effect of varying precision levels has been evaluated once [9] for Denmark. Overall, these "dynamic" LCA studies confirm that some environmental impacts might be reduced or increased substantially when compared to results from models which consider the average annual energy production mixes and demand from buildings.

While past studies clearly support a more regular account of energy dynamics in LCA of buildings, many aspects are still ambiguous for the specific case of Switzerland therefore raising some questions. First, how different would results be when compared to the current Swiss evaluation standard [14] which is based on annual averages for the electricity mix? Second, what is a useful level of temporal precision to describe energy production and consumption when considering a representativeness-to-effort ratio? Third, what is the importance of limiting the details on dynamic models of neighbouring countries when looking at the choices made in the recent Swiss studies [10, 11]? Further evaluations are therefore required to explore and answer these questions and they shape the goals of this work.

2. Case study

A project for a residential building near Fribourg in Switzerland is used as a case study to answer the three questions on energy dynamics from the introduction. This building is meant for three inhabitants and possesses an energy reference area (ERA) of 199 m^2. Standard appliances (i.e. oven, washing machine, dryer, dishwasher, domestic hot water and pumps), lighting equipment and an air-to-water heat pump are considered to evaluate the electricity demand of this single-family home. The building is also equipped with a roof-integrated photovoltaic (PV) installation of mono-crystalline technology with a peak power of 4.5 kW facing east.

The Swiss society of engineers and architects provides the SIA 2024 standard [15] which has been used to evaluate the hourly energy demand for the considered home during a "typical" year. This temporal curve of energy demand has been calculated by adding the provided curves for the standard appliances, lighting and heating. The "typical" heating needs for the year are based on the building components and climatic data from the SIA 2028 standard [16] which is the reference in the Swiss building sector for new projects. The home's energy demand amounts to about 8725 kWh/year (i.e. 43.85 kWh/year·m^2 of ERA). The hourly energy production from the PV installation is calculated with hourly solar irradiation levels in Fribourg for a full east orientation and 45º inclination during a "typical" year. The results, while more detailed, are coherent with values that are obtained from the PVopti Excel tool [17] which is widely used for projects that respect the MINERGIE® certification. The PV installation of this building is expected to produce about 3792 kWh/year (i.e. 19.06 kWh/year·m^2 of ERA). The hourly energy demand and production for a "typical" year are presented in figure 1 (from January 1st to December 31st).

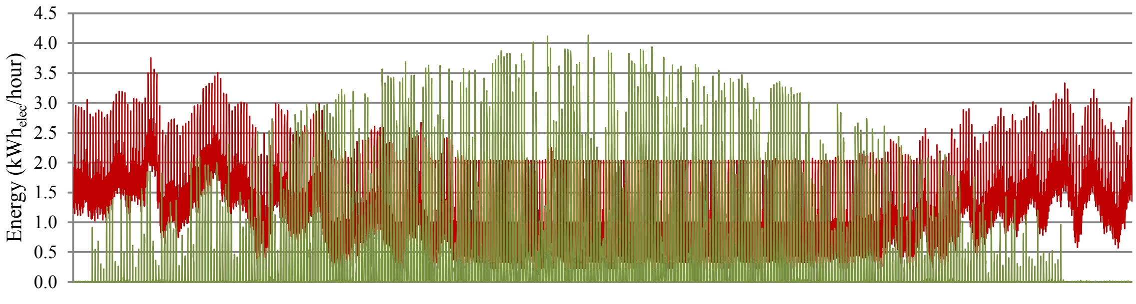

Figure 1: Building's hourly energy demand (red) and PV production (green) over a "typical" year

3. Scope of study

Many different modelling choices have been made to evaluate the potential environmental impacts of the home's energy flows and how different temporal precision levels will affect them within the LCA framework. This scope of study therefore lists all the key aspects which should be considered in the analysis of results and commonly found in LCA studies.

3.1. Functional unit

The chosen function unit (FU) for this assessment is the m^2 of ERA used during a year which represents the indoor floor area of heated rooms inside the buildings. The evaluated potential environmental impacts values are therefore given per $m^2 \cdot$year to present results for new homes which respects the Swiss energy standard.

3.2. Limits of the home's model

The focus on dynamics of energy demand and production for a Swiss residential building justifies the use of a model which concentrates on some components of the building's life cycle. Indeed, the only change between all considered options for this study is the temporal precision of electricity flows during the use stage. Modelling efforts are also directed on intra-annual variations meaning that no evolution on the long-term is considered and thus, analysis centres on variations of impacts for three "typical" years (i.e. 2016, 2017 and 2018). Figure 2 shows the boundary of the modelled system and offers a correspondence with stages defined in the EN 15804 document [17]. The model also details the energy sources of neighbouring countries (i.e. Austria [AT], Germany [DE], Italy [IT] and France [FR]) with a high level of temporal precision (up to hourly variation). The white boxes of figure 2 are defined as system processes since they list all the natural resource extractions and pollutant emissions that are related to the production of 1 kWh of electricity with these sources in respective countries.

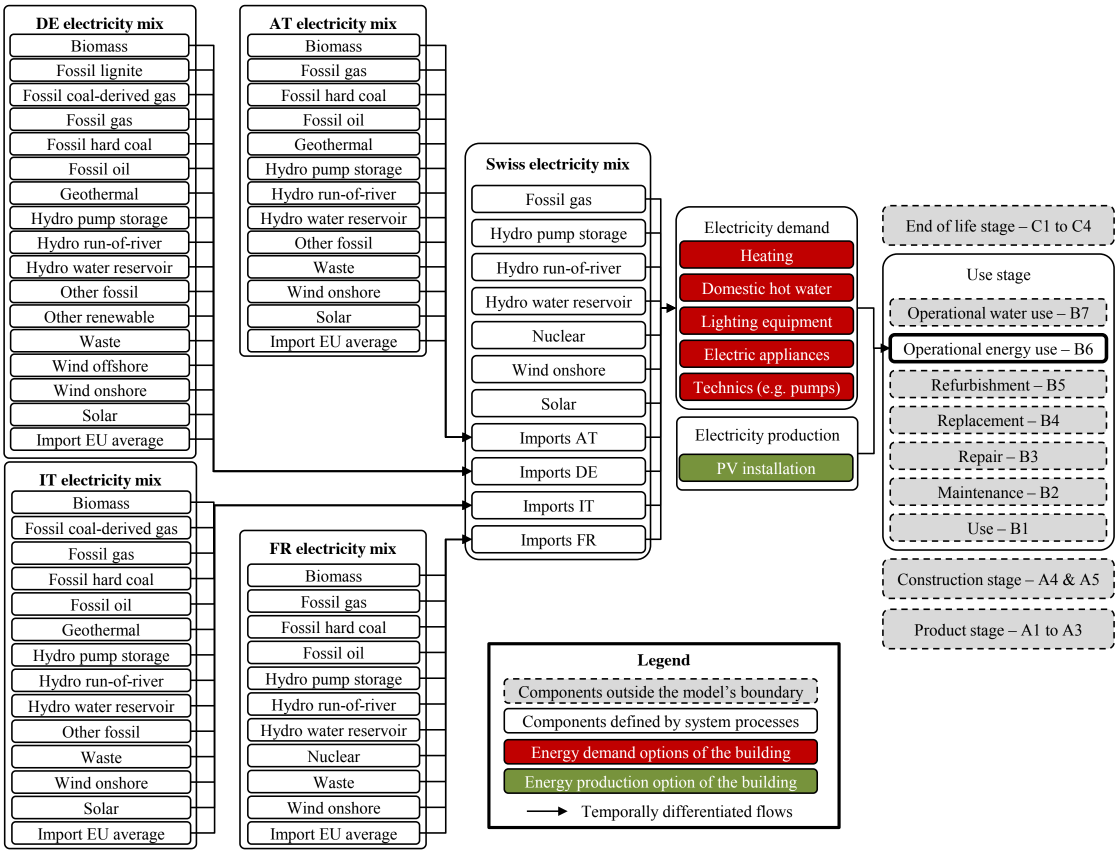

Figure 2: Considered components of the home's model with temporally differentiated flows

3.3. Sources of data

The model of figure 2 is informed mainly by two data sources: the ENTSO-E website and the ecoinvent LCA database. The ENTSO-E website [18] offers statistics on historical electricity generation from different energy sources and importation. The ecoinvent database [19] presents information that can be translated into potential impacts for these energy sources and the European average electricity mix. Combining these two sources of information requires some assumptions.

3.3.1. The ENTSO-E website: It was launched on the 5th of January 2015 and sources its information from electricity transmission system operators (TSOs) or other qualified third parties. The ENTSO-E transparency platform, in accordance with EU Regulation 543/2013, offers information on generation, load, transmission and balancing of 36 countries across the European continent (with Switzerland). The generation data describes the electricity mixes, with the different sources that are presented in figure 2, and informs on exchange values for importation and exportation between countries. The temporal precision of generation statistics varies between 15, 30 and 60 minutes depending on the data provider. Some gaps in the data can be observed which explains why this study only considers the period between 2016 and 2018. This interval of three years permits an analysis with four levels of precision: hourly, daily, monthly and yearly. Figure 3 presents an example of the provided information for the hourly electricity generation in Switzerland for one day (highest precision available).

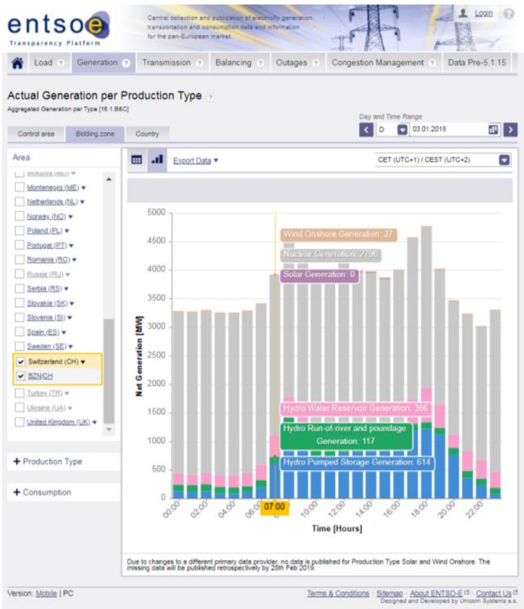

Figure 3: Example of information from the ENTSO-E website for the Swiss electricity mix

3.3.2. The ecoinvent v3.4 cut-off database: The organisation behind the ecoinvent database was founded by institutes of the Swiss Federal Institute of Technology (ETH) domain and the Swiss Federal Offices. It became a not-for-profit association in 2013. One of the core principles of this information source is “thrust in transparency” which means that it offers a comprehensive and detailed description of human activities and their effects (e.g. impacts) on the environment. Many processes of different electricity sources (e.g. coal and nuclear power plant production) are available for countries around the world. Such processes describe supply chains (i.e. link with other processes of human activities) and their elementary flows (i.e. extraction of natural resources and emission of pollutants). For all the relevant energy sources of this case study, the descriptions of processes (i.e. datasets), from version 3.4 cut-off, have been transformed into 4 potential environmental impacts (see subsection 3.4) per kWh of produced electricity with the help of the SimaPro v8.5.2.0 software.

3.3.3. Mapping connections between the data of ENTSO-E and ecoinvent. The differences in structures and levels of detail to describe the energy sources in the ENTSO-E and the ecoinvent database force the creation of a mapping structure to link environmental impacts (based on ecoinvent) to the energy sources statistics of ENTSO-E. These important modelling choices are necessary to calculate the potential environmental impacts of the Swiss electricity mix when ENTSO-E data is used for each hour of the day. Some assumptions on the shares of different technologies from ecoinvent (e.g. boiling or pressured water reactors) that relate to a common energy source in ENTSO-E (i.e. nuclear) were therefore made in this study. Table 1 presents these shares for the Swiss electricity mix. Mappings were carried out for all neighbouring countries (i.e. AT, DE, IT, FR) and readers are invited to contact the corresponding author if they would like to have access to this information. Table 1 shows that the ecoinvent database offers varying levels of details on technologies and it is important to mention that these levels of detail changes between countries.

Table 1: Mapping of links between energy sources for ENTSO-E and ecoinvent database

Energy sources in ENTSO-E	Energy sources as defined in ecoinvent v3.4 cut-off	Shares (statistics from 2014)
Fossil Gas	Natural gas, 500kW electrical, lean burn	100.00%
Hydro Pumped Storage	Hydro, pumped storage	100.00%
Hydro Run-of-river	Hydro, run-of-river	100.00%
Hydro Water Reservoir	Hydro, reservoir, alpine region	100.00%
Nuclear	Nuclear, boiling water reactor	47.35%
	Nuclear, pressure water reactor	52.65%
Wind Onshore	Wind, <1MW turbine, onshore	5.48%
	Wind, >3MW turbine, onshore	9.59%
	Wind, 1-3MW turbine, onshore	84.93%
Solar	Photovoltaic, 3kWp facade installation, multi-Si, laminated, integrated	3.74%
	Photovoltaic, 3kWp facade installation, multi-Si, panel, mounted	3.74%
	Photovoltaic, 3kWp facade installation, single-Si, laminated, integrated	2.48%
	Photovoltaic, 3kWp facade installation, single-Si, panel, mounted	2.48%
	Photovoltaic, 3kWp flat-roof installation, multi-Si	11.35%
	Photovoltaic, 3kWp flat-roof installation, single-Si	7.47%
	Photovoltaic, 3kWp slanted-roof installation, a-Si, laminated, integrated	0.43%
	Photovoltaic, 3kWp slanted-roof installation, a-Si, panel, mounted	6.32%
	Photovoltaic, 3kWp slanted-roof installation, CdTe, laminated, integrated	6.90%
	Photovoltaic, 3kWp slanted-roof installation, CIS, panel, mounted	0.86%
	Photovoltaic, 3kWp slanted-roof installation, multi-Si, laminated, integrated	3.74%
	Photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	28.96%
	Photovoltaic, 3kWp slanted-roof installation, ribbon-Si, laminated, integrated	0.29%
	Photovoltaic, 3kWp slanted-roof installation, ribbon-Si, panel, mounted	4.02%
	Photovoltaic, 3kWp slanted-roof installation, single-Si, laminated, integrated	2.44%
	Photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted	14.79%

3.4. Considered impact categories

The goal of comparing results from a dynamic assessment of energy flows with different temporal precision levels with the current Swiss standard based on annual averages (i.e. KBOB [14]) imposed the choice of three impact assessment methods that are used in this standard. The greenhouse gas (GHG) emissions (in kg of CO_2 eq.) were calculated with the characterisation factors (CFs) of the IPCC2013-100 year v1.03 method [20]. The renewable and non-renewable primary energy (in MJ primary) were computed with the CFs of the CED v2.05 method [21]. The environmental loading points (in UBP) were determined with the CFs of the ecological scarcity (ES) 2013 v1.05 method [22]. All these methods are available in the SimaPro v8.5.2.0 software.

3.5. Calculations of energy dynamics in a Swiss residential building

Once all the data has been obtained from the different sources and processed with a LCA software, it becomes rather straightforward to merge the temporally differentiated information of energy demand with the potential environmental impacts of the Swiss electricity mix for different hours, days, months and years. Then, the environmental impact of energy production from the PV installation is accounted while making the assumption that auto consumption is a priority. This means that only excess demand from the building will be covered by the Swiss electricity mix. The environmental impacts of electricity production from overproduction of the PV installation are not accounted in the impacts of the building (i.e. when production is higher than demand in figure 1). This modelling choice is explained by the idea that the Swiss grid, which uses this overproduction, should assume the impacts for its other customers. It should also be mentioned that the environmental impacts of 1 kWh of PV electricity is computed from the environmental impacts of the installation divided by its electricity production (in kWh) over its full life cycle (e.g. 0.093 kg of CO_2 eq. /kWh over 25 years). The following equation explains the calculation for any time period (e.g. an hour of day or a month).

$$Impact_{\Delta t} = P_{PV,\Delta t} \cdot EIF_{PV} + \left[\left(D_{House,\Delta t} - P_{PV,\Delta t}\right) \cdot EIF_{CH-mix,\Delta t}\right]_{if\ D>P}$$

Where:

$Impact_{\Delta t}$ is the impact of energy consumption for the selected time period Δt

$P_{PV,\Delta t}$ is the production of electricity from the PV installation during Δt

$D_{House,\Delta t}$ is the electricity demand from the different devices in the building during Δt

EIF_{PV} is the environmental impact factor of the PV electricity, which does not change

$EIF_{CH-mix,\Delta t}$ is the environmental impact factor of the Swiss electricity mix during Δt

4. Results and discussion

Figure 4 presents the potential impacts of the annual energy flows (i.e. demand and production) per m^2 of ERA for the four categories of the Swiss standard when system dynamics are considered. The dotted red lines are also offered to present the environmental impacts that are obtained when values of the Swiss standard (i.e. KBOB) are used (e.g. 0.102 kg of CO_2 eq./kWh for the Swiss electricity mix).

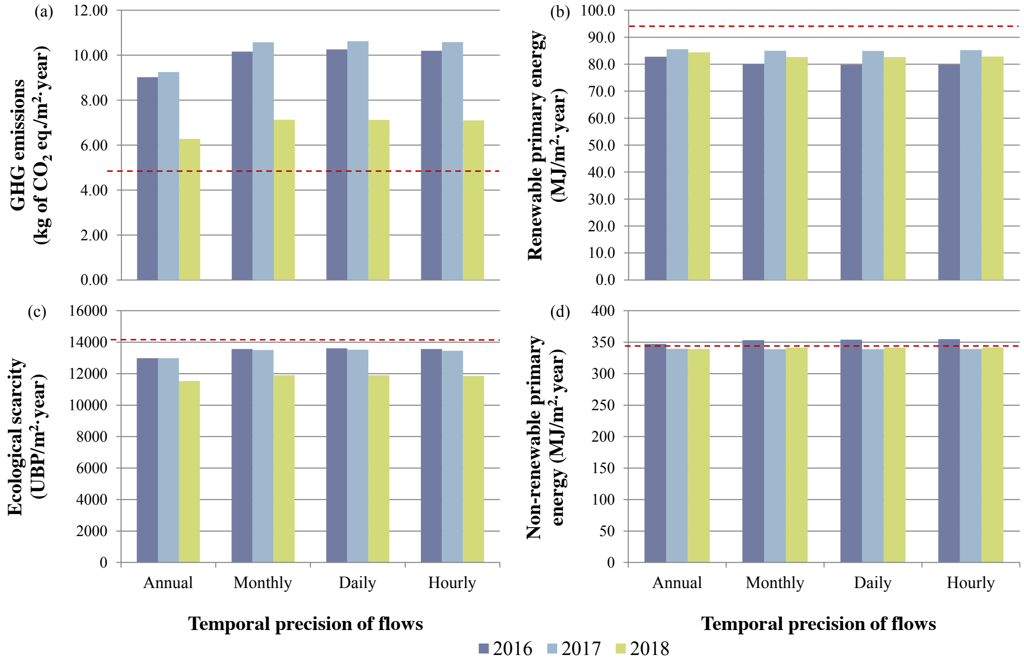

Figure 4: Potential environmental impacts from energy flows in 1 m^2_{ERA} for 2016, 2017, 2018

Results in figure 4 only show a significant divergence between the dynamic assessment and the outcomes of the Swiss standard evaluation tool (i.e. KBOB) for the GHG emissions (i.e. > +65%). The three other impact categories present smaller differences (-12% on average for (b), -7% on average for (c) and -1% on average for (d)). To go beyond this simple observation, two alterations between the annual static and dynamic models are presented in table 2 to show their importance on these observed total differences. It becomes clear that the change of background database (Δ1) and the description of the electricity mix (Δ2) have opposing effects on the three categories with relatively small variation (i.e. b, c and d). Table 2 also illustrate that both alterations have similar levels of importance when absolute difference are considered between the dynamic and standard results.

Table 2: Main contributors to the differences between the dynamic and standard results of KBOB

Categories of environmental impacts	*Step-by-step analysis*					*Share of absolute difference*	
	ecoinvent v2.2+ (KBOB)	**Δ1** database	ecoinvent v3.4 (static)	**Δ2** electricity mixes	Dynamic annual (2016)	**Δ1**	**Δ2**
(a) GHG emissions (kg CO_2 eq./$m^2_{ERA}\cdot$year)	4.40	+23%	5.42	+67%	9.03	31%	69%
(b) Renewable primary energy (MJ/ $m^2_{ERA}\cdot$year)	94.0	+19%	112	-26%	82.8	44%	56%
(c) Non-renewable primary energy (MJ/ $m^2_{ERA}\cdot$year)	347	-22%	272	+28%	347	46%	54%
(d) Ecological scarcity (UBP/ $m^2_{ERA}\cdot$year)	14065	-22%	11026	+19%	13151	59%	41%

Additionally, a relatively important variation of impacts between the annual average values and more precise options (i.e. monthly, daily, hourly) can be observed in figure 4 for GHG emissions (+14% on average) and ecological scarcity (+4% on average). Conversely, results for primary energy use (renewable and non-renewable) are not varying much with an increase of the temporal resolution. The same results show that most of the change for GHG emissions and ecological scarcity can be observed with the use of a monthly precision. This implies that a more detailed model will not change the conclusions of the environmental assessment for the analyses residential building which is representative of future single family housing in Switzerland.

The results of figure 4 also show that differences in electricity production between the years of a building use phase might relate to higher impact variability than the assessed intra-annual variations. Indeed, there is a much larger difference of impacts between 2017 and 2018 (i.e. -32% kg of CO_2 eq. and -11% UBP) than for any of the observed changes with different levels of intra-annual precision. A detailed analysis of the model clearly indicates that this difference is mainly explained by the reduced importation of German electricity during the beginning of 2018. Such an outcome stresses the need to consider the future of the Swiss electricity mix to obtain representative environmental assessments of buildings. Furthermore, it highlights one limitation of this study concerning the small amount of available historical statistics (i.e. 3 years) in comparison to the expected lifetime of buildings (i.e. 60 years). It is also worth mentioning that a detailed description of production sources for neighbouring countries was necessary to make this observation.

To go further on the question of a relevant complexity level for the model of energy sources in neighbouring countries of Switzerland, a comparison of results from this study and those of a recent publication [11] is necessary. In this publication, the temporal variations in primary energy use and GHG emissions have been modelled for the Swiss grid, but this model uses average values to describe the GHG intensity of France, Germany and Austria, while neglecting Italy. On this aspect, the complexity of the model is lower than the one that has been used in this study (see figure 2). The authors of this publication then obtain a level of GHG emission, based on hourly data, which is increased by 1.9% when compared to the result of a calculation with an annual average. This variation is significantly lower than what has been obtained in this study (i.e. +12%) which might partially be explained by the difference in the studied cases (i.e. buildings), but that also showcase the effects of considering a complex model of electricity importations.

5. Conclusion

A LCA study of a Swiss residential building has been conducted with different levels of temporal precision (i.e. hourly, daily, monthly and yearly) to model the potential environmental impacts of the dynamics of its energy demand and production during its use stage. When compared with values from the currently used standard in Switzerland, the results from this study show a significant difference for GHG emissions which can be explained by the use of different sources of data for energy statistics and environmental information. The comparison of results from models with different levels of temporal precision confirms previously observed variations, but also demonstrates that monthly precision is sufficient to make a representative assessment of new single-family housing in Switzerland. The separation of yearly demand and production for 2016, 2017 and 2018 then shows that prospective modelling might be more relevant than intra-annual precision to offer representative assessment. Finally, the consideration of temporal variation from energy sources in neighbouring countries reveals its importance when compared to models which considers average European electricity production.

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Managing Construction Projects: Developing Complexity into Complicatedness

Eber W[1]

[1]LBI Bauprozessmanagement und Immobilienentwicklung, Technische Universität München, Arcisstraße 23, 80333 München, Germany.

eb@bv.tum.de

Abstract. Construction projects are understood as being complex and therefore in need of support through adequate tools to be successfully managed. Among others, the Building Information Model (BIM) is expected to provide a modern and powerful toolset allowing for reliable prediction of the respective development and behaviour. Based on Theory of Systems, the term of complexity in fact matches the principal capabilities of an object-oriented information system where e.g. the Building Information Modelling rests upon. However, any complex system tends to instable behaviour allowing principally for no reliable prediction, in particular in the single run required for unique projects with no possibility to rearrange processes without major losses. Correspondingly, experienced Construction Managers are judging the complexity of projects as a crucial obstacle to efficient execution but declare complexity as not measureable, thus as degree of unmanageability. Therefore, the inherent complexity of interdisciplinary projects needs to be reduced, i.e. transformed into complicatedness, not reducing the effort of elaboration but allowing for stable solutions. In order to achieve such a transfer, the inherent heterogeneity is utilized tracking down the strictness and linearity of the internal and external system borders, thus, investigating the separability of the adjacency matrices. These mainly topological considerations lead to criteria forming substructures finally allowing for predictable behaviour of the project structures with limited uncertainty. Therefrom, we expect some significantly improved understanding of the cybernetics of projects and consequently advanced possibilities in shaping and establishing activity-based risk management, which is crucial to nowadays construction and real estate projects.

1. Introduction

The introduction of Building Information Models (BIM) is currently expected to solve a wide range of construction problems [1]. Resting upon the principles of object-oriented database theories [2], this approach is bound to modelling the complete entirety of elements required for construction and their respective interactions [3]. If in particular the completeness of this model can be ensured undeniably the behaviour of the system can be predicted in detail [4] [5]. Thus, the expectations are based on the human ability to describe a very encompassing unstructured entirety with utmost precision [6]. Besides the fact that many issues required for operational prediction, like contracts, dates and operational i.e. capacity-induced interactions, are principally not available in advance [7], the major problem results from the system's inherent complexity, leading to unstable and therefore nevertheless unpredictable solutions [8][7]. Since the object-oriented approach of BIM is intentionally in no way restricted to systems of low complexity, the principal accessibility of prediction limited due to more abstracts reasons needs to be investigated. Thus, this article focusses on the term of complexity [9] and the therewith resulting inherent issues.

2. Definitions of Complexity

Considering the term of complexity [10] of a system, in particular complexity of the organisation of a project, some confusion exists.

2.1. The Understanding of Complexity in Construction Management

Recent surveys among project managers [11] reveal that complexity is considered to be an existing characteristic of a project, but state it not to be accessible by any kind of measurement. If this would be true, the parameter complexity would serve only as the description of the degree of a project to be not predictable and therefore not manageable. Then, any so-called "complex" project may under no circumstances be initiated since the expected result can in no way be achieved with some certainty. So, either projects are tackled on the background of hope and accidentally succeed or means of dealing with a high degree of complexity are available and hidden beyond the surface of management [12].

2.2. Theoretical Definitions of Complexity

Even if this understanding is more semantical at least the central idea is given by distinguishing between complex and just complicated behaviour. Caldarelli and Vespignani [13] state the criteria for complexity first as heterogeneity over all scales, indicating that average values are not representing the system's characteristics and second as being irreducible, i.e. any attempt of separating parts of the system leads to a fundamentally different behaviour [14]. These criterions in fact allow for no statistical description and therefore represent the absolute limit of unmanageable structures due to complexity. However, in order to transform organisational structures into manageable units, substructures need to be identified which can be treated separately without changing the system's behaviour significantly [15]. Thus, truly complex systems remain complex, but if they were separable to some degree the task would be to eliminate exactly this amount of complexity. Then, based on statistical methods incomplete complexity may be transformed into complicatedness, i.e. into a set of widely independent subsystems with less complexity. On this background, based on Systems Theory, several mathematical definitions of complexity are possible, which are mainly compatible to each other, leaving the difficulty with the translation of organisational systems into abstract systems. The parameter of complexity may be defined as

$$\alpha = \ln(\xi + 1) / \ln N \tag{1}$$

where N represents the cardinality, i.e. the number of primitive elements within the system, and K counts the interactions between them. The interoperability $\xi = K / N$ equals the average number of (directed) interactions per node [16]. In the following, this formal definition is subjected to more meaningful interpretation:

2.2.1. Measure for the Interaction Degree of Primitives. As a classical approach, the parameter connectivity focusses on the number of interactions K within the system related to the number of primitive elements. Based on the known cardinality N and K the complexity is just a logarithmic measure, scaled in a way that maximum connectivity, i.e. each element is connected to each other element, leads to $\alpha = 1$ [17].

2.2.2. Measure for the Relative Information of a Node. The local information of a particular node, based only on structures, is proportional to the number ξ of nodes actively connected to, i.e. where a local token may be transferred to. ξ needs to be increased by 1 to cover the node itself as a possible additional target of the information. According to [18], the information is measured as logarithm of the options, in this case related to the maximum available number of target options which is N. Then, complexity represents the average entropy of a node in comparison to the possible entropy according to Shannon [18]: $E_R = \ln(\nu + 1) / \ln N = \alpha$ [18].

2.2.3. Degree of Emergence of a System's Behaviour in Contrast to Complicated Behaviour. Describing complexity by the number of states a system can occupy leads to a similar explanation. At a certain point of time, the considered system is defined by a multidimensional state within the space of states. Focusing mainly on the dynamics of a system, complexity can be defined by the number of states which are available for a next step which is given by the transition from one state to any logically following step. This is only possible along the directed interactions which are represented again by the interoperability $\xi = K / N$ out of N states available. Then, the logarithmic measure for the number of available states is the given complexity α [17].

2.2.4. Dimension of the Configuration Space of a Project Structure. Positioning all elements in a way that each is the spatial next neighbour to all the targeting elements requires a virtual space with a number of α dimensions. Thus, complexity represents the dimension of the configuration space scaled to a maximum dimensionality of 1, where all nodes can be placed respectively [18].

2.2.5. Degree of Non-linearity of Propagation Deviations. Furthermore, α is determined as the exponent of the structural development of a modification $\Delta(\zeta)$ from one causal situation r to a next logically depending situation r+1. Thus, α reflects the degree of the linearity of the structural development $T(r) \simeq \xi^{1+\alpha r} \Delta(\zeta) / (1-\beta)$ with increasing structural steps r and the positive factor with each step $\omega \simeq \xi^{\alpha}$ [20].

2.3. Complex Solutions to Systems Theory Differential Equations.
Systems Theory describes the behaviour analysing the linear Taylor terms of functions which represent the interaction of nodes. For a set of linear differential equations the solutions are of the type

$$n_i : \frac{\partial Q_i}{\partial t} \simeq \sum_j c_{i,j} Q_j \qquad Q_i = \sum_j g_{i,j} e^{\lambda_j t} \left(+ \sum_j g'_{i,j} e^{2\lambda_j t} + \dots \right)$$

Without limitation to the generality, the solutions [21] are either oscillating, exponentially escalating or in rare cases approaching constant values. Therefrom, the authors conclude the restriction to very clear structures in order to maintain predictable systems' behaviour which is the same as manageable systems. Finally, graph-theoretical tree-structures and network-structures are the only remaining options which correspond well to the common understanding. In this paper, a different, however supporting approach is taken leading to a similar result but based on an investigation of a critical transition in consuming resources.

3. Critical Point of Complexity

A fairly simple consequence of complexity would be the asymmetrical distortion of average values due to higher interoperability values $\xi > 1$ if intermediate results are subject to limited uncertainty [22]. A purely sequential system corresponds to $\xi_{lin} = 1$ and therewith $\alpha_{lin} = \ln 2 / \ln N$. In this situation, the central limit theorem states average values of e.g. duration or consumption of resources for the whole system equal to the singular elements. However, increasing $\xi > 1$ leads to a loss of efficiency due to the absolute requirement of the contemporary readiness of all prerequisites for the subsequent process. In the following, this is presented exemplarily for the duration of processes but holds true for resources and products as well.

3.1. Local Consideration
Let the duration t of a process vary around a fixed value based on a constant distribution (figure 1 and figure 2): $t = t_0 \pm \tau / 2$ respectively $t = t_0 - \tau / 2 + \tau'$, where τ' is a random variable, according to the distribution

$$P(\tau') = \begin{cases} \tau^{-1} & if\, 0 \le \tau' \le \tau \\ 0 & otherwise \end{cases}. \tag{2}$$

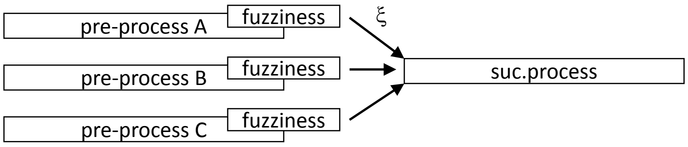

Figure 1. Definition of interoperability

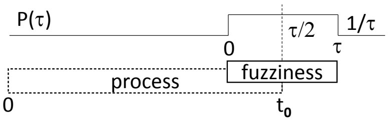

Figure 2. Probabilities of fuzziness

This distribution is normalised and, thus as expected, the average value is

$$\overline{\tau_1} = \int_0^\tau \tau' \tau^{-1} d\tau' = \frac{1}{2}\frac{\tau'^2}{\tau}\bigg|_0^\tau = \frac{1}{2}\frac{\tau^2}{\tau} = \frac{\tau}{2} \tag{3}$$

Combining two predecessors PrA and PrB into one process leads to the probability P of PrA times the probability, that process PrB is already finished, and *vice versa.* Any process duration "finished before" is determined:

$$P_{before\,\tau'}(\tau') = \int_0^{\tau'} P(\tau'')d\tau'' = \frac{\tau''}{\tau}\bigg|_0^{\tau'} = \frac{\tau'}{\tau} \qquad P_{\Pr A \& \Pr B}(\tau') = 2P(\tau')\cdot\frac{\tau'}{\tau} = 2\cdot\frac{\tau'}{\tau^2} \qquad (4)\,(5)$$

Thus, we find as average time for the combined situation:

$$\overline{\tau_2} = \int_0^\tau \tau' 2 \frac{\tau'}{\tau^2} d\tau' = \frac{2}{3}\tau \tag{6}$$

For each number of preceding processes to be taken in, the overall probability is a factor $1/\tau$ for the primary process, the number of processes to have finished before as they can be replaced by the primary process and a factor τ'/τ for each process that needs to have finished before. Thus, the probability for a number of ξ processes to be taken in is:

$$P_\xi = \xi \frac{1}{\tau}\left(\frac{\tau'}{\tau}\right)^{\xi-1} = \xi \frac{\tau'^{\xi-1}}{\tau^\xi} \tag{7}$$

The therefrom derived average time is

$$\overline{\tau_\xi} = \int_0^\tau \tau' \xi \frac{\tau'^{\xi-1}}{\tau^\xi} d\tau' = \frac{\xi}{\xi+1}\tau \tag{8}$$

Remark: The worst case scenario is considered $\overline{\tau_\xi} = \tau/2$ where the indeterminacy is completely turned into reality and therefore to be avoided by any means. Approaching this situation is described by average relative losses $\hat{\tau} = 2\bar{\tau}/\tau$ respectively as add-on to the $\xi = 1$ situation

$$\tau_{add} = \frac{2\xi}{\xi+1} - 1 = \frac{\xi-1}{\xi+1} \tag{9}$$

As can be expected, this equals zero for $\xi = 1$ (linear sequence, no add-on to the average duration of a single process) and approaches unity as the worst case of the given distribution for $\xi \gg 1$. This result can be easily formulated dependent on complexity α and volume, i.e. cardinality N of the system. With $\alpha = \ln(\xi+1)/\ln N \rightarrow N^\alpha - 1 = \xi$ we obtain:

$$\tau_{add} = \frac{N^{\alpha}-2}{N^{\alpha}} = 1 - 2N^{-\alpha} \tag{10}$$

This yields a value very close to the worst case for maximum complexity $\alpha = 1$ if only the number of elements is large enough. The minimal complexity for a linear chain is

$$\tau_{add,\min} = 1 - 2N^{-\alpha_{\min}} = 0 \tag{11}$$

3.2. System-wide Consideration

Within a system, repeated recombination of fuzzy processes needs to be taken into account. Causal interdependencies lead to a system structure, where all elements are ordered according to ranks. Thus, the maximum number of ranks Γ according to the Theory of Graphs describes the maximum length of any causal chain within the considered system. The density $\rho = N/\Gamma$ denotes the average number of elements on the same rank. On each rank r the number of ξ elements are combined and operate on a single element at r+1. Combining ξ elements on a singular rank position differs in no way from combining some elements on r+2 where these are combined from ξ elements on r+1. Therefore, only the number of elements combined on all rank positions needs to be known in order to elaborate the statistical add-on to the overall result. Since on each rank, each element combines from ξ elements, the result comprises the combination of ξ^{Γ} elements. Therewith we obtain for the total system:

$$\mathrm{T}_{add} = \frac{\xi^{\Gamma}-1}{\xi^{\Gamma}+1} = \frac{\left(N^{\alpha}-1\right)^{\Gamma}-1}{\left(N^{\alpha}-1\right)^{\Gamma}+1} \tag{12}$$

The following graph (figure 3) shows the dependency on the cardinality N, the complexity α and the maximum rank Γ.

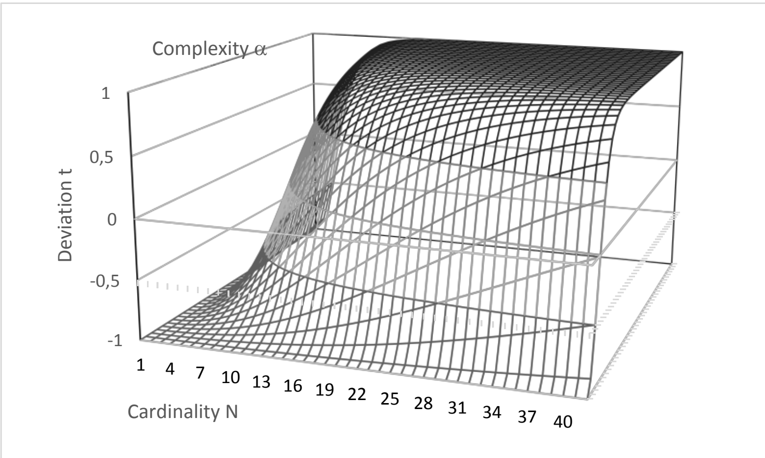

Figure 3. Critical transition of add-on T_{add} *vs* N and α .

The add-on is quickly rising to the worst case for higher cardinality or/and higher complexity. With increasing Γ, the transition becomes very steep and therefore marks a limit of criticality, which is described by

$$0 = \mathrm{T}_{add} = \frac{\left(N_c^{\alpha_c}-1\right)^{\Gamma}-1}{\left(N_c^{\alpha_c}-1\right)^{\Gamma}+1} \quad \rightarrow \quad 0 = \left(N_c^{\alpha_c}-1\right)^{\Gamma}-1 \tag{13}$$

$$\alpha_c = \frac{\ln 2}{\ln N_c} = \alpha_{lin} \tag{14}$$

The critical transition lies exactly where complexity equals the value given for a linear chain. Thus, for any substantial Γ we obtain strongly increasing losses due to complexity as soon as the limit of linear chains is exceeded. Still smaller values α indicate the breaking up of the system into smaller subsystems, where at least some elements have no successor and therefore no part in influencing the rest of the system anymore. The derivative with respect to ξ reveals the behaviour at this border:

$$\left.\frac{\partial}{\partial \xi} \mathrm{T}_{add}\right|_{\xi=1} = \left.\frac{2\Gamma \xi^{\Gamma-1}}{\left(\xi^{\Gamma}+1\right)^2}\right|_{\xi=1} = \frac{\Gamma}{2} \tag{15}$$

The rise of loss is closely coupled to the length of causal sequences Γ. Close to unity, i.e. for negligibly short logical chains, they play no role. Yet as they become longer as is typical for projects, they reach substantial values. Considering the scales of $T_{add} = 1$ as the worst case, this is particularly large as soon as Γ reaches values of significantly more than 2.

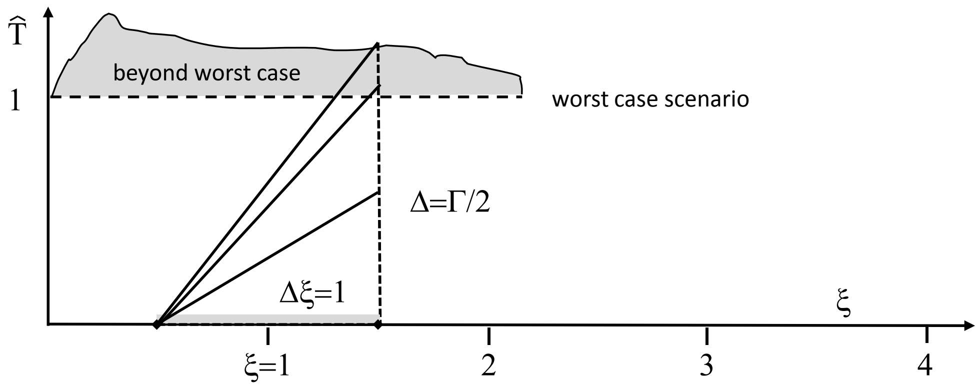

Figure 4. Scaling of derivative at the critical transition

Furthermore, the development close to criticality with respect to N and α can easily be achieved by differentiation. With $N^{\alpha} - 1 = 1 \rightarrow N = 2^{1/\alpha}$, we obtain

$$\frac{\partial}{\partial \alpha} \mathrm{T}_{add} = \frac{\partial}{\partial \xi} \mathrm{T}_{add} \left.\frac{\partial \xi}{\partial \alpha}\right|_{\xi=1} = \Gamma \ln N \tag{16}$$

and

$$\frac{\partial}{\partial N} \mathrm{T}_{add} = \frac{\partial}{\partial \xi} \mathrm{T}_{add} \left.\frac{\partial \xi}{\partial N}\right|_{\xi=1} = \frac{\alpha \Gamma}{2^{1/\alpha}} \tag{17}$$

Thus, at the brink of complexity, losses are rising further proportionally to $\ln N$ which does not compensate for the proportionality to Γ or viewed in regard of complexity α with a factor $\alpha / 2^{1/\alpha}$. Here, only low complexity $\alpha \ll 1$ in comparison to low Γ, i.e. short causal chains, are of help. According to figure 5 e.g. complexity of $\alpha \approx 0,45$ at max would just compensate for causal chain lengths of unrealistically low $\Gamma \approx 10$ for a worst case, but only $\alpha < 0,15$ is capable to secure such a situation to at least a few percent of complete indetermination.

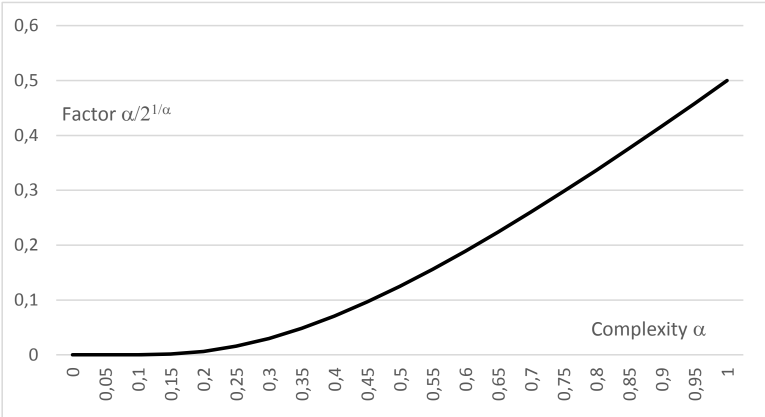

Figure 5. Factor eventually compensating for Length of Chains Γ

In both cases, as long as not all variables are perfectly well-known and not varying, i.e. $\tau = 0$, close coupling of processes leads to unbearable losses and must be avoided by all means. On this background, we conclude the general unmanageability of complex systems.

4. Reducing Complexity

Complexity is defined through the characteristic of a system that no element nor an interaction can be removed or ignored without modifying the systems' behaviour significantly [14][23]. On this background, in fact, no improvement on tackling the situation can be offered [24]. Yet, the question is whether real systems are factually that complex or can be separated into smaller subsystems, which act individually and are mainly not interfering with the remaining system. Then, the overall-behaviour would be just a linear concatenation of the subsystems, which is just complicated, since it demands only industriousness and effort to understand and describe the behaviour, but is principally possible – in contrast to truly complex systems. This leads to an investigation of the separability of a system, formally identical to the question of to which degree the adjacency matrix representing the systems interactions is separable into independent submatrices [25]. Considering the adjacency matrix includes the localisation and sorting out the singular elements, i.e. elaborates the systems' behaviour on local levels [26]. In order to judge a system on a more general level, adequate homogeneity is presupposed since only then statistical reasons will hold [13]. The demand of reducing complexity in order to increase manageability is here given by the attempt to minimize complexity losses. As already mentioned, a different approach by modelling the system via a set of linear differential equations and considering characteristics of stability [27] leads to the same conclusions.

4.1. Issues from Minimizing Losses

The strong dependency of losses on ranks Γ emphasizes the importance of rank-sorted structures, i.e. causal sequences, where cause and effect are clearly defined. This in particular enforces to avoid any fuzzy structures which can not be formulated as graphs.

4.1.1. Loop-Freeness. Obviously, high values of Γ indicate a very high positive gradient close to the $\xi = 1$ limit. This leads to the conclusion that in any case long causal chains need to be broken up. In particular, loops need to be eliminated completely since they principally lead to infinite values of Γ .

4.1.2. Control-Loops. If loops are very short, i.e. eventually comprising only two corresponding elements, the consideration is on a different basis. Such very local loops with no further impact may be understood in detail, therefore used in particular to stabilize elements as negatively effectuating control loops, exhibiting partly oscillating behaviour but dampened with reasonably short time constants. In this case, the behaviour is well understood and is not subject to the overall consideration of stochastic impact. However, since they would stabilize variables, they are strongly contributing to the separation of systems, as they lead to a high degree of independency of formerly strongly coupled segments [28].

4.1.3. Multiple Paths. The exceedingly high gradient of losses is bound to the multiplicity of impact. This implies the need to prefer structures, where impact is being distributed over the graph, but never united. On the background of these arguments only two well-known graph-theoretical structures [29] [30] [31] remain as the goal of restructuring complex systems.

4.2. Resulting Structures Tree and Network

Unidirectional tree-structures maintain clear ranking, no multiple paths and absolute freedom of loops. Since they certainly cannot model complete (complex) systems, they need to be used in particular to operate definition and responsibility issues. Including very local control-loops, for clear structural reasons, absolutely safe results can be constructed and finally obtained. All further interaction must be subjected to graph-theoretical networks [32]. Allowing for almost all kind and number of interactions, which cannot be avoided in production, at least ranks and freedom of loops is enforced. The remaining problem due to multiple paths and possibly high impact-values ξ, however can easily be tackled by subjecting the singular elements, i.e. subsystems, to local control-loops which would ensure the correct (according to the given unambiguous definition) outcome of the elements.

5. Conclusion

Summarising, we obtain a very plain methodology to treat complexity in organisational structures. In any case, complexity itself can not be cured but only reduced, i.e. by eliminating the tightness of interactions. Therewith, the former large complex system becomes separated into a set of less complex subsystems which can be understood and handled more easily. The resulting modified system comprising the subsystems is only helpful if this is less complex than the original, i.e. interactions are less and simple, ideally just a linear combination of the subsystems. Compatible with common understanding, but based on a much more substantial consideration, the resulting structures need to be either graph-theoretical tree-structures or rank-sorted, loop-less graph-theoretical networks. Possibly multiple but strict tree-structures serve to ensure completeness and systematical correctness of the elements to be identified. Separated from this elaboration structure, these elements may be (re-) subjected to their interaction on the basis of well-ordered networks. Factually complex systems would not allow for such ordering due to being irreducible by definition. However, in many cases, hidden separability to some degree is given and the attempt of applying these strict structures reveals less than assumed complexity. Otherwise, in order to artificially produce independency, short control-loops need to be applied. Based on dampening loops, random result variations of processes are forced back to tolerance corridors around the designed values so that successor processes are no more dependent on the exact performance of the predecessors. Within tree-structures, they help separate branches (horizontally) as well as keep hierarchical levels (vertically) apart. In network structures, they serve breaking up causal loops and shortening causal chains in longitudinal direction. Then complexity is transferred into mere complicatedness, where emergent behaviour is replaced by a larger set of independently operating subsystems and their local behaviour. To tackle this, only industriousness is required, but predictable solutions are principally available.

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Multiple Criteria Decision Analysis under uncertainty in sustainable construction: a neutrosophic modified best-worst method

Scherz M[1] and Vafadarnikjoo A[2]

[1] Working Group Sustainable Construction - Institute of Technology and Testing of Construction Materials, Graz University of Technology (A)

[2] Norwich Business School, University of East Anglia, Norwich (UK)

marco.scherz@tugraz.at, amin.vafadar.n@gmail.com

Abstract. Capturing uncertainty in multiple criteria decision analysis (MCDA) is not a new theme but a largely developing topic which is in close connection with uncertainty theories such as fuzzy set and grey systems theories. Due to growing complexity of construction processes mainly because of implementation of sustainability aspects it would be necessary to take advantage of a novel MCDA methodology as an efficient tool to handle the uncertainty in sustainable construction decision making. In this study, we utilise a novel neutrosophic modified best-worst method (NM-BWM) to deal with the uncertainty in decision making in the context of sustainable construction. The method is an integration of neutrosophic set theory (NST) and the modified best-worst method (M-BWM). The NST can provide insights on efficient uncertainty handling of decision makers (DMs) subjective judgements. The BWM is a MCDA method which utilises two vectors of pairwise comparisons (the best criterion to others and others to the worst criterion) to obtain the weights of evaluation criteria. Merits of the BWM include its capability in effectively remedying the inconsistency derived from pairwise comparisons as well as simplicity and less pairwise comparisons compared to other similar methods like analytic hierarchy process (AHP). We show the applicability of the method in a case study with focus on the implementation of sustainable construction.

1. Introduction

The way of thinking in simple logical contexts often leads to overlooking medium- or long-term effects on our immediate environment. Contrary to the objectives of sustainable development, future generations are endangered [1]. The drastic situation of climate change, as well as the increased number of storms, floods, droughts and forest fires, is thus rather due to the actions of mankind in the seventies [2]. As a result, climate protection and disaster control represent increasingly complex challenges for architects and engineers. Sustainable construction is the buzzword at the centre of this development. In order to deal with complex systems and the associated inherent dynamics of the system ”building”, systemic thinking is indispensable [3],[4].

The following article addresses the implementation of sustainability aspects in the early design stage of buildings. With a variety of criteria to consider, the tasks for architects are becoming increasingly complex. The human brain is not able to assess the effects of changes in one factor on more than four interrelated influencing factors [5]. In particular, medium- and long-term effects cannot be assessed without tools for such a large number of related factors. Construction projects exceed this number of interacting criteria by a multitude. One approach to make the complexity of numerous influential criteria manageable are multiple criteria decision making (MCDM) methods.

In the present article the application of a neutrosophic modified best-worst method (NM-BWM) is discussed in order to facilitate and thus advance the implementation of sustainability aspects in the early design stage of buildings - in which numerous non-quantifiable factors and multipe decision makers (DMs) are present. In real-world decision-making environment, there is an uncertainty in DMs opinions which cannot be dealt with properly in the original BWM. In the original BWM, two vectors of pairwise comparisons including best-to-others and others-to-worst vectors are treated with the same level of importance. The NM-BWM can help overcome this shortcoming by incorporating the NST into the original BWM in order to capture the uncertainty of DMs on two vectors. The NST has two main advantages over other similar uncertainty theories like fuzzy set theory; firstly, the information about rejection has effectively quantified in the NST and secondly it has the capability to independently quantify the indeterminacy membership, which adds an extra level of suitability to it for structuring DMs' confidence value acquisition process [6].

2. Literature Background

In this section the literature background of applied methods is described. It includes the subsections sustainability assessment in construction industry (2.1), multi attribute decision making in construction industry (2.2), best-worst method (2.3) and neutrosophic set theory (2.4).

2.1. Sustainability Assessment in Construction Industry

Due to the uniqueness of each individual building, planning according to recurring procedures and processes is not feasible. In addition to the complexity of a building, which is already given by static and physical building requirements, the design process is increased by sustainability requirements. Through standards harmonized at the European level (hEN) and through numerous normative and voluntary instruments - e.g. ISO 14000 series of standards "Environmental management" [7], [8] the implementation of sustainable construction is being promoted. In 2008, the ISO 15392 "Sustainability in building construction - General principles" [9] created a uniform understanding of sustainability in the construction industry [10]. According to the European framework of CEN/TC 350 next to the three classical dimensions of sustainability - environmental dimension, economic dimension and social dimension - additionally functional and technical qualities have to be considered within the sustainability assessment of buildings [11], [12], [13], [14]. Due to the multi criteria interdependencies of sustainability criteria, holistic consideration can only be achieved by a complete set of criteria [15]. Numerous building certification systems (BREAAM[1], LEED[2], DGNB[3], etc.) have already developed complete criteria catalogues for the sustainability assessment of buildings and are suitable for the assessment of the building performance [16]. The implementation of sustainable construction is a multidimensional concept that is gaining relevance in all areas of society [17]. Barbier states that sustainable development involves the simultaneous maximization of environmental, economic and social system goals [18]. However, as Munda has shown, it is generally not possible to maximize different goals at the same time. Therefore, a compromise should be found between different objectives, which can be achieved by applying MCDM methods [19]. The current challenges in the operationalization of holistic design and construction processes are mainly based on imprecise stakeholder requirements and the current lack of suitable methods for controlling life-cycle processes [20].

2.2. Multi Attribute Decision Making (MADM) in Construction Industry

Multiple attribute decision making (MADM) or multiple criteria decision aiding (MCDA) have been increasingly popular in various decision-making fields [49], [50]. For instance, Wang et al. [21] indicated this popularity in sustainable energy because of the multi-dimensionality of the sustainability goal and the complexity of socio-economic and biophysical systems.

In the course of the literature search numerous articles using MADM-methods for the different application in construction industry were found [22]. Already when selecting materials, decision makers have to consider numerous factors (mechanical properties, physical properties, material costs, durability, etc.). A model for the selection of building materials that weights criteria based on the three-pillar sustainability approach was proposed by Akadiri [23]. According to Jahan et al., MADM-methods such as TOPSIS, ELECTRE and AHP are the most frequently used methods in the course of material selection [24]. MADM-methods are also used for the selection of construction machinery. Temiz & Calis investigated the correct selection of an excavation machine for a construction site and compared the methods AHP and PROMETHEE [25]. For the selection of cranes Skibniewski & Chao investigated the application of AHP already in 1992 [26]. In addition, MADM-methods are also applied in the selection of concrete pumps [27]. A further field of application of MADM-methods are transport and logistics. Machharis & Bernardini investigated the application of multi criteria decision methods in transport projects [28]. According to Turcksin et al. the most frequently applied

[1] https://www.breeam.com
[2] https://new.usgbc.org/leed
[3] https://www.dgnb-system.de/de/system/zertifizierungssystem/index.php

decision methods in transport projects are MADM methods (AHP, ANP, MAUT, MAVT), outranking methods (PROMETHEE, ELECTRE) and regime analyses [29]. MADM-methods are also widely used in the field of logistics. Tuzkaya investigated the impact of transport processes on the environment, Wang & Chang applied MADM-methods in the field of green urban logistics or Moghaddam et. al in the field of clean energy for energy efficient buildings [30], [31], [32]. Within environmental topics MADM-methods were used in waste management, energy management, waste water treatment, water quality or air quality [33]. One method developed very late in the history of MCDM and rarely applied in the field of sustainable construction until now is the best-worst method (BWM).

2.3. Best-Worst Method (BWM)

In the field of construction industry BWM was applied in piping selection [34] and in areas of risk assessment [35], [36]. The BWM can help DMs in defining the weights of criteria in a decision-making problem. In BWM, firstly the best criterion (i.e. the most favourable) and the worst criterion (i.e. the least favourable) must be determined by the DM. Secondly, pairwise comparisons are carried out between each of the two criteria (i.e. best and worst) and other criteria. Then, weights of criteria are determined by solving a mathematical model. The simplicity of use, less number of pairwise comparisons and more consistent comparisons compared to other similar methods like AHP have made BWM a reliable method.

2.4. Neutrosophic set theory (NST)

Atanassov [38] introduced intuitionistic fuzzy sets (IFSs) as an extension of the well-known fuzzy set theory of Zadeh [39] to overcome its drawbacks by providing non-membership degree [40]. Smarandache generalised the IFS into the neutrosophic set (NS) to show insights on a more efficient DMs subjective judgements uncertainty handling [41]. It shows fuzzy information utilising the functions of truth, indeterminacy and falsity like IFSs. The distinction between NSs and IFSs is that the function of indeterminacy in NSs is independent of truth and falsity functions [42]. However, application of NSs in practical problems had been challenging because values of truth, indeterminacy and falsity functions were within]0-,1+[[42],[43]. To deal with this issue, Wang et al. [21] introduced single-valued neutrosophic sets (SVNSs) where truth, indeterminacy and falsity functions are real elements of [0,1] [42]. A single-valued trapezoidal neutrosophic number (SVTNN) is also considered as a generalisation of intuitionistic numbers. Recently, SVNSs has received increased attention by researchers from various fields of decision making.

In detail, in this article, the modification of BWM in combination with NST is applied which is called NM-BWM. The applied method is called neutrosophic modified best-worst method (NM-BWM). A decisive question in the selection of the appropriate MCDM method is the handling of uncertainties in the course of the evaluation. In the literature several approaches for the explicit consideration of uncertainties in MCDM methods are outlined which shows the importance of this topic. For mathematical basic definitions of the NST refer to [41].

3. The Neutrosophic Modified BWM (NM-BWM)

The original BWM is described in [37], [44] which follows a five-step approach, while the applied NM-BWM has two additional steps explained in [6]:

(i) DM's Uncertain Confidence on the Best-to-others Preferences
The neutrosophic value of the DM's confidence on the best-to-others preferences (ρ^+) is a SVTNN (Table 1). It reveals the degree of DM's confidence on best to-others vector.

Table 1: The confidence rating scale

Linguistic Phrase	Score	SVTNN	Crisp Value
No Confidence	0	$\langle(0.0,0.0,0.0,0.0),0.0,0.0,0.0\rangle$	0.00
Low Confidence	1	$\langle(0.2,0.3,0.4,0.5),0.6,0.2,0.2\rangle$	0.26
Fairly Low Confidence	2	$\langle(0.3,0.4,0.5,0.6),0.7,0.1,0.1\rangle$	0.38
Medium Confidence	3	$\langle(0.4,0.5,0.6,0.7),0.8,0.0,0.1\rangle$	0.50
Fairly High Confidence	4	$\langle(0.7,0.8,0.9,1.0),0.8,0.2,0.2\rangle$	0.68
High Confidence	5	$\langle(1.0,1.0,1.0,1.0),0.9,0.1,0.1\rangle$	0.90
Absolutely High Confidence	6	$\langle(1.0,1.0,1.0,1.0),1.0,0.0,0.0\rangle$	1.00

(ii) DM's Uncertain Confidence on Others-to-worst Preferences
The neutrosophic value of the DM's confidence on the others-to-worst preferences (ρ^-) is a SVTNN (Table 1). It reveals the degree of DM's confidence on others-to-worst vector.
Finally, by solving model (1) the optimal weights of criteria are achieved.

$$\begin{array}{lrcll}
\min & \varepsilon\left(\frac{\rho^-+\rho^+}{\rho^-\rho^+}\right) & & & \\
\text{s.t.} & & & & \\
& \frac{W_B}{W_j}-\frac{\varepsilon}{\rho^+} & \leq & a_{Bj} & \forall j \in N \\
& \frac{W_B}{W_j}+\frac{\varepsilon}{\rho^+} & \geq & a_{Bj} & \forall j \in N \\
& \frac{W_j}{W_W}-\frac{\varepsilon}{\rho^-} & \leq & a_{jW} & \forall j \in N \\
& \frac{W_j}{W_W}+\frac{\varepsilon}{\rho^-} & \geq & a_{jW} & \forall j \in N \\
& \sum_j W_j & = & 1 & \\
& W_j & \geq & 0 & \forall j \in N
\end{array} \tag{1}$$

4. Case Study

For a first application of the new developed NM-BWM in early design stages of buildings a case study was conducted. The interaction of building components, technical equipment and materials is of crucial importance for the sustainable performance of a building. An important step in early, sustainability-oriented design is the support for the selection of building components that fulfill all requirements of the involved DMs right from the beginning of a construction project. In the course of the case study, the developed NM-BWM approach is tested based on the decision problem "window selection".

4.1. Decision Problem

Window properties - i.e. aesthetics, size, position, relationship between transparent and opaque areas, frame, glazing - have a large impact on the building performance [48]. It is well known that a well-designed and constructed window must perform a number of functions - e.g. sun protection, glare protection, ventilation options, protection against the weather, sound insulation or burglary protection - simultaneously, which can lead to trade-offs in the design stage. Since the focus is on the application of the newly developed NM-BWM method, 8 window types and 6 criteria were selected to define the decision matrix.

4.1.1. Window Types (A1-A8)

In the applied case study a window type consists out of the frame and the glazing. The chosen frame types were timber frames, PVC-frames, aluminium frames and timber-aluminium frames. The glazing distinguishes between double glazing and triple glazing.

Table 2: Selection of window types

	Frame	Glass
A1	Timber	Double glazing
A2	Timber	Triple glazing
A3	PVC	Double glazing
A4	PVC	Triple glazing
A5	Aluminium	Double glazing
A6	Aluminium	Triple glazing
A7	Timber - Aluminium	Double glazing
A8	Timber - Aluminium	Triple glazing

4.1.2. Criteria (C1-C6)

Window selection decision can affect many other criteria. In our study, the identified criteria are exemplary and have been derived from the building certification system DGNB[4]. Regarding the literature, [47] has also analysed 6 exemplary criteria.

(i) **Global Warming Potential (C1) - [$kgCO_2 - eq.$]**
In all phases of their life cycle, buildings cause emissions. The objective of life cycle assessment is to gain information about the total life cycle, to reduce buildings emissions throughout their entire life as much as possible. The measurement of the indicator Global Warming Potential (GWP) happens in kg CO_2 - equivalents. To calculate the CO_2 - potential the EcoInvent V3.3 database[5] was used. The impact assessment was carried out with the EPD2013 method implemented in SimaPro[6]. For the life cycle assessment according to ÖNORM EN 15978 [44], in the case study, the modules A1-A3 were considered only.

(ii) **Initial Construction Cost (C2) - [€]**
All stages in the life cycle of a building generate costs: Construction, Operation, Maintenance and End-of-life [45]. From an economic view, the aim is therefore to minimise the buildings total life cycle costs (LCC). The quality of windows contributes to the building performance in terms of sociocultural and functional, technical, environmental as well as economic qualities. Therefore, out of a holistic sustainability perspective, the initial construction cost for windows must be considered. The costs for the chosen window types were calculated in [46].

(iii) **Sound Transmission (C3) - [dB]**
A minimum level of acoustic quality is necessary to ensure that a building can be used as intended, since the acoustic quality of the room is an important indicator of the comfort and satisfaction of its users. Windows with better sound insulation can contribute to an overall higher sound insulation of the whole building. The indicator for the measurement is the Rw value in dB. The Rw-values for the chosen window types were calculated in [46].

(iv) **Heat Transfer (C4) - [$W/(m^2K)$]**
Thermal comfort in buildings makes an essential contribution to an overall efficient working and living environment. The suitability of the indoor room climate depends on the temperature of the room, the temperature of the surfaces surrounding people, the air velocity in the room and also the relative air humidity in the cooling as well as in the heating period. Assessing the quality of the building envelope in terms of temperature and humidity requires an evaluation of the individual requirements for each of its components. For the measurement in this study, the Uw value of windows (frame+glass) was taken into account. The U-values for the chosen window types were calculated in [46].

(v) **Installation Time (C5) - [h]**
Construction time is a key indicator of the success of any project, as both construction costs and quality are strongly influenced by construction time. The time required to install each component thus contributes to the total construction time of a building. An indicator to characterise the installation time is the effort value. For the component window, the effort value is given as h/pc (hours per piece). The installation time for the chosen window types was calculated in [46].

[4] https://www.dgnb-system.de/de/system/zertifizierungssystem/index.php
[5] https://www.ecoinvent.org/database/ecoinvent-33/ecoinvent-33.html
[6] https://simapro.com

(vi) **Recyclability (C6)**
The construction sector is one of the largest sources of material flows in the world. Construction accounts for almost 50 % of national waste. This criterion describes the recycling options for different window types according to the different materials. For the individual assessment, we use a qualitative evaluation scale such as *excellent recyclability* (1,0), *good recyclability* (1,5), *moderate recyclability* (2,0), *bad recyclability* (2,5), and *very bad recyclability* (3,0).

4.2. Decision Matrix
The decision matrix which shows the performance of each window type (A1-A8) under each criterion (C1-C6) is represented in Table 3.

Table 3: Decision matrix

	C1 [$kgCO_2 - eq.$]	**C2** [€]	**C3** [dB]	**C4** [$W/(m^2K)$]	**C5** [h]	**C6** [-]
A1	188	268	35	1,434	3,795	1
A2	227	336	37	1,159	3,795	1
A3	246	224	38	1,371	3,226	2
A4	366	290	40	1,096	3,226	2
A5	684	403	37	1,5	4,175	2
A6	723	448	38	1,229	4,175	2
A7	334	493	38	1,402	4,554	1,5
A8	373	672	36	1,128	4,554	1,5

4.3. Decision Makers Profile
To obtain the importance weights of criteria (C1-C6), eight DMs who were recognised with their high experience and knowledge in the field of sustainable construction have been asked to participate in the study. They have been contacted by email to provide their pairwise comparisons of 6 criteria using a scale of 1 (equally important) to 9 (extremely more important) based on the original BWM. The participated DMs profile along with their weights (as they were not equally experienced) is provided in Table 4.

Table 4: Decision makers profile and importances weights

	Years of Experience	**Education**	**Weights**
DM1	20	Below BSc	0,13
DM2	31	MSc	0,23
DM3	25	MSc	0,17
DM4	4	MSc	0,08
DM5	6	BSc	0,08
DM6	3	MSc	0,05
DM7	20	MSc	0,13
DM8	20	PhD	0,13

5. Results and Discussion

After obtaining the consistent pairwise comparison data of eight DMs (CR<0.1) then the NM-BWM has been applied and weights of six criteria (C1-C6) have been computed as shown in Table 5. The aggregated weight of each criterion based on obtained weights of eight DMs has been also calculated and revealed in Table 5.

Table 5: Aggregated criteria weights of decision makers

	DM1	**DM2**	**DM3**	**DM4**	**DM5**	**DM6**	**DM7**	**DM8**	**Aggregated Weights**
C1	0,2000	0,3214	0,5217	0,2414	0,2258	0,2060	0,2500	0,2738	0,3044
C2	0,2286	0,1607	0,0580	0,1034	0,2258	0,2698	0,0417	0,1788	0,1450
C3	0,1714	0,0357	0,0580	0,1724	0,1613	0,5151	0,2083	0,0604	0,1277
C4	0,2000	0,3214	0,1739	0,2414	0,1613	0,1714	0,2083	0,1788	0,2206
C5	0,0286	0,0536	0,0580	0,3448	0,3226	0,1349	0,0417	0,0323	0,0957
C6	0,1714	0,1071	0,1304	0,2069	0,1935	0,1663	0,2500	0,2758	0,1778

The decision matrix (Table 3) has been normalised knowing that all the six criteria are of cost nature meaning the lower value of them is better. The final normalised decision matrix has been represented in Table 6. Applying obtained weights of each criterion (C1-C6) shown in Table 5 and getting the weighted average of the normalised values in Table 6, the total weight of each window type (A1-A8) has been obtained as shown in Table 6.

Table 6: Normalised decision matrix and total weights of window types

	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**Total Weights**	**Ranking**
A1	0,7400	0,6012	0,1250	0,0440	0,1667	0,5000	0,4429	2
A2	0,6860	0,5000	0,0750	0,2273	0,1667	0,5000	0,4459	1
A3	0,6598	0,6667	0,5000	0,0860	0,2916	0,0000	0,3508	3
A4	0,4938	0,5685	0,0000	0,2693	0,2916	0,0000	0,3201	4
A5	0,0539	0,4003	0,0750	0,0000	0,0832	0,0000	0,0920	8
A6	0,0000	0,3333	0,0500	0,1807	0,0832	0,0000	0,1025	7
A7	0,5380	0,2664	0,0500	0,0653	0,0000	0,2500	0,2676	5
A8	0,4841	0,0000	0,1000	0,2480	0,0000	0,2500	0,2593	6

Findings (Table 5) showed that based on involved DMs opinions, global warming potential (C1) is the most significant criterion in choosing the best window type. The other significant criteria are as follows respectively: heat transfer (C4), recyclability (C6), initial construction cost (C2), sound transmission (C3), and installation time (C5). The obtained two most important criteria highlight the significance of preserving the heat while providing thermal comfort (i.e. C4) and at the same time taking into consideration the global warming potential (i.e. C1).

The analysis of results (Table 6) revealed that the second window type (A2) with timber frame and triple-glazing is the best choice followed by A1 (timber frame and double-glazing), A3 (PVC frame and double-glazing), A4 (PVC frame and triple-glazing), A7 (timber-aluminium frame and double-glazing), A8 (timber-aluminium frame and triple-glazing), A6 (aluminium and triple-glazing) and A5 (aluminium and double-glazing) respectively. According to the high CO_2 - potential of the alumium frame (see Table 3) the findings are in line with DMs preferences.

6. Conclusion

In this study, a NM-BWM method was applied to capture uncertainty in the DMs opinions in order to obtain weights of criteria derived from the building certification system DGNB. The identified criteria are global warming potential (C1), initial construction cost (C2), sound transmission (C3), heat transfer (C4), installation time (C5) and recyclability (C6). The weights of criteria then used to reveal among a list of eight predefined window types (A1-A8) which ones can perform more/less appropriately in the early sustainable building decision-making process in terms of various six criteria. The analysed eight window types are A1 (timber frame and double-glazing), A2 (timber frame and triple-glazing), A3 (PVC frame and double-glazing), A4 (PVC frame and triple-glazing), A5 (aluminium frame and double-glazing), A6 (aluminium frame and triple-glazing), A7 (timber-aluminium frame and double-glazing) and A8 (timber-aluminium frame and triple-glazing).

The results confirmed that global warming potential (C1) is the most significant criterion in choosing the best window type while installation time (C5) is the least important one in that manner. Furthermore, A2 (timber frame and triple-glazing) is the best window-type choice under various six criteria and A5 (aluminium frame and double-glazing) is least proper one.

One of the limitations of this study which opens an avenue for future research directions is the partial incomprehensiveness of the derived criteria and explored window types. In future studies, researchers may take advantage of a more comprehensive list of criteria to investigate alternatives not only window type but also other components of sustainable buildings. The other shortcoming was a limited number of DMs or experts which can be increased in future investigations to improve the validity of the findings.

The application of MCDM methods in early design stages of buildings was identified as a research gap. Many different MCDA methods were applied for single issues within the field of sustainable construction - e.g. material selection, selection of energy systems, selection for waste management types, window selection - but not for the holistic design of a new building in early design stages. Reasons for that are the numerous criteria and the missing alternatives in the early design stage.

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Consistent BIM-led LCA during the entire building design process

Cavalliere C[1], Hollberg A[2], Dell'Osso G R[1], Habert G[2]

[1] Department of Civil, Environmental, Land, Building Engineering and Chemistry, Polytechnic University of Bari, Via Edoardo Orabona, 4, 70125 Bari, Italy
[2] Chair of Sustainable Construction, ETH Zurich, Stefano Franscini Platz 5, 8093 Zurich, Switzerland

carmine.cavalliere@poliba.it

Abstract. Life Cycle Assessment (LCA) is a suitable method to analyse the environmental impact of buildings' design choices. However, the nature of the building design process leads to a dilemma when applying LCA in early phases. LCA can be fully performed only in the later design phases when complete information is available, but it is too costly to make changes. As a result, LCA is scarcely employed as a decision-making tool. Building Information Modelling (BIM) can assist LCA during the design process. So far, two different approaches are usually adopted to perform the BIM-based LCA of buildings. The first approach concerns performing LCA with a detailed BIM at the end of the building design process. The second approach involves simplified methodologies for early design stages with uncertain data. This study proposes a novel approach for applying a consistent BIM-led LCA from the early design stages to the detailed ones based on lower to higher level of accuracy. Since the BIM elements are specified with increasing level of detail in each design phase, the method uses different LCA databases for the Level of Developments (LODs) of the building elements. Accordingly, LCA calculations are based on mixing the databases in every design phase. This is possible as long as the databases use identical background data. The framework helps to provide consistent information for decision-making throughout the whole design process, both in the later design phases and early ones with a simplified BIM.

1. Introduction

The building sector consumes a large amount of natural resources [1], contributing to their depletion and to the emission of a significant amount of greenhouse gases (GHG) [2]. The growing interest in environmental issues has led to several studies based on Life Cycle Assessment (LCA) since it is recognized as a powerful tool to predict the overall environmental impacts of buildings [3,4].

Over the last years, several studies have combined Building Information Modelling (BIM) with the LCA methodology to investigate the environmental performance of a building element or of a whole building. On the one hand, BIM supports integrated design and improves data management and collaboration between the different stakeholders. BIM also provides an effective way to investigate the options for the reduction of GHG emissions with regards to the materials processing, delivery, and construction methods [5]. On the other hand, LCA is a suitable method for assessing the environmental performance of buildings during their whole life cycle.

However, methodological challenges on the BIM-based LCA can be found the literature. For example, existing studies focus on a specific stage when conducting BIM-based LCA calculations without referring to the entire design processes. Moreover, most papers on BIM-based LCA methods do not declare the Level of Development (LOD) which the BIM model refers when conducting the LCA [6]. The LOD concept is crucial for BIM-led LCA. It defines the minimum content requirements for each BIM element at different progressively detailed levels of completeness.

The aim of this paper is to provide a framework which empowers LCA to be used as a consistent decision-making tool during all phases of the design process. The novel approach considers the available information in the BIM with as much accuracy as possible in each stage. This way it is possible performing continuous LCA over the entire building design process by using the data provided by BIM. Different LCA databases are employed with regards to the LODs of the BIM elements. Since different types of BIM elements are modelled with different LODs in each design phase, the LCA is performed by consistently mixing the LCA databases. This is made possible as long as the databases use identical background data. This approach has not been considered by any of the published studies before and helps to provide information for decision-making throughout the whole design process, both in the early design phases and later phases with a more detailed BIM.

2. Literature review

The use of the BIM-based sustainability assessment tools is increasing together with the studies focused on methods for the environmental impact assessment. The development of methods that integrate BIM and LCA is dramatically growing.

In general, two different approaches exist to perform the LCA of buildings based on BIM. The first trend concerns performing detailed LCA with specific building performance simulation tools. However, it requires linking LCA with a detailed BIM and can only be applied in the advanced design stages because of the lack of data in the early design stages. Additionally, only experts can use the method and designers find difficult to apply it at the early design stages due to the number of variables and tools involved. The second trend refers to simplified approaches only for early design stages. This simplified approach cannot match the complex data available in detailed BIM in advanced design stages.

The existing literature for both trends is summarized in Table 1. As can be seen, all reviewed papers only refer to a single trend, without considering the entire design process. Furthermore, only few studies set the LOD of BIM elements. Ajayi et al. [7] and Röck et al. [8], for example, set the LOD 200 to support their early analysis. Also LOD 300 was declared in two cases by Lee et al. [9] and Yang et al. [10] to support detailed analysis.

The main problem is that these trends are not linked and they require different tools, databases and assumptions. To overcome these limitations, this paper proposes a framework to link both trends by performing continuous LCA calculation through the entire design process.

3. Method

The framework is based on the authors' previous work and it is developed for the Swiss context, but it could be applied for other countries as well [11]. The approach is based on the application of different LODs for the LCA calculation depending on the design process phase. The method is depicted in Figure 1.

The first step is the definition of the LOD evolution. For this paper, the design process is divided into five phases that correspond to the phases 31 to 52 as defined in the Swiss Order for services and fees of architects SIA 102:2014, namely Project Planning (PP), Project (P), Building Permit Application (BPA), Tendering (T), and Construction (C). Then, the LODs are defined in four steps, from low information content (LOD 100) to the highest one (LOD 400).

Table 1. List of BIM-based LCA studies.

Ref.	Trends		LOD	Tools	Impact	FU	DB	LCA phase
	2nd	1st						
[12]		●	–	Revit, Navisworks, Excel, API	ECOE; EE	Complete building	ICE	–
[7]	●		200	Revit, GBS, ATHENA Impact Estimator, Excel	GWP; HH	Complete building	ATHENA Impact Estimator	A1-A3, A4-A5, B1-B7, C1-C4
[13]	●		–	Dprofiler, CostLab, eQUEST, SimaPro, ATHENA EcoCalculator, Excel	EIF	Complete building	Athena Eco Calculator	A1-A3, B1-B7
[14]	●		–	Revit, Dynamo, Excel	ReCiPe indicators	Walls and roof	Ecoinvent	–
[11]	●	●	100 to 400	3D model, Excel	GWP	Complete building	Swiss building db, KBOB, Bauteilkat	A1-A3, B4, C3, C4
[15]	●		–	Revit, Excel	ECE	1 m^2 of GFA	EPD	A1-A3
[16]		●	–	Revit, Excel, SIMIEN, SimaPro 7.3	ECOE; OCOE	1 m^2 of HFA	Ecoinvent Version 2.2	A1-A3, B1, B4, B6
[17]	●		–	Grasshopper, Rhinoceros	PET; PERT; PENRT; GWP; EP; AP; ODP; POCP; ADPE	Complete building	ökobau.dat, EPDs	A1-A3, B4, B6, C3,C4
[18]		●	–	Revit, Excel, SIMIEN, SimaPro 7.3	ECOE; OCOE	1 m^2 of HFA	Ecoinvent Version 2.2	A1-A3, B4, B6
[19]		●	–	BIM tool (N/S), Excel	ECOE; OCOE	Complete building	ICE	A1-A3, B6
[20]	●		–	Revit, Ecotect, IESVE, Excel, Athena Impact Estimator	AP; EP; GWP; HH; ODP; PEC; PCSP; REP; WRRU	Complete building	ATHENA Impact Estimator	A1-A3, B6
[21]	●		–	Revit, Athena Impact Estimator, Excel				A1-A3, B1-B7
[9]		●	300	Revit, Korea LCI database	ADP; AP; EP; GWP; ODP; POCP	Complete building	Korean LCI	A1-A3, A4-A5, B1-B7,C1-C4
[22]	●		–	Grasshopper, Design Builder, DIVA, Ladybug,Galapagos, Octopus,Rhinoceros	GWP	1 m^2 of HFA	EPD Norway, Ecoinvent	A1-A5, B4, B6
[23]		●	–	Revit, Revit DB link, MS Access, Athena Impact Estimator, Excel, Visual Studio	CO_2; SO_2; PM; EP; ODP; PSP	Complete building	ATHENA Impact Estimator	A1-A3, A4-A5, B1-B7, C1-C4
[24]	●		–	Revit, Tally, GBS	AP; EP; GWP; ODP; SMP; PET; PERT; PENRT	Complete building	GaBi database	A1-A3, B1-B7, C1-C4
[25]	●		–	Revit, Revit API, External db	EE	Complete building	ICE, Chinese handbook	A1-A3, A4-A5
[26]	●		–	Revit, Insight	GWP; AP; EP; ODP; ADPele; ADPfoss; TETP FAETP; HTTP; MAETP; POCP;	Complete building	EcoHestia	A1-A3, A4-A5
[27]		●	–	Revit, Ecotect, Excel	COE	Complete building	ICE	A1-A3, A4-A5, B1-B7, C1-C4
[8]	●		200	Revit, Dynamo, Excel	GWP	1 m^2 of GFA	Ecoinvent	A1-A3, B4, C3-C4
[28]		●	–	Revit, Power Pivot, FME, Google Maps API	EE	External wall	EPD database	A1-A3,A4
[29]		●	–	Revit, Dynamo, MySQL, Grasshopper, Slingshot, Archsim, Octopus,EnergyPlus	EE, OE	Complete building	ICE	A1-A3, B1,B4,B6, B7
[30]	●		–	Revit, Excel	ECOE	Complete building	ICE	A1-A3, A4
[31]	●		–	ArchiCAD, Excel	COE	Complete building	Korean LCI	A1-A3, B1-B6
[10]		●	300	Revit, Excel, Glondon BIM5D, eBALANCE, Designbuilder,	GWP	Complete building	Chinese db, Ecoinvent, ELCD	A1-A3, A4-A5, B1-B7, C1-C4

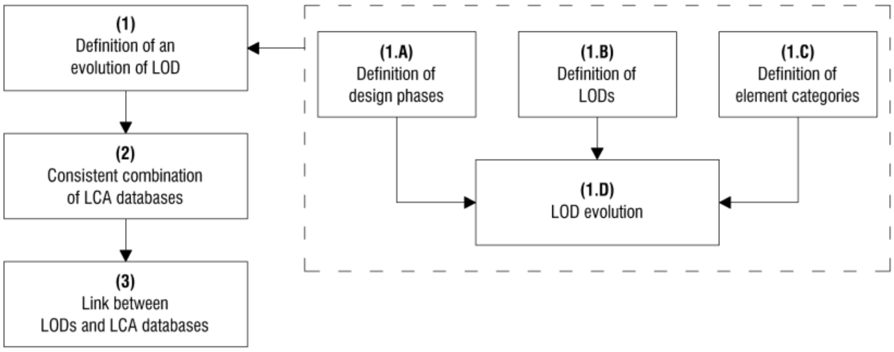

Figure 1. Schematic workflow of the proposed method.

The LODs of different BIM elements do not always simultaneously evolve across the design process, but refer to the aim of the different design phases. While general decisions such as the size and the shape of the building are usually already fixed in the PP phase, decisions on material choice are taken along all the different phases. For example, the load-bearing elements are typically defined with a higher detail in the early design phases while the finishing may only be defined late during the construction phase. Therefore, the different construction categories have a different LOD evolution. For that reason, the Swiss building element classification scheme for cost estimation e-BKP-H SN 506 511 is used to identify the building parts. It is depicted in Figure 2. The scheme considers the building as composed of eleven *building elements*. Each *building element* consists of several *building components*, which have different functions, and belong to different *construction categories*. For this paper, four construction categories are defined according to this scheme, namely *Structure* (all load-bearing parts), *Envelope* (façade and roof covering), *Interior* (non-load-bearing walls and floor finishing), and *Technical equipment*.

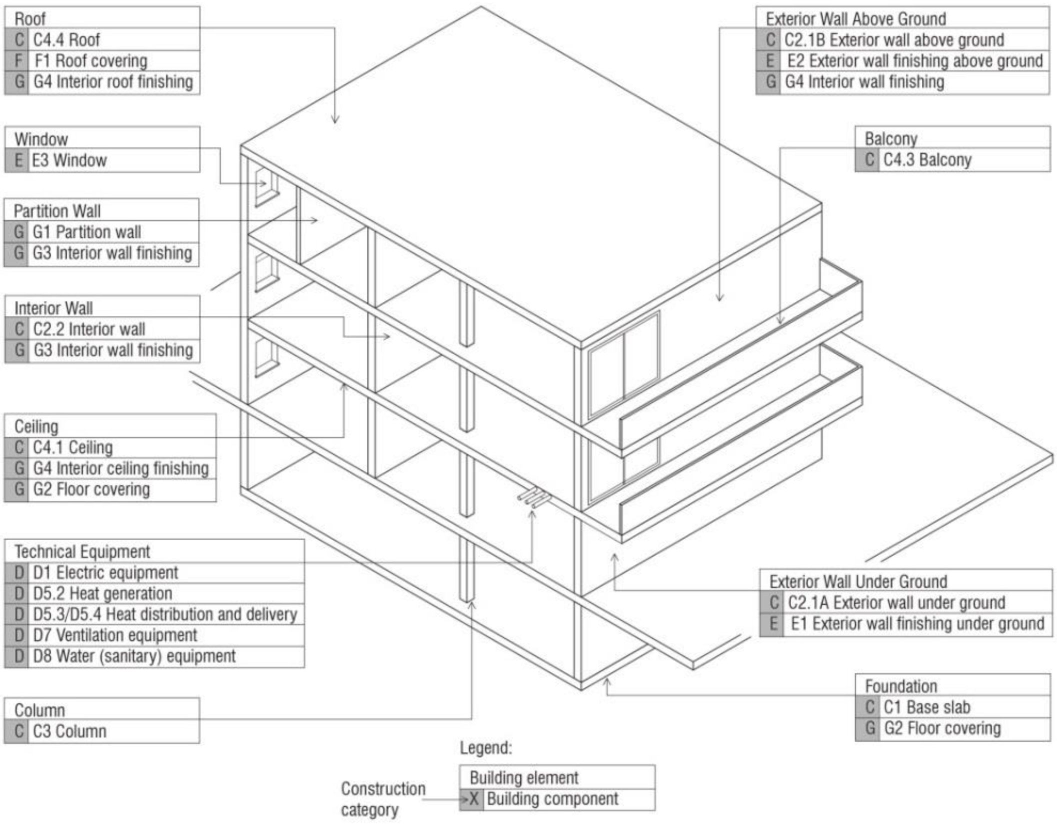

Figure 2. General description of the building, building elements, building components, and construction categories.

Here, it is assumed that all building components belonging to the same construction category are developed at the same LOD at a specific design phase. The LOD evolution is shown in Figure 3.

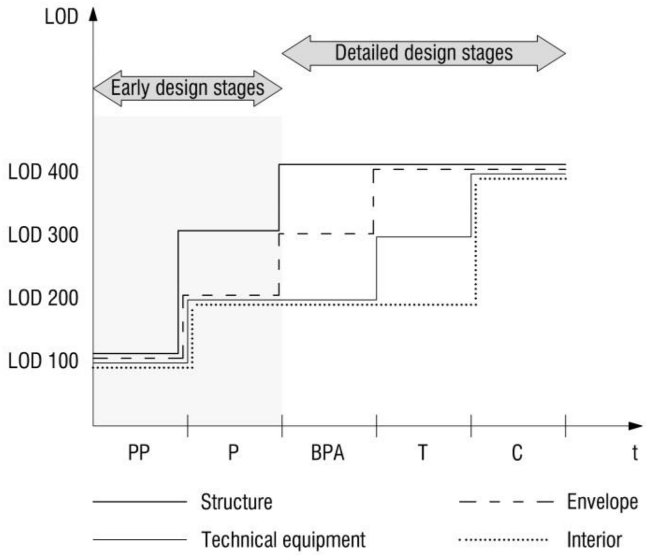

Figure 3. Design process and LODs for different construction categories. (PP) Project Planning, (P) Project, (BPA) Building Permit Application, (T) Tendering and (C) Construction.

The second and the third steps of the framework aim at proposing a consistent combination between different LCA databases and linking them to the LODs. Here, various LCA databases are employed. In Switzerland, LCA data for building materials are provided in a list called *KBOB Ökobilanzdaten im Baubereich*, but to facilitate the application of this data, the building component catalogue *Bauteilkatalog* has been developed by providing the environmental impact of pre-defined typical Swiss constructive solutions according to the Swiss building classification system. Both databases are based on the same background data (Ecoinvent 2.2) and they can be consistently mixed.

The LCA databases are linked according to the LODs as shown in Table 2. Before the design process starts there is no BIM. At that stage, only the square meters of floor area could be known. Therefore, it can be called pre-LOD. Hence, the environmental impact is calculated using the average impact per m^2 of floor area.

When LCA databases are used averaging the values (e.g. Pre-LOD, LOD 100 and LOD 200), the minimum and maximum values can be calculated to show the LCA variability. In fact, in the early design stages the exact final technological solutions of the building elements are unknown.

Table 2. LCA databases used for different LODs.

LOD	Database	Use of Database
Pre-LOD	Swiss Buildings Database	Average value at building level
100	Bauteilkatalog	Average value at building element level
200	Bauteilkatalog	Average value at building component level
300	Bauteilkatalog	Specific value at building component level
400	KBOB	Specific value at material level

4. Results

The method is applied to a real building called *WoodCube*. All material properties are obtained from a published LCA report [32]. Quantities information of different materials and components are extracted from the 3D model to an excel spreadsheet. These are then used to perform the LCA according to the method. The building elements and related building components are provided by Cavalliere et al. [11]. The functional unit of the performed LCA is the whole building with a reference study period of 60 years according to SIA 2032:2012 [33]. Regarding the system boundaries, the LCA is performed focusing on the cycle modules A1-A3, B4, C3 and C4 [34].

The life cycle impact assessment provides results using the GWP in kg CO_2-equivalent as the environmental indicator. The values are provided per year.

When performing the analysis at the building level, the LCA results show a general coherence throughout the design process. From the PP phase to the C phase, the GWP in each design phase is within the variability of all the previous phases. The use of the Swiss buildings database at the Pre-LOD leads to a consistent result until the BPA phase. The results in the T and C phases do not fall within the variability of the Pre-Design phase. This is due to the limitation of the Swiss buildings database because it is based only on fifteen residential buildings resulting in a limited variability range.

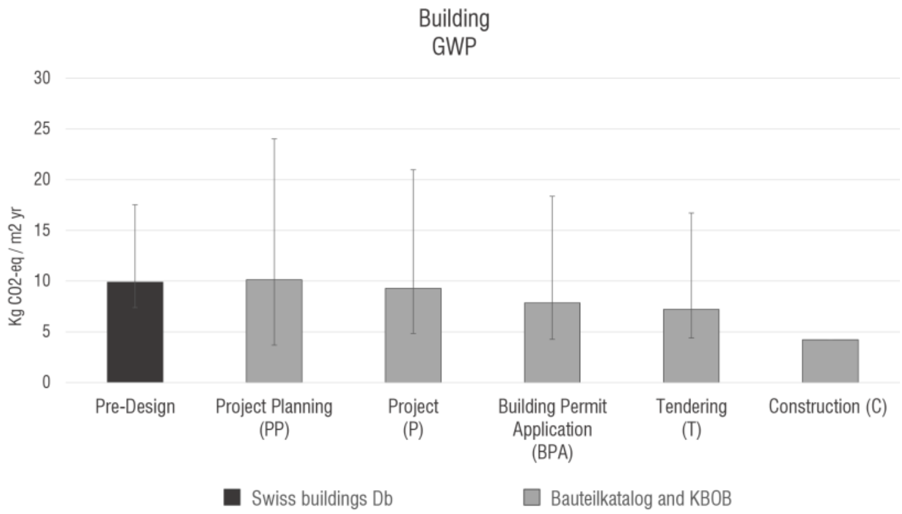

Figure 4. GWP of the building during the design process

Here, the LOD evolution of building elements is based on the typical Swiss architecture practice. Actually, LOD evolution for the building components can be different, because design teams could adopt different LOD evolutions according to their own design best practices. Therefore, different scenarios concerning the LOD evolution have been considered (see Table 3). This allows testing the sensitivity of the method towards the LOD evolution.

Table 3. Evolution of LOD during the design phases depending on the scenario

Building components	Design phases				
	PP	**P**	**BPA**	**T**	**C**
Structure	LOD 100	LOD 300	LOD 400	LOD 400	LOD 400
Envelope	LOD 100	**LOD 200/300**	LOD 300	LOD 400	LOD 400
Technical equipment	LOD 100	LOD 200	**LOD 200/300**	**LOD 300/400**	LOD 400
Interior	LOD 100	LOD 200	LOD 200	**LOD 200/300**	LOD 400

The results considering the different scenarios show a general coherence throughout the design process phases and a low sensitivity to the assumed LOD evolution. As can be seen in Figure 5, bottom and top values do not change much as well as the value after the tendering phase, but they can change the decision choice in the PP phase.

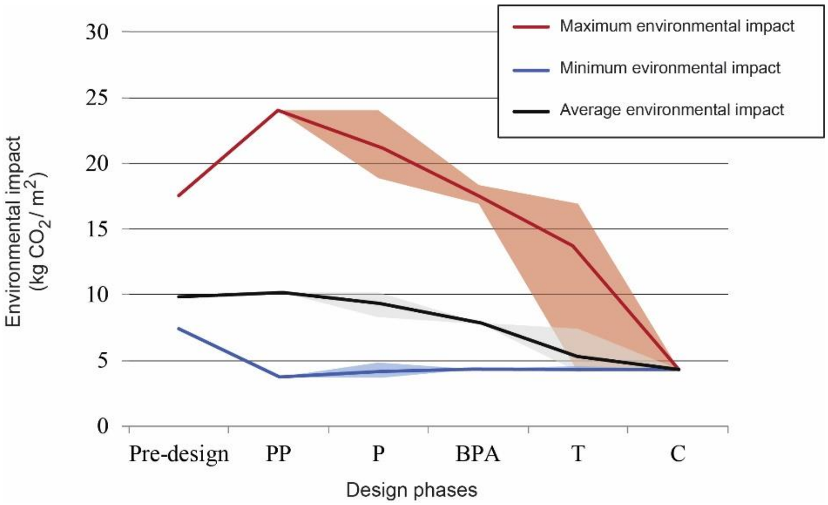

Figure 5. Variability of top/bottom values and LCA results for all scenarios considered.

5. Discussion

The application of the proposed method demonstrates one way to solve the dilemma of applying LCA in the design process. Within the information processes at the different design stages, it is crucial to define which information is needed and how detailed it must be. BIM objects are modelled with different LODs depending on the BIM uses and the project milestone, which usually grow reflecting the project progression. Hence, as the project grows, BIM elements are modelled with more information in order to support more detailed analyses.

The proposed method and its application to a real case-study building show that it is possible to continuously perform the BIM-based LCA throughout the whole design process by mixing various LCA databases, which is possible as long as they use identical background data. The previous work carried out by the authors shows that the LCA results are consistent in general in terms of variability of the different building elements [11]. Minor inconsistencies for individual elements are not visible in the overall results. In fact, the environmental impacts of the case-study building in a specific design stage fall within the variability range of the previous one. Furthermore, it could be shown that results have a low sensitivity towards the assumed LOD evolution, allowing the method to be adapted to the individual workflow of the design team.

The method should evolve in the future. The study is mainly based on the embodied impact calculation since it will became more relevant when referring to very energy efficient residential buildings as demonstrated by recent studies [35]. To further improve the proposed framework, the operational impact should be included and additional case studies should be investigated since the general approach of the methods is identical. The study was applied to the Swiss context by using Swiss databases and standards, although different LODs scenarios were evaluated. Further investigation could be integrated in the future with the reference to different national contexts.

6. Conclusion

BIM-led LCA is recognized to be a powerful approach to reach sustainable building projects. However, it is currently difficult to apply the LCA during the entire building design process because the necessary data are only completely available in the latest phases. The proposed approach divides the building into functional elements, which consists of several building components. Then, the building components have different functions, and belong to different construction categories because they are typically modelled at different LODs in different planning stages. The LCA is consistently performed by mixing the LCA databases according to the LOD of the building elements at different design stages. By involving the use of different databases that match the LOD of the BIM elements, LCA can be conducted with the maximum level of information available at the current design stage, providing a continuous workflow over the building design process. Hence, the LCA results are as accurate as possible at all times.

As demonstrated by the case study, it is possible to forecast the final environmental impact from the early design stages. According to the method, the results show that the variability of the environmental impact decreases from the early design phases to the final one because estimations are performed from lower to higher accuracy based on increased LOD. The environmental impact in a certain design stage is within the variability of the previous one, confirming the reliability of the proposed method. As a result, the method enables the use of LCA as a decision-making tool to reach more sustainable solutions from the early to the detailed design phases.

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BIM-integrated LCA - model analysis and implementation for practice

Forth K, Braun A, Borrmann A

Chair of Computational Modelling and Simulation, Technical University of Munich, Arcisstr. 21, 80333 Munich, Germany

kasimir.forth@tum.de

Abstract. Ecological impacts of buildings can be quantified using the method of Lifecycle Assessment (LCA). With the help of digital methods and semantic building models (BIM), those impacts can be reduced by investigation of variants and their LCA comparison. However, there is a large deviation in the results due to inaccuracies in the modeling and the calculation tools. This paper proposes an improved workflow of BIM-integrated LCA avoiding those inaccuracies. As a first step, various sources of error are identified using a model analysis, which is examined with 25 models focusing on geometry and materiality. Thereby different workflows are investigated, modeling recommendations are derived based on the error analysis, and the findings are implemented in a prototype. Through an optimized calculation process, the semi-automatic calculation of life cycle assessments becomes faster, more consistent and more accurate due to the improved integration in BIM.

1. Introduction

Since ancient times, buildings have great importance for society. Today, they account for most of humans' daily lives and, according to the broad definition, real estate accounts for 19% of total gross value added [1], making it an important economic sector with many jobs. However, the construction industry also contributes significantly to climate change and other environmental problems. According to the European Commission, European buildings account for 42% of final energy consumption, 35% of greenhouse gas emissions and 50% of materials produced in their production, use, and dismantling [2]. Also, they are responsible for 30% of water consumption and a third of all waste [3]. This increases the need to identify and reduce the environmental, economic and social impacts of buildings. A promising approach lies in the formal assessment of a building's environmental footprint. Individual analyses and, since the 1990s, holistic approaches such as the sustainability certification of buildings, which are also known as Green Buildings, are an important step forward.

In a proposal for discussion for the new "Building Energy Act" (GEG) from February 2018, the German Sustainable Building Council (DGNB) proposes that in future the resulting CO2 emissions should be balanced rather than primary energy consumption. "Embodied emissions (production, usage, and maintaining, recycling) will also be accounted for from 2025 so that in future the entire life cycle will be covered" [4]. This approach, which has been extended to include embodied energy, is intended to create a goal-oriented, holistic approach.

In this respect, there are great opportunities to benefit from the ongoing digitization of the construction sector to cope with the environmental challenges. This means that in the long term it is desirable to automate criteria for sustainability certificates, such as life cycle assessments (LCA), to the greatest extent possible using the BIM method [5] which includes a comprehensive digital representation of a building.

The integration of the BIM method into the LCA calculation is intended to simplify the work process and thus make it possible to optimize the LCA in earlier planning phases. Also, increased efficiency regarding time and complexity can reduce the workload and thus contribute to broader dissemination of the performance of life cycle assessments.

Although there are already existing software products which try to use the BIM method in the LCA calculation, the use of the BIM method in the LCA calculation is not yet optimized. However, the quality of BIM models is not yet thoroughly mature due to the short application time. Therefore, there are still different problems with the application of these programs, which should be analysed in more detail.

The paper presents an experimental study that shows that problems and requirements of the BIM-integrated LCA considering different workflows and model requirements, to make the data transfer between architect and Green Building Auditor or the life cycle assessment experts smoother in the future and to minimize the loss of data. On the basis of this results, the concept for an improved workflow was developed. It has been implemented in a software prototype that is discussed in detail. Using the prototype, it was possible to show that errors were significantly reduced.

2. Related work

In this section, a short overview of the state of the art is shown. The major challenge is the semantic linking of the BIM model with the LCA model. BIM programs can be used to determine areas and masses automatically. The goal, however, is a fully automated LCA process that can be realized with the help of an integrated BIM and LCA model. This increases data consistency, makes the verification process for sustainability certificates more accurate and increases efficiency by shortening the processes.

García-Martínez et al. compared different integration approaches in their paper "Critical Review of BIM-based LCA method to buildings" [6]. They find that there are major difficulties in mapping all life cycle phases, especially the use phase and end-of-life phase, in the calculation. In most studies, manual adjustment and addition of mass constellation and material properties were required. Therefore, they call for further research to improve and standardize the BIM integration of LCA and propose user-friendly handling of the calculation tools.

Furthermore, Díaz and Álvarez Antón have investigated different approaches to LCA calculation in the planning process [7]. It becomes clear that through BIM integration a BIM model is already available in early phases, which leads to early optimization of the results through automated calculations. Furthermore, a real-time calculation is desirable to reduce the time required for an LCA.

Díaz and Álvarez Antón distinguish between two approaches, how such integration can look like [8]. The first method presented contains an automatic inventory analysis linked to LCA datasets. To ensure a consistent calculation, the BIM model must be created and maintained without errors. This avoids the repeated manual input of data for the LCA. A further disadvantage is the lack of research into the compatibility between BIM models and LCA tools as well as errors in IFC (Industry Foundation Classes) export and import.

The second approach provides for the implementation of environmental impact information in BIM objects. This means that the impact categories and environmental impacts can already be displayed when the architects and planners select materials. However, this method requires training of the designers so that this information can be evaluated correctly. To counteract an excessive demand, Schlenkrich suggests alternatively listing only selected categories [9]. This method can already be applied in the earliest planning phases and thus actively intervene in the decision-making process of material selection. However, this approach has the disadvantage that material alternatives are compared and the quantities of materials in the comparison are neglected. Thus, the estimation is less precise than an LCA that addresses the complete building model [8].

As early as 2003, Neuberg developed a "software concept for the Internet-based simulation of the resource requirements of buildings" [10]. As part of his dissertation, he realizes an ecological assessment of buildings with the help of the IFC data format. In addition to a life cycle assessment, he also implements an integrated energy demand calculation by German energy efficiency regulations of building (EnEV). "The implementation of these dynamic component properties takes place as a module for extending the AutoCAD database" [10]. At that time, not enough LCA databases were available, and life cycle assessments were mainly carried out for research purposes. In addition, impact categories other than those established today, such as cumulative energy consumption and cumulative material consumption, were taken into account. Neuberg's method makes use of an open interface, where the parameters of the materials can be individually adapted and extended by external data sets. However, the addition of additional component layers afterwards and the assignment of end-of-life scenarios or the consideration of composite materials is not possible. For these reasons, his approach not fully applicable for today's practice.

Tsikos and Negendahl have developed a method using *Revit*, *Dynamo,* and *Excel* to calculate an LCA using an Integrated Dynamic Model (IDM) [11]. Their aim was to achieve a fully automated work process. Material allocation is carried out with the aid of a "permanent link" between an external *Excel* database and the materials in *Revit*. The encoding is performed according to the Danish system BIM7AA [12]. Although LCA calculation results are generated within one minute, the quality depends strongly on the BIM model, the accuracy of the database and the take-off method implemented in Dynamo [11]. Inaccuracies of the BIM model can be adjusted later in the model, although this procedure seems cumbersome. On the contrary, this paper is intended to make a specific contribution to optimizing the compatibility between BIM models and LCA tools and to find a consistent and transparent calculation approach.

3. Methodology and procedure

The aim of this chapter is investigate different workflows and occurring problems of BIM-based LCA. The general workflow of the model analysis consists of three stages. The first stage is the creation of models based on the catalog of the investigated BIM-models. The models are modeled with two BIM-capable authoring tools, *Revit 2018* by Autodesk in "Revit" data-format (RVT) and *ArchiCAD 19* by Graphisoft in "Plan" data-format (PLN) and exported into the vendor-neutral IFC data format. Then *Solibri Model Viewer* is employed to check the data quality of these models and adapt them so that the models have identical masses and materials if necessary.

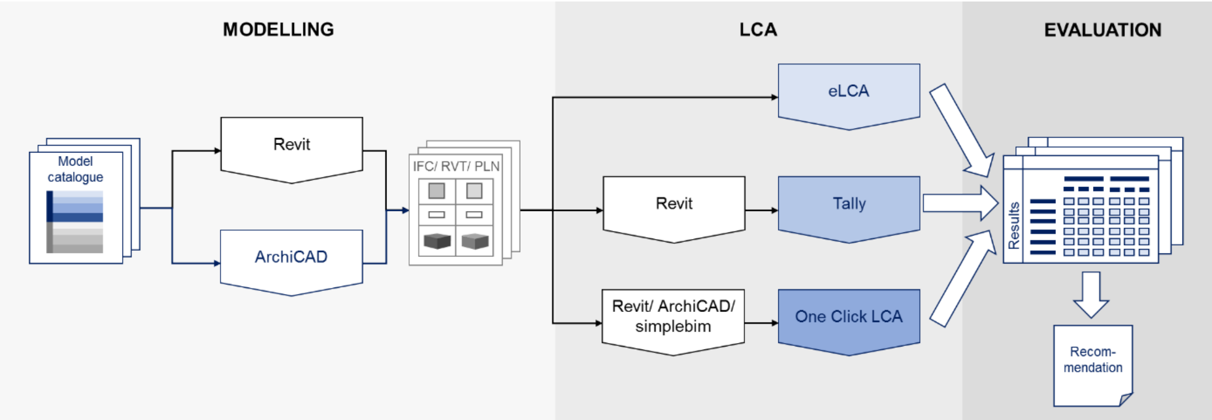

Figure 1. The procedure of the model analysis of BIM-integrated LCA workflows

The second stage is the actual life cycle assessment. This consists of the application of the three different work processes. The tool for the conventional workflow used is *eLCA*, which draws its mass balances based on the models created in *Revit*. In the semi-automatic working process, the data models are imported into *Revit* and calculated with the LCA tool *Tally*. In the fully automated working process, the models are loaded into *ArchiCAD*, *Revit,* and *simplebim,* and the life cycle assessment is calculated there using the *One Click LCA* plug-in.

The third stage consists in the evaluation. All results of the respective eco-balancing with *eLCA*, *Tally* and *One Click LCA* result in a result matrix for each model. These are analysed, and problems and conspicuities are described to formulate general and specific findings finally and to derive recommendations from these. The different work processes, as well as the results of the respective programs and data exchange formats, are taken into account. As the different result of each LCA-software are not compareable with each other due to different databases, the results of each LCA-Software have their own Ground truth which are investigated in the error analysis [13].

3.1. Boundary conditions

The investigation presented here does not aim at improving the LCA results through different material or design choices of the models, but helps finding the best possible implementation of BIM-integrated life cycle assessments about the work process and data requirements. Clear framework conditions are the prerequisite for a reliable evaluation and preparation of recommendations.

Initially, the same databases and an identical approach should be defined for all LCA tools. Due to large data gaps in building technology, this topic is not addressed in this paper. However, for the LCA calculation of the models according to the calculation system of the German Sustainable Building Council (DGNB), the energy consumption in the use phase according to the current German regulations (EnEV) is required, which is not available for the individual models. Here, the focus is on the building construction in the manufacturing (A1-A3) and end-of-life phase (C3-C4), as well as module D. Operational energy, plant technology, and transport are neglected.

Due to the great diversity, ÖKOBAUDAT serves as the common database for all life cycle assessments, which is based on GaBi data records. The impact categories considered are Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Photochemical Ozone Creation Potential (POCP), Acidification Potential (AP), Eutrophication Potential (EP) and Primary Energy, differentiated into non-renewable (PENRT) and renewable (PERT) depending on the LCA calculation program. The service life of the structures is set to 50 years.

3.2. Case studies

Table 1 + 2. Model catalog for Case studies of the model analysis, grouped by Form and Material.

		Modellgroup	Model	
Form	F1	Ground floor	angular	F1e
			round	F1r
	F2	Multistory	suspended ceiling	F2z
			galery with cloumns	F2g
	F3	Sloping walls	outside inclined straight wall	F3ag
			outside inclined round wall	F3ar
			inclined inside straight wall	F3ig
			inside inclined round wall	F3ir
	F4	Roof	saddle roof	F4s
			saddle roof with corner	F4e
			hip roof	F4z
			pent roof	F4p

		Modellgroup	Model	
Material	M1	Monolithic	reinforced concrete	M1s
			brick wall	M1m
			timber	M1h
	M2	Multi-layer	reinforced concrete + EPS	M2s
			brick wall + XPS	M2m
	M3	Construction	mullion-transom facade	M3p
			wood frame construction	M3h
	M4	Windows/ doors	wood frame	M4h
			aluminium frame	M4a
			plastic doors	M4k
	M5	Roof	warm roof (flat)	M5s
			brick covering (saddle roof)	M5z
			sheet metal cover (pent roof)	M5b

To produce a valid and meaningful evaluation of the data requirements for a successful BIM-integrated life cycle assessment, a wide range of applications using BIM models is required. Table 1 + 2 show the model catalog, which was first created and then converted into BIM models using *Revit* and *ArchiCAD*. They are then made available on the proprietary and the IFC data exchange format. In the model catalog, different complex geometries, materials and building constructions are covered. The model catalog differs in the two groups “shape” (subdivided in the groups “ground floor”, “multistory”, “sloping walls” and “roof”) and “material” (subdivided in “monolithic”, “multi-layer”, “construction”, “windows/doors” and “roof”).

The nomenclature of the individual model groups results from the initial letters of the group's form and material, the sequential numbering depending upon the complexity of the investigation as well as the clearly characteristic model abbreviation. The basic form has a square ground plan (10.00m x 10.00m), which is slightly modified depending on the study model. The height of the floors is 3.00m with a clear room height of 2.80m for the most part. The outer walls of the models are 30cm thick, the ceiling 20cm.

3.3. Results

Table 3. Comparison of the results of the model analysis.

LCA-Software	Tally			One Click LCA										
LCA-Plug-In	revit	revit	revit	revit	revit	revit	simplebim	simplebim	archicad	archicad	archicad			
File-Format	RVT	IFC	IFC	RVT	IFC	IFC	IFC	IFC	IFC	IFC	PLN			
BIM-Software	revit	revit	archicad	revit	revit	archicad	revit	archicad	revit	archicad	archicad	●	◆	■
F1e	●	●	●	●	●	●	●	●	●	●	●	11	0	0
F1r	●	●	●	●	●	●	◆	◆	●	●	●	9	2	0
F2z	●	●	●	●	●	●	●	●	●	●	●	11	0	0
F2g	●	◆	●	●	●	●	●	●	■	●	●	9	1	1
F3ag	●	●	●	●	●	◆	■	●	●	●	●	9	1	1
F3ar	●	■	■	●	■	■	■	■	●	●	●	5	0	6
F3ig	●	●	■	●	■	■	■	◆	●	●	●	6	1	4
F3ir	●	●	■	●	■	■	■	■	●	●	●	6	0	5
F4s	●	■	■	●	●	■	●	●	●	●	●	8	0	3
F4e	●	■	■	●	●	■	●	◆	◆	●	●	6	2	3
F4z	●	■	■	●	●	■	●	●	◆	●	●	7	1	3
F4p	●	■	■	●	●	■	●	◆	●	◆	●	6	2	3
M1s	●	●	●	●	●	●	●	●	●	●	●	11	0	0
M1m	●	●	●	●	●	●	●	●	●	●	●	11	0	0
M1h	●	●	●	●	●	●	●	●	●	●	●	11	0	0
M2s	●	●	●	●	●	●	●	●	●	●	●	11	0	0
M2m	●	■	●	●	■	●	■	◆	■	●	●	6	1	4
M3p	●	■	■	■	●	●	●	■	●	●	●	7	0	4
M3h	●	◆	■	●	●	■	◆	◆	●	■	●	5	3	3
M4h	●	◆	■	●	■	■	■	■	●	◆	●	4	2	5
M4a	●	■	■	●	■	■	■	■	◆	●	■	3	1	7
M4k	●	■	■	●	■	■	■	■	■	●	●	4	0	7
M5s	●	●	●	●	●	◆	●	◆	●	●	●	9	2	0
M5z	●	■	■	●	■	■	◆	◆	■	■	●	3	2	6
M5b	●	■	■	●	■	■	◆	◆	■	■	●	3	2	6
●	25	11	11	24	16	10	13	10	17	20	24	181		
◆	0	3	0	0	0	2	4	9	3	2	0		23	
■	0	11	14	1	9	13	8	6	5	3	1			71

Legend: ● correct result
◆ slight deviation
■ strong deviation

Table 3 shows a matrix of all 275 LCA calculations categorized by models and its BIM Authoring software, data format, LCA-Plugin and LCA-Software. The results are divided into the categories “correct”, “slight deviation” and “strong deviation”.

Most errors occur during the software-independent export into the IFC file format [13]. Also, IFC imports in the respective BIM programs also result in deviations of the model about geometry and material assignment. The more complex the original model, the higher the error rate. There are major problems and thus optimization potential especially with unconventional geometries, such as sloping walls, as well as window and door components and multi-layer roofs.

The causes for the calculation deviation are mainly because of differences of quantity take off in ArchiCAD and Revit and their IFC im- and export and missing or incorrect building components or material layers. One of the reasons are different geometric representations of connecting walls in ArchiCAD and Revit. IFC models of more complex models are missing components like roofs, walls, windows or component materials and layers.

The LCA software Tally couldn’t calculate the construction phase of reinforced concrete for the Revit models. Also incorrect IFC-export of dummy-material in ArchiCAD leads to deviations in the

LCA results. One Click LCA has partially calculated all layers of multi-layer component structures (IFC models) together.

In general, it can be stated for all BIM-integrated life cycle assessments that these can only be as accurate as the BIM model was generated. In current practice, the BIM models should not be assumed as complete. Even in the analysis of simplified models, even minimal differences in modeling had a strong impact on the results. Missing parts or component components lead to poor calculation results without being recognized at first glance. It is sometimes only possible with great effort to adjust the missing information for the calculation afterwards since the programs usually lack the necessary transparency in the calculation steps.

Also, there is no interface in the LCA programs where specific data records, such as EPDs (Environmental Product Declaration), can be individually and easily integrated into the specified database. This is desirable if specific products are used for which EPDs are available. The datasets are partly based on different sources, so that large differences in the results also arise here. For the German market, Ökobaudat has established itself, which is available transparently to everyone and can be supplemented with individual EPDs.

As far as the working process is concerned, it can be said that the conventional method of operation is extremely time-consuming, especially when drawing up the mass balance. This problem intensifies by large, complex construction projects and is impracticable in the long run. Therefore, an automated component-specific material setup with subsequent manual or automated material assignment should be preferred and is associated with considerable time and cost savings.

A fully automated work process is not necessarily more effective than a semi-automated. Smaller errors in the model and the material allocation are not noticeable at first in full automation and have to be searched for afterward. In a semi-automated process, all materials are assigned manually, whereby missing component layers or components can also be adapted directly in a single step.

Although the promise of a fully automated LCA calculation sounds convincing, transparency and comprehensible adaptability suffer from this. With an ideal BIM model, the results can achieve a high degree of accuracy. Nevertheless, to skip the step of material allocation or its control would be negligent, since it sometimes leads to considerable error divergences. A check of the component-specific building materials for completeness and quantity is therefore urgently recommended, as is precise post-processing of the material take-off through correction and additions.

A semi-automatic work process is therefore recommended. A component-specific allocation of the materials allows these to be allocated exactly even in the case of inaccurate models with missing information's. A unique, direct assignment of the same materials is desirable. Faulty components should be marked as such to correct them during post-processing. Also, specific information such as layer thickness, composite content, service life or end-of-life scenarios of the building materials can be adapted in more detail.

4. Improved workflow with a prototypical implementation

We propose a workflow whose aim is to enable complete transparency and the possibility of exerting influence in the LCA calculation process, in which the data for calculation and allocation are presented in a comprehensible manner. Adjustments for individual parameters can be made easily, quickly and precisely using *Excel* interfaces. This includes the modification of layer thicknesses, composite proportions, lifetimes or end-of-life scenarios of building materials. With this approach, however, the real-time calculation is still not possible. Also, this interface is only intended for *Revit* models, so no qualified evaluation of an IFC model is created. Although the planned procedure is more cumbersome than the fully automatic calculation, it can ensure sufficient quality of the life cycle assessment with exact results.

4.1. Procedure

As with all life cycle assessments, a distinction is initially made between three parts: the model, the life cycle inventory analysis and the impact assessment. For this reason, any model is first created or loaded in *Revit*. In the next step, the Life Cycle Inventory Analysis, Dynamo Player is opened, and the *Excel* file is linked to create the material allocation. The Dynamo Player is a reduced application that makes it easier to execute Dynamo scripts without having to open them. All you need to do is specify all the required input parameters in the *Excel* sheets.

Once the Dynamo script has been executed, the *Excel* file opens to check the boundary conditions, such as net-space area, project lifetime, LCA phases, etc. The following parameters can be checked. Subsequently, the components and the corresponding materials are checked and adjusted if necessary. In the last step, the Life Cycle Inventory, the energy sources, and the electricity and heat requirements are set up using German regulations (EnEV).

During the impact assessment, the LCA calculation file is opened in Dynamo Player, and the completed material allocation and the still empty output *Excel* file are linked to export the LCA calculation. The dynamo player file is then executed, and the LCA results are automatically inserted into the *Excel* template provided for this purpose.

4.2. Implementation of the prototype in Dynamo and Revit

After a comparison of relevant component groups in the calculation according to DGNB, LEED, *Tally,* and *One Click LCA*, a selection was made for the prototypical implementation in *Dynamo* for *Revit*. First of all, a distinction is made between volume components, which include walls, ceilings, roofs, and foundations. The second group is referred to here as element components and consists of windows, doors, stairs, facade elements and posts as well as ceilings. Structural elements such as columns and girders also form a relevant group but are initially left out due to their implementation in *Revit*. The plant technology includes all mechanical, electrical and plumbing (MEP) components and forms the last grouping.

First, all component-specific materials are summarised, different information, like component name, area, volume and quantity is queried and compiled and finally exported to an *Excel* template for the Life Cycle Inventory. For the sake of simplicity, problems with the geometry export of windows, facade posts and stairs are no longer taken into account for the rest of the process and can be further developed as the prototype is further developed.

The subsequent *Excel* export contains the folders boundary conditions, material assignment, component overview, and energy requirement. Under boundary conditions, the net space area calculated from Dynamo as well as the pre-defined information on the observation period, relevant life cycle phases and calculation methods according to DGNB can be adapted. When assigning materials, the individual materials must be referenced to an LCA data set, and the values of density, service life and composite materials can be adapted or supplemented. All components can be adapted in the component overview folder. This includes the addition of layers, geometric checking of the volume, the characteristic length, the area or the number. In the last folder, the energy requirements and any missing MEP components are supplemented with the respective data sets.

The impact assessment is then calculated automatically. The calculation follows the formulas of the DGNB calculation system using the information of the *Excel* sheet Boundary Conditions, the references from the material allocation and the datasets of the structural and MEP components. The results are shown for the whole project grouped by construction, equipment, and usage, subdivided by production, preservation and deconstruction.

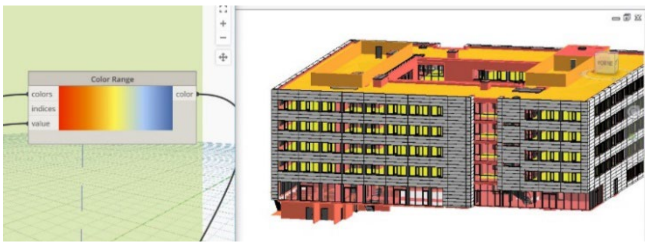

Figure 2. Visualisation of component specific results with colour coding in *Dynamo* and *Revit*

On another *Ex*cel sheet, the results are shown component-specific, which can be used to color code the Revit Model according to their total impact on the embodied energy (Figure 2). This visualization helps to identify optimization potential during the planning phase and has a positive effect on the optimization workflow.

4.3. Validation of the prototype

In the following, the prototype will be quantitatively validated. For this purpose, the model M1s is calculated as an example reference object. The calculation method corresponds to the life cycle assessment according to the DGNB system 2018. The service life of the building was assumed to be 50 years. The data basis is Ökobaudat 2013.

The error deviation of 1.13% results from the more accurate mass determination through BIM integration. The actual volumes of the component-specific materials are determined, whereas in conventional balancing the calculation is based on the product of component area and layer thickness. Besides, with the own prototype, the approach of density accumulation can be bypassed by the method of the specific assignment of composite materials and thus a more exact calculation can be achieved. The correct results of the own prototype validate the calculation method and functionality of the prototype.

5. Discussion and Outlook

This work aimed to investigate BIM-integrated life cycle assessment about its operability and weaknesses. Initially, model analyses were carried out with existing software programs.

The calculation results show that even with simple models of the IFC files there are large deviations in the results. This leads to the conclusion that the "open BIM" approach is error-prone and often leads to incomplete and incorrect BIM-integrated LCA.

In general, a more precise nomenclature of materials with qualitative name affix is recommended to guarantee a correct, component-specific material allocation. For example, this can be the minimum compressive strength class for concrete, the tree species or material type for wood, or the type and processing of metals.

Therefore, the core of this approach was to develop a separate concept for an LCA calculation tool using *Autodesk Dynamo* and *Excel* interfaces. It realizes a compromise between the automation of the component-specific materials and subsequent adaptability according to the given component catalog. All components relevant for the LCA calculation are read out via dynamo, whereby problems still arise with the geometric export of stairs, windows, and doors, facade elements as well as beams and supports. In contrast to existing programs, this approach ensures a precise and transparent LCA calculation even for imperfect, complex projects. Due to the open interfaces, it is possible to make comprehensible adjustments to the materials. However, programming complex models with *Dynamo* and Python scripts are still computationally complex and was just used to prototypical implementation. Together with the exact geometric mapping, this offers further optimization potential.

The modeling recommendation for an effective BIM-integrated LCA is the naming of the components according to the component catalog and a precise nomenclature of the building materials, which also includes qualitative material properties. Post-Processing of the mass installation as error correction is necessary to ensure a correct and complete life cycle assessment.

For future work, a workflow with real-time calculation would be the next step. This way of feedback of BIM-based design decision support helps optimizing the design according to its ecological impacts in early design stages. The difference to Hollberg's Parametric Life Cycle Assessment [14] would be that BIM models could be used for existing semantic information about the building constructions and materials.

Another focus of future work in this field of BIM and sustainability is to supplement Life Cycle Assessments with the aspect of life cycle costs (LCC) to take the economic dimension into account. Further BIM-compliant criteria according to green building certificates are available in the areas of socio-cultural and functional quality as well as technical quality. After a general potential analysis, which criteria are suitable for a BIM-integrated verification, it is necessary to integrate the different calculation criteria into BIM programs.

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Identification and comparison of LCA-BIM integration strategies

Wastiels L, Decuypere R

Belgian Building Research Institute (BBRI-CSTC-WTCB), Belgium

lisa.wastiels@bbri.be

Abstract. With increasing use of BIM (Building Information Modelling) in the design of construction projects, opportunities arise to integrate Life Cycle Analysis (LCA) in early design phases efficiently with minimum additional burden for the design team. Different levels of integration can be envisaged, ranging from a BOQ export (Bill Of Quantity) based on the BIM-model to import in native LCA-software, up to a real time LCA-calculation within the native design environment, giving real time feedback on design decisions, or alternatively utilizing the standardized BIM-information exchange format IFC. Based on the evaluation of existing tools, this paper focuses on the possible workflows for the integration of LCA and BIM. A comparative analysis between these different information flow structures exposes their advantages and disadvantages, depending on the design phase they are used in and the availability of generic, product-specific or manufacturer-specific LCA-data.

1. Introduction

The AEC sector (Architecture, Engineering and Construction) is going through an important digitization process, with the rocketing adoption of BIM (Building Information Modelling) in the different design and construction phases, allowing for an efficient exchange of building information between the different specialists and reuse of information in different phases. This creates opportunities to more efficiently carry out multiple analyses based on the available building information while minimizing the need for manual data entry in the discipline specific simulation tools.

At the same time, growing concerns about the environmental impact of buildings trigger a demand for thorough Life Cycle Analysis (LCA) in the design phase. However, the integration of LCA in the design process is not mainstream yet. LCA databases and tools being in full development, and there is still uncertainty on how to best align the demands from the LCA practitioner with those of the rest of the design team. Consequently today it remains unclear how to seamlessly integrate the LCA analysis in the global BIM based design workflow.

Many questions on how to unambiguously include discipline specific parameters in the Building Model are being treated in CEN TC 442 WG4 on 'Data Dictionaries' already. However, in order to tackle certain issues specifically associated to the execution of LCA studies based on BIM models, more insight in the possible workflows for this integration is needed.

Whereas most papers focus on the evaluation of the results of different BIM integrated LCA tools (including [1]) or the user requirements for individual LCA tools (including [2]), the objective of this study is to identify and develop feasible workflows to perform building life cycle analyses based on BIM models, together with the industry. Based on these workflows further guidelines can be developed for structuring the LCA data (generic, product/brand specific, sector average) for use in BIM workflows.

Insights were gained through an evaluation of existing tools in combination with focus group discussions with BIM and LCA experts from the construction sector (engineers, architects, contractors, manufacturers, government, research bodies).

2. Screening of existing tools and methods

For this study existing national and international tools and methods were screened, amongst which Elodie (France), Totem (Belgium), Tally, One Click LCA and USai. For the selection of tools, the main goal kept in mind was the establishment of a building LCA study and the link with a BIM software environment for (part of) the data collection or modelling. The evaluation focused on the integration of the LCA calculations with the BIM model, and more specifically on the type of data and calculation steps occurring within the BIM environment and those occurring within a separate LCA assessment tool. Specific attention was given to the required modelling approach in order to allow for the linking between the BIM and LCA environments (e.g. level of material or level of building element). The design and evaluation process is evaluated and broken down into different steps in order to better understand the interaction between them, as well as the implication in terms of possibilities and workflow.

2.1. Main elements and terminology of the BIM and LCA integration

Based on the evaluation of the tools a set of main elements and terminology can be described, relevant for the understanding of the integration of BIM and LCA and the definition of BIM-LCA workflows. Below an overview of the most relevant items is included.

Generic LCA database. Database containing generic LCA data that is not linked to a specific manufacturer or product.

Specific EPD database. Database containing LCA data that is specific for a certain manufacturer or product, usually based on a EPD (Environmental Product Declaration).

LCA profile. A set of LCA data for a certain material type or a combination of materials. This can either be a generic set of LCA data, an EPD, or a combination of both.

LCA software. Software tool specifically developed for the execution of an LCA. Expert tools include the possibility to calculate according to different LCA methodologies. Other tools usually include a specific database of LCA profiles (for a specific methodology). These tools support the insertion of material quantities (directly of via a file-import), the linking of LCA profiles to the materials or compositions, and the calculation, visualization and analysis of the environmental impact.

BIM objects. BIM objects are digital representations of building products which are used to build up a BIM model. BIM objects can be generic (e.g. a generic masonry wall) or can be provided by a manufacturer who can include all product and manufacturer specific parameters in the BIM object. A BIM object contains information on different parameters. LCA data can be associated to a BIM object through specific parameters.

Native BIM software. Software tool for modelling a building in 3D with the attribution of additional information to the elements within the model.

LCA plugin. An LCA plugin is a software component that runs within an existing computer software (e.g. a native BIM modelling software) and adds functionality to this software specifically designed to support a life cycle analysis.

IFC. IFC (Industry Foundation Classes) is an open file format facilitating the exchange of BIM models between software tools from different vendors.

BIM viewer. A software tool which allows for a BIM model to be inspected. A BIM viewer does not support the creation or modification of the (geometric) BIM model. However, certain BIM viewers support the addition or modification of certain parameters.

2.2. Landscape of tools and process steps for BIM based LCA

Since the introduction of BIM based design and life cycle analysis in the design practice, a wide variety of tools both for BIM and LCA have been developed, each supporting different steps in the BIM based and LCA based design process.

The process for designing a building in BIM and then using this information for performing an LCA study, contains at least these steps:

1. Modelling: The BIM model is developed by a BIM modeler. The geometry of the building is modelled based on BIM elements containing additional information.
2. Setting up a bill of quantities or BOQ: Based on the BIM model, a list of elements and/or materials with their respective quantities is established.
3. Establishing LCA profiles: the environmental impacts of the different materials and products used in the building are identified and quantified in LCA profiles. Depending on the situation, the LCA practitioner can fall back on generic or EPD-data. These LCA profiles can either be developed at the material level, or at the level of a building component (assembly of materials).
4. LCA profile attribution: The material quantities from the BOQ have to be linked to the corresponding LCA profiles (which are expressed in environmental impacts per unit). This might not always be an explicit step and could be integrated within the previous step where the LCA profiles are established.
5. Calculation of the environmental impact: based on the BOQ, the attributed LCA data and the LCA methodology specified in the tool, the LCA calculation can be executed.
6. Visualization and analysis: The results of the LCA calculation are visualized and analyzed by the LCA practitioner.

For this paper, we differentiate between four different types of tools: native BIM software, BIM viewers, LCA software and LCA plugins for native BIM software. The table below visualizes the supported steps in the design process for these different types of tools (**Table 1**).

Table 1. Supported steps in the design and life cycle analysis according to the type of tool.

	Modelling	Setting up BOQ	Establishing LCA profiles	LCA profile attribution	Calculation of env. impact	Visualization and analysis
Native BIM software	✓	✓				(✓)
BIM viewer		✓		(✓)		(✓)
LCA software			✓	✓	✓	✓
LCA plugin for native BIM software		✓		✓	✓	✓

3. Workflows for the integration of LCA and BIM

Different strategies can be used for organizing a design workflow that integrates building data coming from a BIM model in the LCA analysis. In relation to the direction of the data flow, two main strategies can be distinguished:

1. Geometrical and possibly also material related information is extracted from the BIM model in the form of a bill of quantities (BOQ). Based on this information on the quantities (and type of material) the LCA calculations are performed in specialized LCA software.
2. Specific LCA data can be added to the BIM model by use of specific parameters. The LCA calculation is performed within (a plugin for) the BIM software.

Some intermediate strategies can be determined between these two extremes. Below, five main strategies are described into further detail based on the screening of existing tools and expert discussions. In practice, more strategies can be conceived, combining aspects of the five proposed strategies. The choice for a strategy depends on the tools used by the designer and LCA professional, and their respective available functionalities for integration, the availability of the relevant information in the BIM model, the availability of LCA data, the scope of the evaluation, etc.

3.1. Strategy 1: Bill of quantities (BOQ) export

A life cycle analysis always starts with an inventory of the building materials based on a bill of quantities (BOQ). For a BIM based project design, this BOQ can be extracted from the native BIM model in the form of a spreadsheet.

In this first strategy, the BOQ is (directly) imported in a dedicated LCA software. The remaining workflow takes place within the LCA software. The LCA practitioner manually links the different building components (with their quantities) to predefined LCA profiles available in the LCA software database or creates new LCA profiles where needed. The LCA calculation, visualisation and analysis is performed within the software as for a traditional LCA study. A representation of the workflow is available in **Figure 1**.

Iterative design might not be supported using this strategy. Depending on the tool used, importing an updated BOQ spreadsheet in an existing LCA calculation set, while preserving the already defined links between the building components and the LCA profiles, might not be possible. The data availability and verifiability depend on the quality of the data in the LCA software. A visualisation of the results (environmental impacts) in relation to the building elements depends on the visualization possibilities of the LCA software.

This workflow describes how most BIM integrated LCA calculations are currently performed.

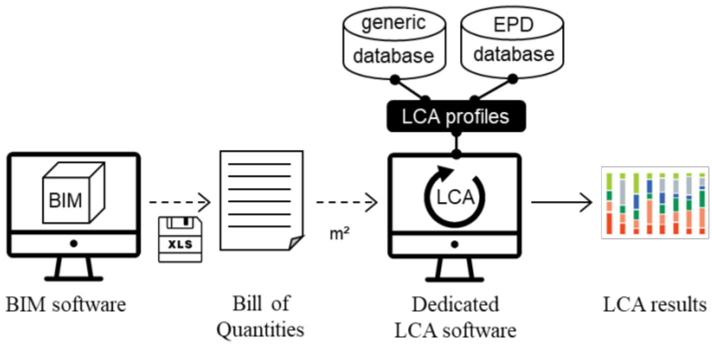

Figure 1. Workflow based on a bill of quantities (BOQ) export from the BIM model

3.2. Strategy 2: IFC import of surfaces

In the workflow defined by strategy 2, the geometric BIM model is imported "as such" in the dedicated LCA software. Usually, an open exchange format like IFC is used for the transmission of the BIM model, but the use of native BIM file formats is also possible, depending on the features the LCA software provides.

The imported data includes at least the geometric parameters, based on which the material quantities (surfaces, volumes) can be determined, but will in many cases include the Global Unique Identifier (GUID) and the component or material name as well. Based on these imported data, the LCA practitioner will link the building components to predefined LCA profiles available in the LCA software databases (which could be a generic or a product specific database, or a combination of both). Finally, the LCA calculation, result visualization and analysis is performed within the dedicated LCA software. See **Figure 2**.

The main difference with strategy 1 is the automatic import of the data and the possibility to maintain a link between the data. When the GUID is imported and stored in the LCA software, an iterative design process could be supported, allowing for quantities and descriptions to be updated based on a new version of the IFC file without losing the existing links to LCA profiles.

The Belgian TOTEM-tool is an example of this strategy [3].

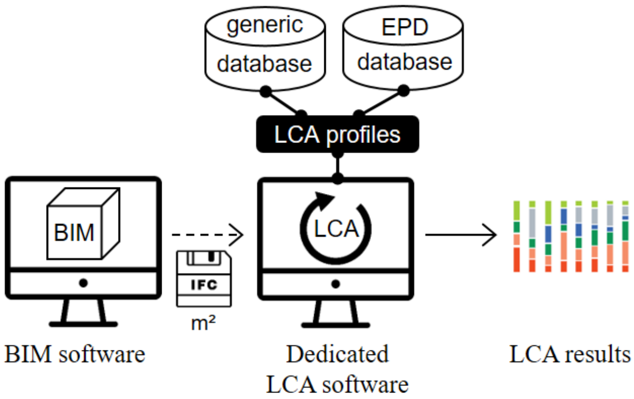

Figure 2. Workflow making use of an IFC import into the LCA software

3.3. Strategy 3: BIM viewer for linking LCA profiles

In the third strategy, the LCA profiles are attributed in an intermediate step in a BIM Viewer environment. This requires the export of a BIM model from the native BIM software by means of an IFC file. Within a specific BIM viewer, containing functionalities for this task and a list of available LCA profiles, the LCA practitioner or potentially the BIM modeler can attribute LCA profiles to the building components.

The geometric data is then sent to a dedicated LCA software, together with their associated LCA profiles. Based on these LCA profiles, the LCA calculation can be completed in the LCA software, followed by result visualization and analysis. The workflow is represented in **Figure 3**.

The advantage of this approach is that the attribution of the LCA profiles can occur within a 3D environment, while keeping the in-depth LCA analysis in a dedicated LCA environment. Also the link between the geometric data and the LCA profiles can be maintained for further reference during an iterative optimization process.

An example of this strategy is the eveBIM-viewer where FDES-profiles (=Environmental Product Declarations from the French program Inies) can be attributed to building components before exporting to the dedicated Elodie software [4].

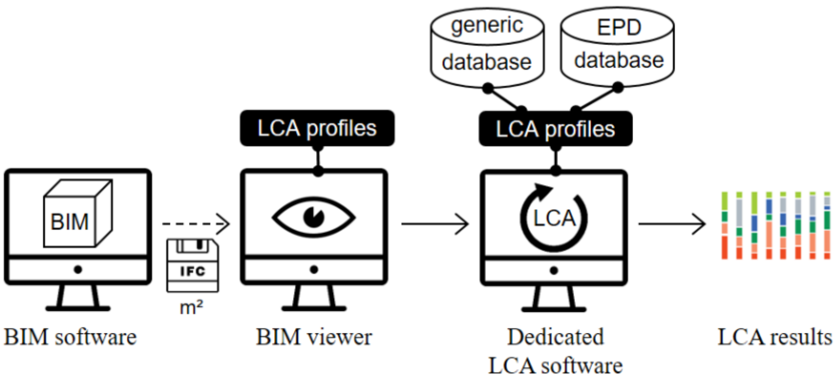

Figure 3. Making use of a BIM viewer to associate environmental data (LCA profile) to the building geometry.

3.4. Strategy 4: LCA plugin for BIM-software

Strategy 4 strives for a maximisation of design process steps to be performed within the native BIM environment, by means of specific LCA plugins. With these plugins, LCA profiles can be attributed to

BIM objects within the native BIM environment. All further steps, including the calculation, result visualisation and analysis are done within the LCA plugin (see **Figure 4**). Consequently, the dedicated LCA software is no longer used but replaced by the use of a plugin.

Up to now, this strategy seems to allow for LCA analyses with generic LCA data only (based on the databases of LCA profiles included within the plugin). An important advantage compared to the previous strategies is that the LCA results potentially can be visualized in the geometric model providing an instant view on the hot spots or most important impacts.

The tools Tally [5], One Click LCA [6],USai/Eco-Sai [7] and CAALA [8] work with plugins for BIM software.

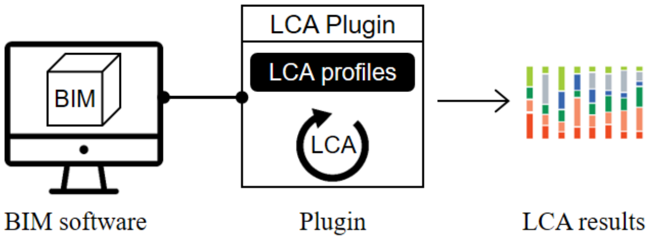

Figure 4. Workflow based on use of an LCA plugin for the BIM software.

3.5. Strategy 5: LCA enriched BIM objects

In the fifth strategy, LCA information is included in the BIM objects that are used in the BIM model, instead of being attributed to the appropriate building components in a later stage by an LCA practitioner. The LCA profiles are thus immediately associated to the geometric and material data inserted in the BIM environment. The further steps of this workflow could include a calculation and analysis with a plugin in the dedicated BIM software, or an export to a dedicated LCA software. A visualization of the workflow is given in **Figure 5**.

When generic BIM objects are used, generic LCA data will be used. However, manufacturer or product specific BIM objects could contain manufacturer or product specific LCA data as well. These BIM objects do not necessarily contain all the LCA data themselves, but could contain a reference to an LCA profile for which the data is stored in a dedicated LCA tool or database.

This strategy has a high potential as all data can be centralised within the BIM objects and a design optimisation process can potentially be supported with real-time information on the environmental impacts. On the other hand, with LCA profiles linked directly to the BIM objects, a trade-off between different materials might necessitate changing the BIM objects in the model, which is more laborious than changing the LCA profile in a dedicated LCA software.

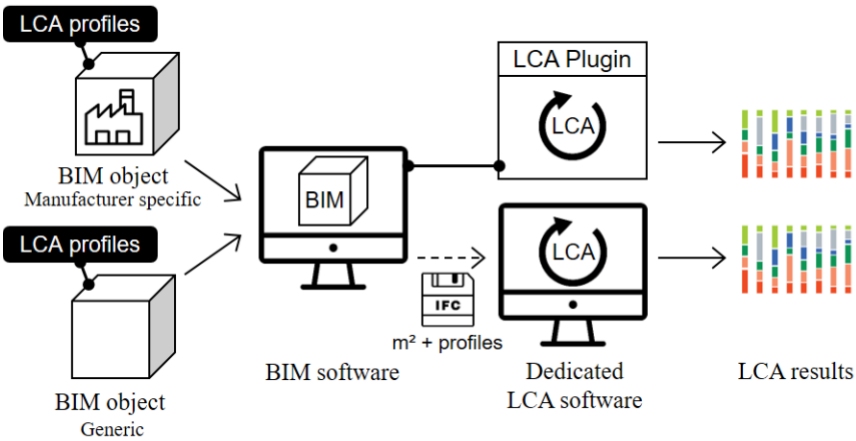

Figure 5. Workflow where BIM objects are enriched with LCA-based information or references.

For now, it appears this strategy has not been implemented yet, due to a lack of available BIM objects with LCA data, and a lack of consensus on how to structure LCA data and profiles. The level at which LCA data is available (e.g. EPD data for cement) will not always coincide with the level for which BIM objects are provided (e.g. wall). Furthermore, other difficulties have to be tackled first. LCA data is often valid for specific situations only (e.g. for a specific size of a certain building component). As a result, the LCA data might not be valid anymore after resizing of the BIM object.

4. Expert discussion on workflow and user needs

An expert group with Belgian LCA-practitioners was brought together in order to assess the current workflows for LCA analyses and to evaluate the future applicability of the different proposed workflows. Insights from these discussions have been integrated in the workflow assessment in the previous part. A more comprehensive report of the discussion on the applicability of the proposed workflow strategies for different disciplines and design and construction phases is given below.

4.1. Applicability of workflow strategies for disciplines and construction phases

Different needs exist in relation to the different disciplines making use of LCA and BIM, and the objective of the LCA study.

For example, for structural works, due to the low variety in used materials, it is feasible to perform an LCA in the early design phases based on a rough BIM model. Quantities are fairly easy to specify and the number of materials to be associated is limited. It would therefore be feasible to implement any of the proposed strategies for this type of analysis. Even in the absence of readily available BIM objects containing LCA data, a design office could invest in creating a set of BIM objects for the limited amount of materials used themselves, and thus implementing strategy 5 internally.

For the architectural design, the specifications have to be more detailed (loadbearing materials, insulation, finishing materials). Differences in materials will have significant impacts on the LCA results. When there is a trade-off between different building materials in an early design phase, it is very likely that an optimization from an environmental point of view is performed at the level of the building element, rather than at the building level, thus ignoring the relative weight of the building material in the total building. This optimization can easily be done within a dedicated LCA environment.

For a thorough building level LCA study for an architectural design to be executed in an early phase, Moreover, due to the large quantity of materials used in architectural design, an easier access to LCA data is needed. Several material choices and technical execution details are still open or specified with a very low level of detail. In that case, it is very likely that the BIM model does not contain sufficiently detailed information at the material level to allow for an LCA calculation. At that moment a need exists for a database with generic information on building compositions and their associated LCA profiles.

In this early phase, support for an iterative design process is essential too, rendering strategy 1 unfit for this situation.

Strategy 5 seems a promising workflow from an architect's perspective for providing easy access to LCA data, notwithstanding the current lack of LCA data enriched BIM objects and the difficulties this poses for manufacturers. However, it is less supportive for an iterative approach. When multiple material options without important geometric differences are to be evaluated, different BIM objects would have to be incorporated in the BIM model. In this situation, strategies 2, 3 or 4 might be more efficient, since multiple material options can be compared based on only one BIM model.

Special attention has to be given to public tenders, where the BIM model needs to be manufacturer independent. In these projects, the use of BIM objects with EPD data could therefore cause problems.

If the goal of the LCA is a "post-construction" assessment of the environmental performance (and thus not an optimization process) it becomes easier to determine which information should be available to allow for a calculation. In that case an approach where environmental data is linked to the objects in the BIM model (by means of parameters with a GUID) seems feasible. A complete BIM model of the building "as-built" can be fed with this specific information.

The most suitable workflow will thus be related strongly to the objective of the LCA calculation, the time phase in the project and the discipline.

4.2. EPD data in BIM models and objects

A specific point of attention concerns the use of EPD data associated to BIM objects. First of all an EPD can be country specific, including specific indicators or not, or being representative for the transportation or End of Life treatment in a specific country of region. The use of EPD information from different EPD programs within one BIM model should be avoided. A second point concerns the verifiability of the environmental data associated to BIM objects in a BIM model. For example, data from an EPD might be valid for a specific product with specific dimensions (e.g. a window of a certain size) but might lose its validity when the object is being scaled. Thirdly, it is very likely that EPD data will not be available for all materials or components of the building. In order to allow for a correct LCA evaluation within the BIM environment, there is a need for databases with generic objects including generic LCA data and for guidelines for the proper use of EPD data linked to BIM-objects.

5. Conclusions

The digitization of the design process through the use of BIM, and the growing need for the inclusion of environmental considerations early on in the design process, urges for an efficient exchange of building information between the design team and the LCA practitioner. Even though different tools supporting this integration already exist, there is still much uncertainty on how to best integrate the LCA analysis in the BIM supported design process.

This paper proposes five strategies for workflows, ranging from a BOQ export from a native BIM model to be imported in a dedicated LCA software, which corresponds to how most LCA practitioners perform the integration today, to the inclusion of LCA data in BIM objects before they are incorporated in the BIM model.

Besides the availability of tools and databases to support the proposed workflows, many other considerations influence the choice for a strategy to be implemented in a design practice, including the need for support for an iterative design approach, the use of generic versus product specific LCA data, the need for real-time feedback for design decisions, etc. Nevertheless, the five proposed strategies form a basis for further research on the optimization of the integration of LCA studies in BIM supported design processes.

Acknowledgements

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BIM for public authorities: Basic research for the standardized implementation of BIM in the building permit process

Plazza D[1,2], Röck M[1], Malacarne G[2], Passer A[1], Marcher C[2,3], Matt D T[2,3]

[1] Working Group Sustainable Construction, Institute of Technology and Testing of Construction Materials, TU Graz, Inffeldgasse 24, Austria – 8010, Graz

[2] Fraunhofer Italia Research, Via A. Volta 13 A, Italy - 39100, Bolzano

[3] Free University of Bozen-Bolzano, Universitätsplatz 1, Italy - 39100, Bolzano

E-mail: daniel.plazza@tugraz.at

Abstract. The building permit is an indispensable connection between the approval authority and the executive client within the construction process. Moreover, sustainability criteria do not have sufficient regard in the building permit process in the area of research. To lay the foundation for a state-of-the-art digitalization of the building permit process, the study identifies the information requirements relevant to implement the BIM methodology taking into consideration the available sustainability aspects relevant to the process. A detailed evaluation of the building permit process and the analysis of projects that have gained building permission in the last five years in the area of study of South Tyrol (Italy) gives us a better understanding of the organizational structure and responsibilities in the process. The authors use the data of in-depth process analysis to assess a defined catalogue of basic requirements for BIM methodology in the building permit process. As a result, the analysed BIM-integrated approach enables an early-stage identification of approval compliance, which can be evaluated in the building permit process. A good understanding of the current process must be considered a key factor of a successful introduction of BIM for the building permit procedure.

1. Introduction

Dealing with building permits is regarded to be one of the main business regulations indicators in a country's business environment [1]. The building permit is, therefore, an indispensable link between the approval authority and the executing client. At the same time, the inclusion of sustainability criteria is one of the most important steps in the promotion of sustainable housing [2].

The current state of the art on the building permit process shows that the successful use of digital information systems contributes to the increased efficiency of the building permit handling process [3]. A notable example is CORENET, COnstruction and Real Estate NETwork, which is used in Singapore and has significantly shortened the processing time since the introduction in 1995 [4]. As predicted by Michael Hammer in 1990, the use of the power of modern information technology to radically redesign business processes has contributed dramatically to improvements in their efficiency [5].

In Italy, the DM 560/2017 [6] regulates the gradual implementation and mandatory use of BIM in public procurement from January 1, 2019. While the majority of the stakeholders of the construction industry expects BIM to be a priority in the next 5 years [7], BIM in the public administration of the research area suffers from a relatively low level of awareness. Considering the fact that local provincial and municipal governments play a fundamental role in the implementation of the EU and national policies [8], the Italian Autonomous Province of Bozen (South Tyrol) was selected as research region for the purposes of this research.
This study aims to define the basis for a standardized procedure for the implementation of BIM in the building permit process. Studying the building permit procedure in the area of study is important for three main reasons: 1) The insufficiently investigated requirements represent a barrier to the standardized implementation of BIM in the building permit process; 2)The gap in informational knowledge on the building permit procedure in the area is a potential loss of efficiency in the construction process; 3) It is consequently intentional to enhance the information that is already available in the current process, by furthermore highlighting redundant information requirements, and make it available as a future BIM-based process. Therefore, it is fundamental to investigate, whether BIM would partly help to resolve the data handling issues [9]. Although many new buildings have sustainability ratings, they comprise a minute amount of the total impact of the built environment [9]. The consideration of sustainability criteria in the early design stage of the building permit planning stage is therefore essential for the support of sustainability in the construction industry.

2. Methodology

The methodology is structured in three investigation sections: The introductory section covers a comprehensive building permit research of the current as-is process. It is followed by the statistical evaluation of past building permit applications and then an information requirements analysis is performed.

2.1. Building permit process research

To define the legal framework of the building permit process, the authors analysed the regulations and laws in the area of investigation. In this research, the authors divided regulations and laws into two groups of primary and secondary sources. The primary sources are defined as documents of the direct legislation such as the National Legislation and the legislation at the provincial and municipal levels. Secondary sources are documents that have been deduced from them, such as relevant documents for the energy certification of buildings in South Tyrol. These are provided, for example, by the KlimaHaus Agency, a subsidiary corporation of the Autonomous Province of Bolzano. The agency was founded for the energy certification of buildings in South Tyrol.
The energy certification class directly influences the building permit approval in relation to the maximal permissible building volume. In fact, if the applicant declares that the new building – he/she wants to build – will achieve an energy certification class higher than the minimum prescribed by the legislation, a larger building volume can be built.
For each of these sources, the relevant content for the building permit has been identified and referenced in a data sheet.
Based on the legal basis, the authors determined the triggers of the building permit process, the individual process steps, the key individuals involved in the execution of the process steps and recorded the corresponding process in diagrams.

2.2. Statistical evaluation of past building permit applications

For the statistical evaluation of the submitted building permit applications in the area of study, the authors asked the association of municipalities in South Tyrol (Consorzio dei Comuni della Provincia di Bolzano) for insight into the database of the software G-Office. G-Office is a back-office software solution used by the technical offices of the South Tyrolean Municipalities, for the management of the administrative procedure documents, including the building permit procedure. The data from the building permit application is inserted manually into the G-Office software as shown in figure 1. For the scope of this research, the association has granted access to the following G-Office data: project title, project description, construction typology, data details (application date, date of approval), land-use plan zoning and the KlimaHaus certification classes. In consultation with the municipal authorities, the authors have studied the data of the building permits of the last 5 years (2014 – 2018). The analysis of the data has been performed using SPSS, a software package for statistical analysis.

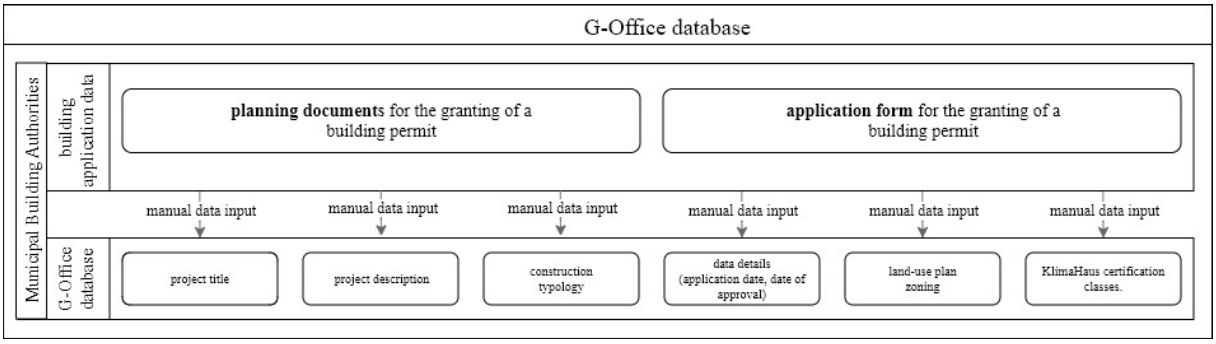

Figure 1. The figure shows the data information flow of the data analyzed in G-Office.

In order to be able to better allocate and compare the data sets, municipalities have been sorted according to their geographical size and population.
From the data set, the authors determined the number of building permit applications submitted per year. This information was supplemented by the duration of the building permit procedure (i. d. from the application to issuing of the building permit). The authors continued the investigations by determining the distribution of the building typology, the distribution of the applications per land-use plan and the present frequency of the KlimaHaus certification. In conclusion of the analysis, the authors determined the number of applications submitted as a variant.

2.3. Information requirement definition
The requirements for the implementation of BIM in the building permit procedure were derived from the laws and regulations investigated in 2.1. In more detail, the technical specifications based on the legal requirements and the specifications defined by the process were analysed by the authors.
The following six source documents were analysed: the application form for the granting of a building permit, the municipal building code (regolamento comunale edilizio) [10], a questionnaire of the National Statistics Institute (ISTAT) on building permits [11], the "Decreto del Presidente della Provincia 9 novembre 2009 , n. 541" (the Regulation concerning the Removal and Overcoming of Architectural Barriers) [12], the "Decreto del Presidente della Giunta provinciale 23 maggio 1977, n. 22" (the Regulation on Hygiene and Health Standards) [l3] and the KlimaHaus technical guideline for new constructions [14]. The requirements were listed individually in a data set and grouped into information categories. This analysis highlighted all the redundant information and the duplicates information currently requested by the applicant. Moreover, the authors determined whether the individual requirements are directly objectifiable and quantifiable and if a unit of measurement can be assigned to the values.

3. Results

3.1. Building permit process research - As-is Analysis
At the national level, two sources regulate the building permit process: the "Testo Unico delle Norme per l'Edilizia", the Italian consolidated building law (Decree of the President of the Republic no. 380/2001) [15] and the Public Procurement Code (Decree-Law no. 50/2016) [16].

Legislation at the provincial level is based on two relevant laws: the valid Regional Planning Law No. 13/1997 [17] and the Regional Law of 17 December 2015, no. 16 [18], which regulates public procurement. At the municipal level, the municipal building code [10] regulates essential parts of the building permit procedure. The principles that are decisive for the building permit procedure are defined in the municipal land-use plan.
The authors identified the following entities as key figures for the process:

- Applicant: the client who submits the application for a building permit to the building authority of the relevant municipality.
- Municipality: the authority is mainly responsible for the processing of the building permit application.
- Within the municipality, the building authority, the mayor and the building commission: they are responsible for the execution of the building permit approval.
- Provincial administration: issues expert opinions and permits in special cases.
- Planner: a qualified person authorized to submit building documents and drawings.

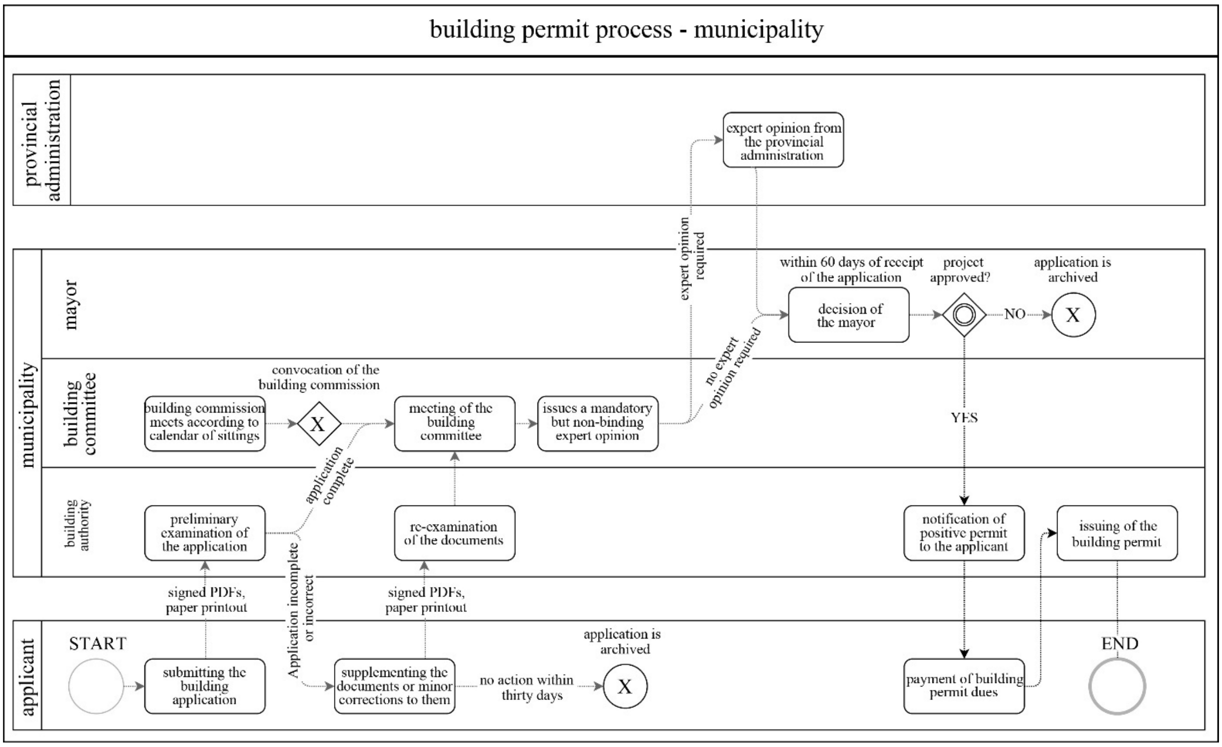

Figure 2. This figure shows the as-is building permit process analysis.

The process for obtaining a building permit, as illustrated in figure 2, starts with the submission of the building permit application. In the next step, the submitted documents are pre-checked by the building authority. At this stage, if required by the building typology, the applicant will submit a self-declaration for the KlimaHaus class. However, this document is not checked for technical content or otherwise analysed. All further steps of the sustainability certification process take place at a later stage after the building permit has been issued. This reflects the weak role of sustainability aspects in building permit process. If the building permit application is incomplete, the staff of the municipal administration will ask the applicant to complete the documents within 30 days. Once this deadline has passed, the application will be archived without further notice. Upon the complete submission and the successful examination, the building committee reviews the application and delivers a non-binding expert opinion on the building permit application. The composition of the members of the building committee is defined in Art. 115 of the Regional Planning Law No. 13/1997. If reports from the

provincial administration are required, the mayor may not grant any authorisation before the final report has been received. The mayor's decision on the application for authorisation will be sent to the applicant within 60 days after receipt of the application or after submission of additional documents requested.
This process shows that the review of the project documents takes place at an early stage in the process for obtaining a building permit and concentrates on the authorities within the municipality. This fact facilitates a possible implementation as there is a limited number of parties involved.

3.2. Results of the statistical evaluation of past building permit applications
Categorization: The municipality category is allocated based on the population size. Municipalities with less than 3000 inhabitants are classified as small municipalities in the study area (3 units), municipalities with 3000 - 10000 inhabitants as medium-sized municipalities (3 units) and municipalities with more than 10000 inhabitants as large municipalities (2 units).
Typology: Since the building typology is not predefined in G-Office, the number of typologies found is high, reaching 287 different records. The evaluation of figure 3 shows the top 10 of the evaluated building typologies. The evaluation of the percentage distribution of the submitted building permit procedures shows that the typologies "renovation" 17.3%, "attention" 15.9%, "extension" 11.6% and "new building" 10.8% were most frequently found.
The "attention" entry suggests that the building typology was not accurately specified, and a placeholder was used instead.

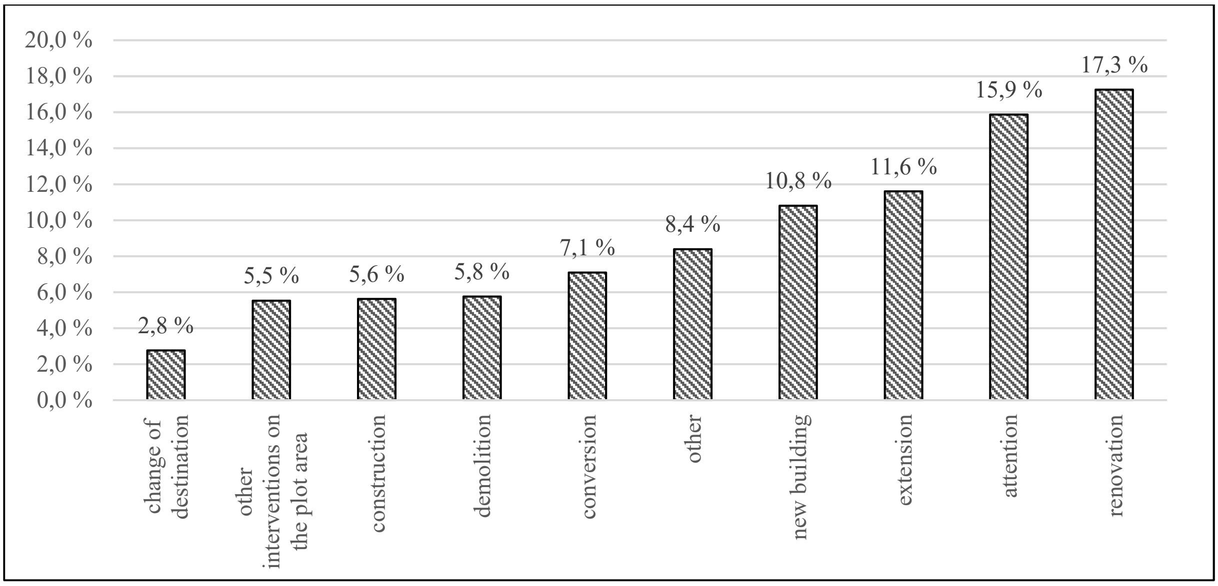

Figure 3. The graphic shows the top 10 distribution of the building typologies of the past building permit applications.

Duration of the building permit process: A cross-comparison of the different municipalities shows that the distribution varies from municipality to municipality. The average duration of the procedure is 90 days. In large municipalities, the duration of the proceedings is the shortest, 77.93 days and 81,15 days respectively. In the small and medium-sized municipalities, by contrast to the large municipalities, there is no clear difference in the average process duration.
KlimaHaus classes: Only 3,3% of the building procedures analysed provides the KlimaHaus class. The 30 %, of the KlimaHaus classes recorded, are Class A, the second-highest climate house. This class corresponds to the nearly zero-energy building – NZEP class according to the EU Directive 31/2010/EU, Art. 2, Para. 2.

Variant: The data set shows that 16.8% of the building permit procedures involve subsequent changes to the building application that has already been approved. This procedure is necessary, if for example, changes are to be made to the planning prior to the start of construction or if changes to the project are necessary during the construction phase.

3.3. Results of the information requirement definition
The subsequent analysis of the source documents revealed that there are nearly 450 specifications requirements by the building permit. These include technical specifications, legal requirements as well as specifications required by the building permit procedure itself.
Requirement categories: The authors classified the information specifications, detected from the six source documents listed in 2.3, into the following requirement categories: specifications of the building (60.0%), building services systems (9.4%), surroundings (4.9%), urbanistic specifications, (3.8%) owner of the property (3.8%), location of the building (3.8%), energetic specifications (3.8%), planner (3.8%), applicant (2.9%), other (1.6%), materials (0.7%), infrastructures (0.4%), description of the work (0.4%) legal specifications (0.2%).
Redundant information requirements: In the categories, the authors found that 20.2% of the information requirements are redundant. Two different types of duplicates can be detected. Information requirements can be found multiple times in the same source document (8.9%), or multiple times in different source documents (11.3%).
Objectifiable and quantifiable information requirements: As illustrated in figure 4, the evaluation shows that 91% of the requirements are objectifiable and quantifiable. Only 9% of the requirements are neither objective nor quantifiable. These requests are, for example, reports, descriptions or undefined specification. 37% of the requirements are immediately objectifiable and quantifiable. 63% of the requirements must be calculated or derived and are therefore not directly derivable from the requirement.

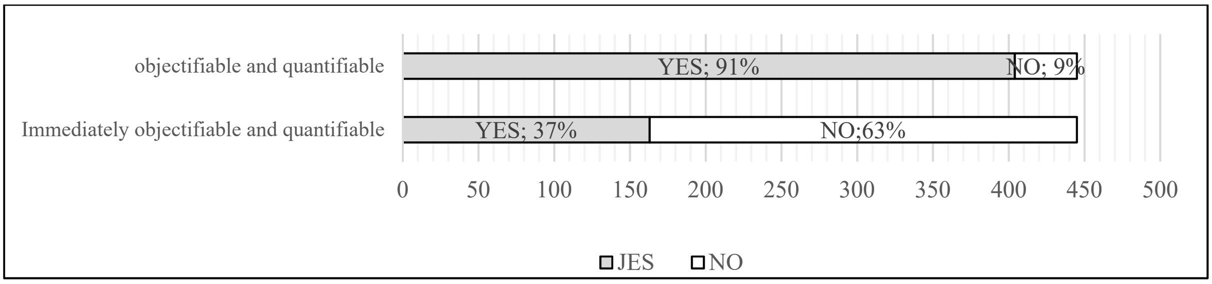

Figure 4. The graphic shows a representation of the objectifiable and quantifiable entries of the information requirement definition

Unit of measurement of the information requirements: To each information requirement, the authors assigned a unit of measurement. In total, 37 different units of measurement were assigned. The most frequent units in the data set are meters (26%), followed by text entries (23%), true-false entries (11%), drawings (8%) and 7% both for generic number entries and square meters.

4. Discussion

All three methodical investigation sections unanimously reveal weaknesses points for general procedures of the building permit process as well as for the application of the sustainable criteria. The currently partially digitalized information flow can be supplemented by the BIM methodology without far-reaching adjustments to the approval process. The results show that the current process is BIM adaptable in a fundamental way without major changes to the processes currently in use. It is reasonable to assume that a considerable shortening of the duration of the building permit processing

time can be achieved. However, the complex legal frame and the resulting high number of necessary procedures are expected to limit the overall efficiency of the building permit procedure.
The low data quality of the examined G-Office database indicates that at present the building authorities are feeding the database in a partially negligent way. Since the information-technical complexity increases further with BIM-based procedures, it is necessary to asses which measures can support the acceptance by the users and the required careful handling of the data.
A further explanation for the low data quality can be traced back to the lack of preselection datasheets. So, for example, to describe the same information requirement, often different terms were chosen. This shows that the use of templates and standards is essential when managing information requirements.
Based on the evaluated data, the authors determined that the detail level of the information requested by the approval process is noticeably high. In addition, a sufficient set of sustainability aspects can be found in the analysed documents. In fact, in many cases the data required for an early-stage assessment and/or consideration for the approval compliances is available. Due to the current processing procedures for the building permit documents, a significant part of this data cannot be directly retrieved and is therefore not accessible to public administrations. The unification of the requirement catalogue is necessary in order to avoid duplicate data.
It can be assumed that the immediately objectifiable and quantifiable information requirements can be seamlessly integrated into a BIM-based workflow. Since the information requirements are mostly clearly objectifiable and quantifiable, a considerable degree of semi-automated verification of today's information requirements is possible.
The research is to be understood as proof of concept to define the information requirements for a building permit process in the area of research.

5. Conclusion

The paper represents a starting point for the technical implementation of a BIM-based building permit process in the area of study and provides the basis for the first use cases. The determined process-based requirements show that sustainability aspects are not taken into consideration sufficiently. Without much additional effort, existing information requirements can be used for the early design stage implementation of basic sustainability aspects. The very complex approval structures and requirement profiles need to be adapted and streamlined to enable a smooth implementation. There were notable positional differences between the municipalities, with the consequence that the implementation in a first step will be limited to individual building typologies. The results show, however, that significant performance optimization is to be expected in the investigated area. The investigation is the first step towards a broad application of digitised information systems in the approval process.

6. Acknowledgements

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A cross-platform modular framework for building Life Cycle Assessment

Kiss B[a], Röck M[b], Passer A[b], Szalay Z[c]

[a] Department of Mechanics, Materials and Structures, Budapest University of Technology and Economics, 111 Budapest, Műegyetem rkp. 3
[b] Working Group Sustainable Construction, Institute of Technology and Testing of Construction Materials, TU Graz, Inffeldgasse 24, 8010 Graz
[c] Department of Construction Materials and Technologies, Budapest University of Technology and Economics, 111 Budapest, Műegyetem rkp. 3

kiss.benedek@szt.bme.hu

Abstract. In recent years the application of Life Cycle Assessment (LCA) for assessing and improving the environmental performance of buildings has increased. At the same time, the automated optimization of building designs is gaining attraction for both design and research purposes. In this regard, a number of issues persist when aiming to optimize building's environmental impacts along the design process. Firstly, as LCA applies a life cycle perspective, many aspects have to be considered (e.g. energy demand in operation as well as consumption of resources and energy for production and end of life treatment) and a variety of specific calculations is needed (e.g. building energy performance simulation, material quantity take-off). Secondly, sophisticated software packages are available and being used for each of these calculations (e.g. software for building modelling, dynamic energy simulation, quantity surveying). Though many of these software packages are currently standalone applications that rely on human interaction, there is an increasing trend to provide an application programming interface (API) that enables customization and automation. Thirdly, the mentioned processes and calculations are influencing each other in various ways and several scenarios have to be assessed. Thus, a comprehensive and modular approach is required that promotes interconnectivity of the different software solutions and automation of the assessment. In this paper we propose a modular cross-platform framework for LCA of buildings aiming to support flexibility and scalability of building LCA. We present a conceptual framework, example data exchange requirements and highlight potential implementation strategies.

1 Introduction

The building and construction sector is related to around 40% of global primary energy consumption as well as a similar magnitude of global greenhouse gas (GHG) emissions and waste produced. Assessing and reducing the energy consumption, GHG emissions and other related environmental impacts across the building life cycle – i.e. from material production and construction, to building operation, incl. maintenance and replacement, down to the final processing at the end of life of buildings – has thus become an important point on the global agenda. Most measures in recent years have been focusing on increasing the energy efficiency of building operation in order to reduce energy consumption and the related GHG emissions. However, in recent years, the importance of assessing and optimizing the environmental performance across the building life cycle is becoming evident. In order to achieve a science-based quantification of environmental impacts of processes and products, the method of Life Cycle Assessment (LCA) has been developed and is increasingly applied. However, its application to buildings is still hindered by several challenges, e.g. compilation and processing of extensive inventories of the complex product system 'building', mapping of inventories with related data from LCA databases, as well as the handling of trade-offs between embodied and operational impacts, to name just a few. In recent years, the application of Building Information Modelling (BIM) has gained interest, hoping to increase the applicability of LCA by managing the related data via a digital building data model. This integration of LCA into BIM has since been demonstrated in several papers with different maturity. In the following we give a brief overview into the state of play based on a literature review.

1.1 Literature review

The application of LCA for buildings' environmental assessment has been of increasing interest for more than 5 years in the literature. However most of the papers were focusing on the applicability of BIM for building LCA [1] or the extension of BIM [2] to include environmental data. Soust-Verdaguer and colleagues [3] evaluated the limitations of BIM-based LCA in a comprehensive review. They identified three levels of integration, from which only the third level includes automated data exchange. It is also recognized that this is not the current practice yet. On the other hand Hollberg and Ruth [4] applied a different approach focusing on the parametric definition and optimization of the model instead of starting from a predefined BIM geometry model. They emphasized the advantages of a parametric model in optimization processes and in early design stages. Other studies were focusing on the data management to bridge the gap between the input requirements of an LCA and the data availability in BIM. Cavalliere et al. [5] defined the minimum requirements to include environmental data in BIM models. They developed an "architecture of variables" so that the various parameters can be included depending on the life cycle stage and the available data. Tecchio et al. [6] on the other hand described a hierarchic decomposition structure for building model data and proposed a method to conduct LCA even if the data availability is low and the information is underspecified. Further studies applied LCA on case studies [7]–[9], most of them facilitated some features of BIM (e.g. extract material quantities, visualization of 3D building model, etc.), but they either use some self-developed tools (e.g. Excel spreadsheet) [9] or apply commercial plug-ins [8] to evaluate the environmental impacts. Both approaches have their limitations that is discussed later in this paper. Some papers were focusing on the evaluation of LCA results through different visualization techniques by using the capabilities of a complex 3D building model [10]–[12]. The extended integration of LCA into the design practice [13] and into certification systems [14] is also in focus of recent research.

1.2 Analysis of existing practice

Based on the literature review, there has been increasing interest in the last few years focusing on the application of LCA in building design practice. However, no common practice or exact specification has been developed yet that facilitates the implementation of different software independent from the used methodology. There is an increasing number of existing software tools, and each of them is based on the own considerations of the developer team. In this research, six experts from different countries have been interviewed about their practice in the application of LCA for buildings. The detailed assessment of the interviews is carried out in the framework of the IEA EBC Annex 72 [15], and is out of scope of this paper, but the most important findings are summarized in the following.

There are two major different approaches to achieve the integration of LCA into design practice. The first one has evolved from the traditional practice of design that is based on human interaction between stakeholders supported by CAD drawings and text documents (legacy method). Throughout the years, usually import and export possibilities have been developed to speed up manual work, or automation facilitates the fast processing of the input data. This approach has the advantage that full control over the calculations is in hand of the expert. The other approach is the extension of BIM solutions to include LCA in the workflow. This is a more straightforward solution to support information exchange between stakeholders, but on the other hand the exact specification of the calculations is usually out of the hand of the LCA expert if a deep integration is achieved.

Based on the experts' opinion the following major requirements can be expressed against a platform for building LCA: *Transparency*, that covers both the background data that the assessment is working with (original source, presumptions, uncertainties) as well as the calculation methodology (bill-of-quantities, replacement, energy demand, etc.). *Interchangeability*, that allows the integration of external solutions such as BIM, and finally *automation*, so that the assessment does not need too much manual work, and as a consequence it might be accessible for a wider audience.

1.3 Scope of this paper

There is a high need for the integration of Life Cycle Assessment into design practice [13]. However, there are some challenges that need to be faced before implementing such a system. First, the steps of the calculation need to be interchangeable, which means that alternative solutions should be easy to apply for each component. Second, the framework should be interoperable so that many external existing solutions (e.g. BIM software) can be connected to provide input to the calculations. Third, the system should be scalable in terms of the level of detail of the calculation. In an early design stage low information granularity is available, but after construction the calculation can be done based on much more specific information. The framework should be able to handle this problem.

Additionally, there is high focus in current research [13] on how the calculation can be transparent for externals. This includes the transparency of the source data, the way how the bill of materials is extracted, as well as the consideration of time-specific issues of the environmental impact or the application of generic or manufacturer-specific construction products, etc.

In this paper we propose a conceptual structure that supports the modular implementation and the interchangeability of modules as well as the other requirements stated above. First, we introduce the modules and the components, after that we define the conceptual exchange requirements in the system of the modules. The novelty of this approach is that the focus is on the application of existing solutions for each module instead of creating the next software from scratch. The same requires that a change of one component shouldn't necessarily mean a new structure for the framework.

2 Definition of the modules of the framework

The following concept is based on own considerations concluded from the analysis of the current practice and the requirements of the experts. The structure of a building LCA calculation can be generalized to four major modules: background data, modelling, calculation and postprocessing. The main data flow is represented on Figure 1. In the usual case input is provided to the background data and to the modelling module, however, the background data is established prior to and independently from a single calculation (e. g. database), on the other hand the input to the modelling is given specifically for each calculation (usually manually). Output is provided either directly after calculation (e.g. raw data for further use in other systems), or after post-processing (e. g. visualization). The splitting of the latter two modules is necessary because both incorporate various methodological questions that are independent from each other (e. g. how to account for the replacement of the building elements in the calculation component, or how to aggregate the results into a single indicator in the postprocessing component). Each module consists of components that are described in the following.

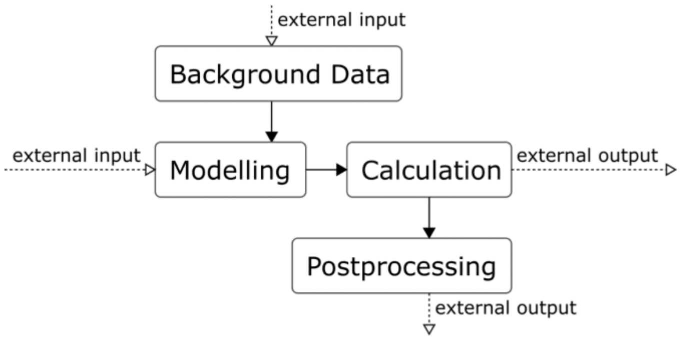

Figure 1. *Conceptual representation of the modules and the data flow in the framework*

2.1 Background Data module

The first separate major module of the framework is called the background data module. This incorporates all the predefined information that is established independently from an assessment case. A component in this module is represented usually by a database (or a table in a simple case) that holds static data. The module includes five optional components (Figure 2).

2.1.1 Material Environmental data

First and most important is the database for material environmental data. There are two different options for this component. The first and most commonly used is a collection of environmental impact information for a wide variety of building materials and for multiple environmental indicators. The impact is quantified on a per mass/volume/piece basis and the characteristics of the impact assessment method (e. g. weighting) is hardcoded into the results. This is called a Life Cycle Impact Assessment (LCIA) database. An example for this case is an EPD database. The other option is a link to a full LCA database, including all unit processes and elementary flows (e. g. ecoinvent processes). In this case the impact assessment method can be later incorporated in the calculation and is not limited to the predefined impact categories. This option also facilitates the update of other related processes in the database (e. g. electricity mix) during calculation.

A further issue related to this component is the inclusion of time- and geographical dependency for the environmental impact associated to the material. Time is an important factor since the reference service period of buildings is most of the times estimated to be longer than the service life of the building components, so replacement is necessary. But the impact associated with the production of the replacement component is going to happen in the future when the available technological circumstances may be different from the current situation. The geographical location is also an important factor since many construction materials are locally produced and may rely on different technology and may use different energy resources (e. g. electricity mix). There are two proposals to overcome this issue: the use of a multi-dimensional database (time and geolocation as the second and third dimension), or the use of an adaptive database, where the environmental impact can be recalculated based on the time and location variables.

2.1.2 Material life cycle data

The second component of this module hold information on the life cycle properties of the materials that are independent from the environmental impact. The most important property is the service life of the materials, but other life cycle related data could be included such as transport and disposal scenario as well.

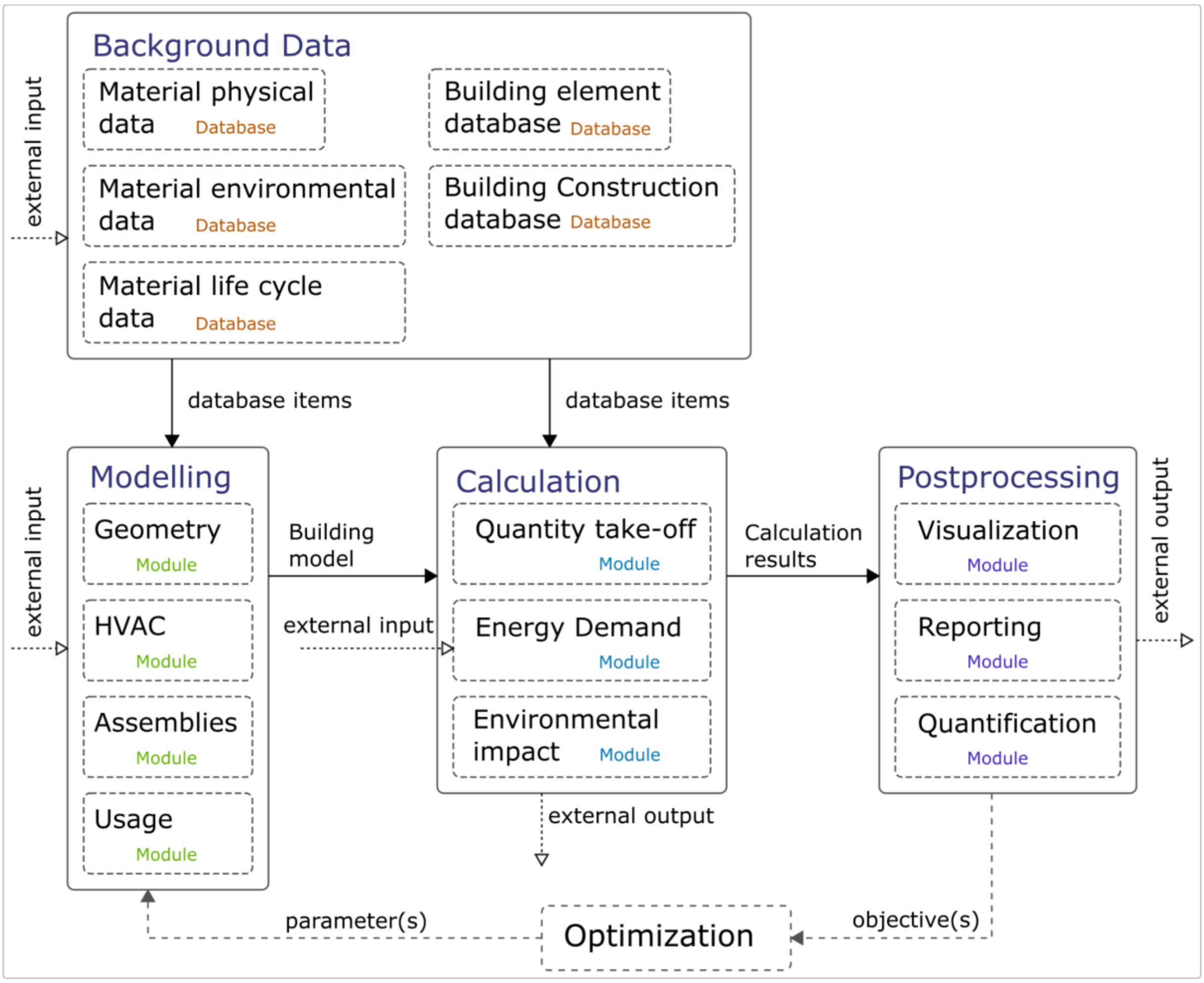

Figure 2*. Visual representation of the framework structure and components*

2.1.3 Material physical data

The third component incorporates all physical data related to the materials such as density, thermal conductivity (λ) or specific heat capacity. Depending on the type of energy and building physics calculation, the entries can range from a single number to complex temperature- and humidity-dependent functions.

2.1.4 Building element and Building construction data

The last two components facilitate the use of the system in early design stages and for decision support [10]. In this case the environmental impact is associated to a construction (assembly of building materials, e. g. masonry structure) or to a building element (multi-layered construction, e. g. wall). The entries in this database can be established prior to the modelling of a building based on industry practice and existing solutions with help of the Material Environmental Database component.

2.2 Modelling module

The second major module is called the Modelling. This incorporates all actions that aim to establish a complete building model that is further used in the calculation module. The granularity of the model can range from the single definition of surface areas (without explicit geometry) and construction assemblies to the parametrically defined full model including geometry and HVAC systems. At this point many external applications can provide an input such as BIM capable systems. There are four major modelling components described in the following.

2.2.1 *Geometry modelling*

This component provides the geometrical information of the model. In a simplified case, the geometry can be defined implicitly by determining surface areas for different types of building surfaces. In a more favourable case, the geometry is defined explicitly in a 3D space. This option supports the 3D representation of the model that can be further used for different LCA visualization options. A third option is the parametrical definition of the building geometry which further includes the optimization possibility.

We can distinguish between two different options for the structure of the geometrical model. The first is based on the practice of energy models, which is usually a surface model divided into thermal zones. The second approach is the exact geometrical modelling of the building elements which is closer to the BIM practice. The advantage of the former over the latter one is the direct input to the energy calculation, but on the other hand there are many simplifications in terms of the bill of quantities (described later). The inverse is true for the “BIM” type of model.

2.2.2 *Assemblies*

The “assemblies” component describes all composite structures used in the building including the inhomogeneous materials (e.g. masonry made from brick and mortar) as well as the layered constructions (e.g. wall structure). As a further extension, joints can be defined at this point which represent the connection between constructions, and additionally can include geometrical properties too.

2.2.3 *HVAC*

The last two components of this module are mostly used if an energy calculation is part of the assessment. The “HVAC” component is used to describe technical systems (heating, ventilation, air conditioning, etc.) installed in the building. The level of specification can range from a single general system (e. g. residential gas heating), to very detailed model including all pumps and pipes.

2.2.4 *Usage*

The last component of this module includes all user-specific information about the building such as occupancy schedules, door and window opening schedules, temperature setpoints, etc. (depending on the type of energy calculation) as well as life cycle related usage information such as renovation cycle, expected type of usage or expected lifetime of the building.

In most of the cases, all the information that is added to the calculation system in the modelling module can be described in a BIM model, however further attention should be paid to the exchange requirements between the database module as well as with the calculation module, an example is provided in the last chapter.

2.3 *Calculation module*

The calculation module provides the heart of the framework. This module is intended to perform all transformations and evaluations that provide all information which is not included explicitly in the model. The module includes three components described as follows.

2.3.1 *Quantity take-off*

For a building life cycle assessment, the amount of materials used in the building needs to be quantified in order to calculate the embodied impact as well as other related impacts (transport or disposal). Therefore, this component takes the model of the building as input and provides the bill of quantities (list of materials with amounts) for which the environmental impact can be assigned to.

The required calculations are highly dependent on the type of the model. For example, for the “surface” type of model the volume of material used at the joints needs to be added/subtracted depending on the reference line of the surface in the wall construction (innermost/outermost surface). Inhomogeneous constructions (e.g. wooden roof systems) serve as another good example, as the profile used in the construction may be described indirectly (e.g. beam size and axis distance) without explicit geometry.

The type of output can depend on the purpose and type of the result evaluation. For a simple calculation the list of all materials may be sufficient, but if the assessment aims to locate the surface of the model with the highest impact, the provided amounts need to include a placeholder (where it is located in the building).

2.3.2 Energy calculations

The highest impact related to the operational phase of the building is usually caused by the operational energy use. To include this in the assessment, an energy demand calculation needs to be done. The type of calculation can range from a simple seasonal steady-state method to a very detailed energy simulation with an hourly resolution. The type of calculation again highly influences the required input from the model. This component can take further external input that may not be included in the model, for example weather data for the specified location of the building.

2.3.3 LCA calculation

This component is used to allocate the impact to the materials and energy that is used by the building during its life cycle. Also, other life cycle specific calculations are performed here, such as the counting of replacement of the building components as well as the calculation of transport and disposal scenarios for each material. The required output of this component depends on the type of applied postprocessing. This component can include methodological options, for example static/dynamic LCA calculation or localized/general evaluation. A static calculation means that all input data (e. g. environmental impact of brick production per kg) is expected to remain the same during the life cycle of the building. On the other hand, in a dynamic calculation the environmental impacts of the unit products assumed to change over time (e. g. because of the change in the electricity mix), and therefore they need to be updated during calculation. Depending on the available information, the localization of the building may also influence the results of the assessment (through transport distances and available manufacturing technology).

2.4 Post-processing module

The structure of the framework implies that all manipulation of the raw output of the calculation module is processed in the postprocessing module. This module aims to provide a range of options to communicate and interpret the results of the assessment. In a simple case the output can be a simple aggregated number based on a corresponding environmental impact indicator. In a more detailed case further visualizations can be performed (in graphs or on the 3D model of the building), examples are available in the literature [12], [16]–[18]. In some cases (e. g. certification) a full report needs to be created based on the results of the calculation, which can be done with a designated component. These three components cover a good range of possible postprocessing options, but the list is not limited to them.

2.5 Optimization

In the favourable case of an automized model generation an optimization module can be introduced in the system. The module takes one or several well quantified outputs of the postprocessing module, they serve as objective(s). It modifies the designated variables of the modelling module which act as parameters in the optimization. This way any optimization algorithm can be implemented in the workflow that is independent from the type of problem (e.g. evolutionary algorithms or other derivate-free algorithms). This structure does not support the application of derivate-based optimization processes, because derivates are not available in the mathematical problem associated with building LCA, since many parameters are discrete and non-numeric (e.g. type of material).

3 Example application of the framework using existing software tools

While the aim of the previous chapter was to define the framework as general as possible, in the following we present a case study for the application of the concept where already available software is used for some modules.

3.1 Parametric modelling with building optimization option

The case study introduces a workflow where the focus is on the automatic model generation possibility (Figure 3). This means that manual input is only needed at the initial step, where the fixed parameters and the optimizable parameters of the model are defined. The entire framework is based on Grasshopper[1] environment. The Background Data consist of two components, a predefined custom database for material physical data (e.g. thermal conductivity) and lifecycle information (e.g. estimated service life) and an environmental database (e.g. ecoinvent) in OpenLCA[2]. The Modelling module is based on the Ladybug&Honeybee[3], and only the Geometry and the Assemblies components are used. In this case, default values are used for the HVAC systems and for the corresponding schedules. The energy demand is calculated with EnergyPlus[4] (through Honeybee). The results are visualized with Rhino3D[5] (the modelling tool that the Grasshopper environment is based on). Finally, the optimization is carried out with the Octopus[6] plug-in. In this case only three other custom components need to be created (e.g. using the python component of Grasshopper), the quantity extraction based on the model, the calculation of the environmental impact based on the inventory created by the previous component and the quantification of the selected results to provide numerical input to the optimization module.

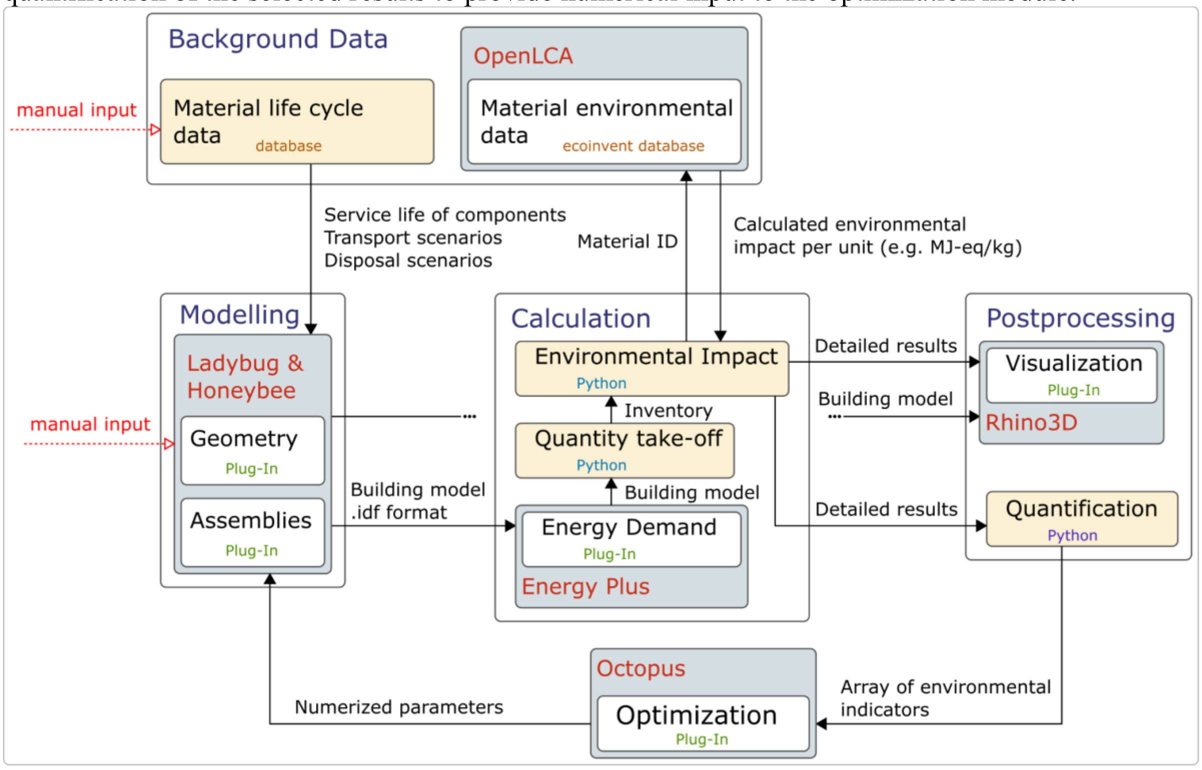

***Figure 3**. example application, setup of the framework and external software used.*

[1] https://www.grasshopper3d.com/
[2] http://www.openlca.org/
[3] https://www.ladybug.tools/honeybee.html
[4] https://energyplus.net/
[5] https://www.rhino3d.com/
[6] https://www.food4rhino.com/app/octopus

This application requires specific exchange information between the components. The modelling module takes additional input from the material database and extends the generated idf model (the standard input file of Energy Plus) with additional information needed for LCA (service lives, transport and disposal scenarios, and a reference ID to the environmental database). The output of the energy demand component is the same building model along with the calculated energy demand. The quantity take-off component uses the same model to create the inventory of the building (including the embodied materials and the operational energy use). The environmental impact is associated with the elements of the inventory based on the database ID. The impact of the inventory elements is provided by OpenLCA. Finally, the detailed results and the building model are passed to the visualization component to create views of the actual solution. In this case the quantification component is only used to extract (or aggregate) selected results to provide a numerical input (as objective) for the optimization component. This optimizes numeric parameters, which are translated into modelling parameters (e.g. different options for insulation material) and the calculation cycle is repeated until a specific criterium is met by the optimization component.

4 Conclusions

In this paper we presented a conceptual structure of a modular cross-platform framework for building Life Cycle Assessment. This approach aims to support interchangeability and interconnectivity of the different available software tools that are used for the specific aspects of LCA. We defined the conceptual workflow and illustrated the exchange strategies between the modules on a case study application. This also showed that for most of the modules existing software can be used by establishing the interface between them. High-level programming environments (such as Grasshopper or Dynamo) make the development of such interfaces easy and fast. During the development, the modules can be created and updated step-by-step so that the first simple version can be utilized from the very beginning. Also, fundamentally different components can be developed side-by-side (e.g. for simulation or steady-state methods for energy calculation) and they can be compared based on the same case studies. This structure also supports the parallelization of calculations that is very useful for the case of optimization especially if the calculations need high computational capacity.

The structure also aims to provide options for different levels of calculation, so that the framework can be utilized already in an early design stage with low information availability as well as at a late stage when detailed calculations can be done.

Acknowledgement

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6D BIM–Terminal: Missing Link for the design of CO_2-neutral buildings

Figl H[1], Ilg M[2], Battisti K[3]

[1] IBO - Austrian Institute for Building and Ecology, Austria
[2] ib-data GmbH
[3] A-NULL Development GmbH

hildegund.figl@ibo.at

Abstract. By 2050, the building sector has to become nearly CO_2-neutral in order to achieve the climate protection targets of the Paris agreement. This tremendous challenge can only be met by taking the carbon neutrality into consideration from the early stages of the planning processes. The overall aim of the project is to provide a life cycle analysis throughout the entire planning and construction process of a building with a special focus on CO_2-neutrality. To this end, Building Information Modeling (BIM) is an appropriate method. The project aims to close the gap between specialist consultants and BIM applications. For that, relevant data for cost estimation, scheduling construction planning and management or sustainable building aspects, shall be added automatically to BIM elements. This data exchange shall be carried out using open BIM and IFC interface according to ÖNORM A6241-2 via a central platform, the "6D BIM Terminal". For more complex calculations the respective specialist planning software shall be made ready to exchange data in IFC format. Thus, life cycle analyses and life cycle cost assessment, as well as specifications for tender, can be performed on the basis of the building model. The expected results of the project are as follows:

- The prototype of a "6D BIM Terminal"
- Interface for existing specialist planning software to the 6D BIM Terminal
- Guidelines for planners
- List with the required properties (PSet's)

1. Introduction

1.1. Motivation

By 2050 at the latest, the building sector will have to become "largely" carbon-neutral if the climate protection goals of the Paris Agreement shall be achieved. Since carbon neutrality of buildings (Zero Carbon Buildings) is a major challenge, it must be part of the building design from early stages of the planning process and must not be ignored at any stage. At the same time, the CO_2 reduction should be affordable and should not be at the expense of other environmental aspects. Therefore, costs, as well as other life cycle indicators, are also needed for the overall optimisation of CO_2-neutral buildings.

Building Information Modeling (BIM) as a process of optimizing the design of buildings using an intelligent digital building model that can be collaborated by the whole planning team offers the best prerequisites for the continuous consideration of ecological aspects during the whole planning process. However, while in other countries (Great Britain, Norway) the 3D-BIM mode of operation has been anchored in planning practice for some time now, German-speaking countries have only recently begun to face up to this technology. In the further dimensions of time (4D), costs (5D) and sustainability (6D), there are hardly any applications throughout Europe. Hence, specialist planners and consultants who do not work on the basis of CAD programs operate predominantly outside the digital building model – also in supposedly BIM-based planning.

1.2. Objective

The overall objective of the project "6D BIM Terminal: Missing Link for the Planning of CO_2-neutral buildings" is the lifecycle analysis of buildings during the planning and construction phase with a special focus on the planning and construction of CO_2-neutral buildings. This shall be done by closing gaps between BIM-based design planning and engineering design. Data that goes beyond geometric and design information and is necessary for the consideration of costs, deadlines and sustainability aspects (4D, 5D and 6D) shall be supplemented as automated as possible with the help of predefined reference BIM elements. The data structure of these BIM elements shall be based on (inter) national standards (IFC, bsDD, ASI property server). The project focuses on the life cycle analysis of the building materials and technical building equipment used in the building, as there are still the essential barriers to the exchange of information between design software and specialist planner software.

In addition to planners and civil engineers, the process should also support procurers and calculators. Therefore, a further aim is to compile the BIM elements from items of the Austrian Performance Description for Building Construction ("Standardisierte Leistungsbeschreibung Hochbau", LB-HB) and thus to create tender specifications largely automated on the basis of the digital building model.

The process shall take place via a central platform, the "6D BIM terminal". Bills of quantities, LCA data, life cycle costs and the list of tender items shall be generated based on the digital building model.

The results are intended to support SMEs in particular. They should facilitate the entry into complex BIM planning, which is more than just a 3D planning. Since the results should be general and the SMEs shall not be forced to buy expensive software and training, the data exchange should be done using open BIM.

2. Methods

The work packages defined for the implementation of the "6D BIM Terminal" are:

- Development of process patterns – based on use cases (survey of software producers and users, analysis of processes, responsibilities, data interfaces, software components)
- Properties for building elements and HVAC: Definition of the property set (PSets), identification of missing or incorrect properties in the IFC standard and ASI property server, formulation of missing items in the Performance Description for Building Construction
- Conception and development of the "6D BIM Terminal"

Applied methods and standards for the calculation of LCA and cost data are:

- LCA according to ISO 14040/48, EN 15804 and baubook acceptance criteria
- Life cycle costs according to ÖNORM B 1801
  Note: In ÖNORM A6241-2, there is a concrete indication that the ÖNORM B1801-1 object construction is to be applied for time (4D) and the costs (5D); in the field of sustainability (6D), no information is given on the methods to be used.

3. Results

The expected results of the project up to November 2019 at a glance:

- Preparatory standardisation work: Identification of the properties required for the life cycle analysis (PSet's) incl. guide for planners and specifications for software houses
- Reference elements: Catalogue with 6D BIM components that can be used as a reference and adapted to specific projects
- The prototype of the "6D BIM Terminal" with a functional user interface, API interfaces and reference catalogue as a tool for cross-organizational collaboration that enables the exchange

of 3D planning programs with complex BIM systems for the specialist planning by generating complex 6D BIM elements from "simple" 3D elements.

3.1. Preparatory work: properties of building materials and building elements

3.1.1. Standards, References

For a planning team whose members usually use software programs from different distributors a neutral transfer format is required for the different data in order to work on a common building model. An internationally standardized database, model and file format are the Industry Foundation Classes (IFC). These have been an official ISO standard (ISO 16739) since the IFC4 was released [1]. The IFC standard is based on building objects, such as walls, columns, etc. for architectural planning; pipes, air outlets, heaters, valves, etc. for technical building equipment. The IFC does not only define the building objects, but also the properties for these objects.

The international reference database for IFC-based properties is the buildingSmart Data Dictionary (bSDD). The bsDD serves as an extension and namespace for the IFC data model. It allows the linking of terms and expressions, their dependencies and definitions (data type, units, value ranges, ...) across different languages.

For the national application of BIM technologies in Austria, OENORM A 6241-2 [2] was created by the Austrian Standard Institute (ASI). This standard regulates the technical implementation of a uniform, structured multi-dimensional, BIM-based data model. An important part of the ÖNORM A 6241-2 is the so-called ASI property server, which is unique in Europe. The online database (http://db.freebim.at) defines a multi-dimensional data model and exchange format for inter-disciplinary cooperation on the basis of the "IFC4 Add 1" standard. ÖNORM and property server are intended to create the basis for the "exchange of graphical data and related factual data" on an IFC and bSDD basis. All characteristics, materials and values defined in the data structure of the property server are identified by a unique identification number (GUID) assigned by bSDD and thus fixed once and unchangeable for Austria.

3.1.2. Matching the properties

Data required for 6D planning are costs, deadlines, LCC and LCA indicator values. The technical description of materials is based on building physics / structural properties and the positions of the Performance Description for Building Construction (LB-HB).

The building physics and building ecology properties and values for the reference elements in the “6D BIM terminal” come from www.baubook.info [3], an online database for ecological construction products. Cost data, dates and positions of Performance Description for Building Construction (LB-HB) are stored in the construction software ABK. At the beginning of the project, these characteristics were compared with the BIM standards and references (IFC, bsDD, ASI property server).

As a result, IFC, bsDD and the ASI property server turned out to provide a useful working basis, but needed a variety of revisions or additions:

- The existing building physics and building ecology properties lack clear definitions.
- The properties regarding the life cycle analysis of materials and elements are incomplete, obsolete or wrongly defined.
- The BIM properties are still largely missing for elements in the HVAC area.
- The BIM properties are practically not used in practice.

Hence, a key outcome of the project is the Property Set, which will be forwarded to the ASI standard groups and to the local group of bsDD (bsAT – building smart Austria).

3.2. 6D BIM Terminal

3.2.1. Principle idea

Currently, only 3D information is output by the CAD programs; the other features for the material and element description of the IFC4 format have not been supported by any CAD software yet. The CAD software tools are capable of exporting IFC4 compatible data, but in fact they are conversions of older IFC formats. Therefore, the 6D BIM-Terminal should enable specialist planners from the various disciplines to import 3D data via the IFC interface, to automatically supplement the data required for the 4D, 5D and 6D planning in the respective project phase and subsequently to export them in the appropriate format again. The 4D, 5D and 6D properties should be semi-automated assigned via matches with a reference element catalogue.

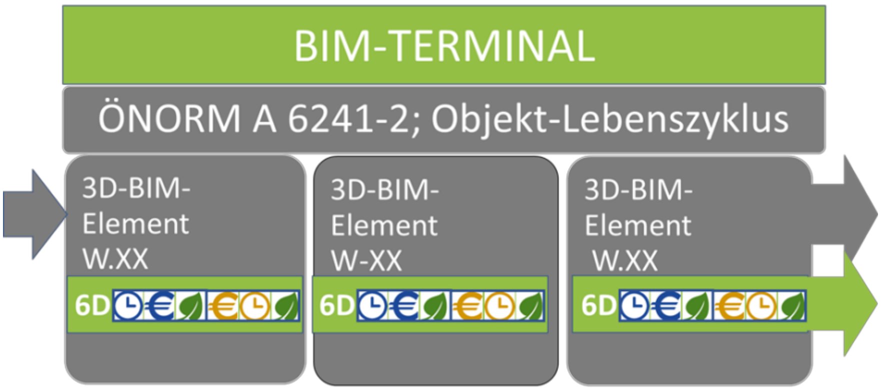

Figure 1: In the “6D BIM terminal”, the 3D information from the CAD programs is read in and supplemented with missing 6D information (4D: time, 5D: installation costs, 6D: LCA data, in each case for the construction and follow-up costs). Specialist consultants can read out the data they need, filtered from the BIM terminal.

3.2.2. Reference elements

One focus of the project is the creation of a reference element catalogue with prefabricated elements according to BIM standards. The composition of the reference elements comes from the “IBO Passive House element catalogue” [4]. These elements are available online in the www.baubook.info database [3] with building physics and life cycle assessmet data. The data is either used directly in baubook for LCA calculations or passed on to other software programs as energy performance calculation tools free of charge via an XML interface.

The existing XML interface has been used to transfer the baubook elements to the construction management software ABK. These elements include the material structure and formulas for the calculation of the life cycle assessment data as well as essential building physics properties such as the U-value. With the likewise imported baubook LCA data for building materials, the LCA indicators of the element can be calculated directly in ABK. More important, in ABK the cost data and the tender items from the Performance Description for Building Construction (LB-HB) were assigned to the elements. For the assignments, the corresponding properties (e.g., materiality, thickness, and height of an element) had to be aligned with the 26,000 tendering items of the LB-HB. If several matching positions were found, the entire item group was assigned to the element and the most ecologically and economically relevant items pre-selected as the default value. This tendering item is automatically activated as soon as an IFC object is matched with the reference element in the “6D BIM terminal”.

The reference elements shall be the main part of the functionality of the “6D BIM terminal”. Suitable models for regular updates and additions to the element catalogue are currently being developed.

3.2.3. Process flow (Figure 2)

In the current process description for the “6D BIM terminal”, the following roles are modelled:

- Designer (responsible for digital building model)

- Procurer (responsible for tender)

Both of them can start the process (has to be defined in the BAP (BIM Processing Plan)).

A central document for a project is the project element list (PEL). The basis of the PEL is a project element catalogue (PEC). The PEC can be derived from a general element catalogue.

Within the project element catalogue the designer has to provide the data the procurer needs in order to be able to determine (deduce) the corresponding tender items and masses. These data shall allow for the automated creation of the call for tenders, the life cycle costs and the life cycle assessment later in the process. In the further process, the catalogue will be exchanged between the designer and the procurer, since the procurer may add further elements or specify individual elements. Hence, it is important that the responsibility for the creation and maintenance of the project element catalogue is time-related in the hands of one role. The project element catalogue can also serve as a base document for requirement formulations to the BIM model as part of a BAP (BIM Processing Plan).

Finally, the designer creates the BIM model in a BIM-capable software using the requirements for objects and properties as described in the agreed project element catalogue. He converts the created model from the own modeling software into the IFC format and sends the IFC model to the procurer for further processing. The procurer checks with suitable software whether the model contains the required classifications and properties. The successfully checked IFC elements are imported into the “6D BIM terminal”. Within the “6D BIM terminal” the IFC elements have to be assigned to reference elements from the project element catalogue. These reference elements contain a rule set which activates the allocation of the appropriate tendering items to the corresponding IFC elements. In the “6D BIM terminal” prototype, initially only the predefined reference elements will be available. Subsequently, a wide variety of stakeholders (manufacturers, software companies, specialist planners) are to import further reference elements in the specified format. Format and workflow are currently being defined.

The generated project element list is the data basis for an AVA software to use this list (database) to generate a tender in the desired form (ONLV Format according to ON A2063 [5] in Austria).

Note: At this point, the BIM based pathway could be abandoned and offers could be obtained in a traditional, classic way.

For bidders, a data package is prepared that allows to identify in the BIM model for each bid position those elements that trigger a position or deliver the masses for a position. The data package contains the project element list (PEL), the associated IFC data and an ONLV file. As a result, the bidder will be able to identify the structural conditions for positions more clearly and to be able to calculate prices more precisely. The bidder returns a priced offer in the classic ONLV data format. After examining all offers, a classic awarding documentation will be created in the ONLV data format. This is in turn transmitted to the bidder by means of a data container consisting of the project element list (PEL), the associated IFC data and the awarding documentation.

LCA and LCC data can be produced as a by-product of the tendering process when the project elements are mapped with the reference elements. In early planning stages the LCA&LCC data can be generated using the same logic as described in the process flow for the tendering process above. In this case the role of the “procurer” is taken by the LCA and/or LCC consultants.

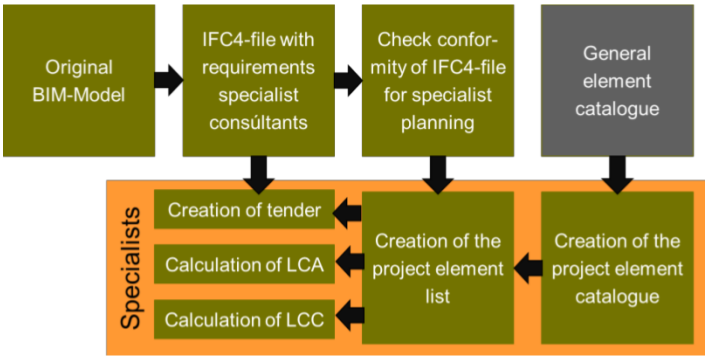

Figure 2: The designer creates the BIM model in a BIM-capable software using the agreed requirements for objects and properties and converts it to the IFC4-format. The conformity of the IFC file is checked and then imported into the "6D BIM terminal". Within the "6D BIM terminal" the IFC elements are linked with reference elements from the project element catalogue. These reference elements contain a rule set which activates the allocation of the appropriate tendering items, LCA and LCC data to the corresponding IFC elements.

4. Conclusions

The "6D BIM terminal" will provide a tool for cross-organizational collaboration. The "Cooperation Tool" enables the exchange of existing 3D planning programs with complex BIM systems. The prerequisite is that the data is transferred via IFC4 to the BIM terminal. The tools will be operated by the project partners as a platform and provided to other software houses and stakeholders after the end of the project. Thus, the "6D BIM terminal" should also support for specialist software solutions outside the project team.

The main hurdles of the project An essential aspect of the project is the data exchange via open BIM. The biggest hurdles in the project therefore lay in the underlying standards, since relevant properties are incomplete, obsolete or wrongly defined, are largely missing as for the HVAC and are practically not used in practice. Hence, a key outcome of the project is the Property Set, which will be forwarded to the ASI standard groups and to the local group of bsDD (bsAT – building smart Austria).

The project results will be finished in November 2019.

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Step-by-step implementation of BIM-LCA: A case study analysis associating defined construction phases with their respective environmental impacts

Di Bari R[1], Jorgji O[2], Horn R[1], Gantner J[2], Ebertshäuser S[3]

[1]Institut for Acoustics and Building Physics, University of Stuttgart, Stuttgart, DE
[2]Fraunhofer IBP Institute for Building Physics, Stuttgart, DE
[3] Department Building Lifecycle Management, Karlsruhe Institute for Technology, Karlsruhe, DE

roberta.di-bari@iabp.uni-stuttgart.de

Abstract. Building Information Modelling (BIM) supports construction processes by dealing with the variety and complexity of design in a single virtual model. The model may also be complemented by the static and energy performance of buildings. Facing the growing demand of sustainability strategies in the construction sector, the consideration of environmental information within the planning process influences the decision making of planners and stakeholders. Nevertheless, the life cycle assessment of buildings has been so far excluded in BIM, due to the high variety of accurate information and time required. In this paper, a systematic framework is presented and applied to a case study. BIM-LCA assists actors along the planning and designing phase, from the building conception as a whole, up to the elements' details and materials' definition. BIM and LCA intertwine in an application scheme of seven phases for integral planning and four levels of structural composition of a building. With respect to these, involved actors examine potential solutions through a tool which exploits alternative specifications in order to assess the environmental impacts. The goal of this paper is to demonstrate the application of a BIM-LCA model regarding decision making for reliable values of environmental impact in a given structural level of the building. The main findings of this framework are due to the multitude of actors and information orchestrated, namely to uncertainties which characterize the whole planning process and data handling. Through BIM-LCA, actors are assisted by ensuring flexibility of models and consistency of results throughout planning and designing.

1. Introduction

The construction sector is responsible for 50% of global greenhouse gases and roughly 40% of the total raw material consumption: as one of the main contributors to global environmental impacts, it is in the last years under particular attention in order to achieve a substantial change. [1]

For the environmental improvement of the building's lifecycle the LCA method is well established and gained importance, mainly as basis of the building certification labels and building product declarations. Its procedure consists in the calculation of a building-LCA by collecting materials and products over the whole life cycle. On the basis of the analysis, information can be selected and all relevant environmental impacts are calculated [2][3]. Even if LCA results depend mainly on materials, it is possible to gather more and more specifications on component or whole final product level within comprehensive building LCA tools and databases. This is justified from the variety, complexity and interconnectedness of the products which do not allow for simple solutions for complete building LCAs: the design of the building shell, for instance, is important for the energy consumption, the location of the building can define transport distances and users' habits determine resource consumption during use and the maintenance and refurbishment activities [3].

Such observations lead to a paradox: a comprehensive LCA can be only carried out after the final design on the products through a detailed ex post data collection but the buildings impact is strongly defined during its conception, namely in the first stages. When the environmental impact is not only to be assessed but to be optimized, the LCA has to be applied in these early stages already. However, differently from technical and economical dimensions, the environmental value of a construction is yet hardly included during the early decision making process.[4] In addition to this, discussions about the current decision making approaches are ongoing: with the rising of building performances and complexity, the ordinary organizing and planning procedures are getting demanding in terms of costs and time; for such reasons, they are considered no longer suitable and further more integrated and dynamics strategies are investigated [5][6].

As solution to this matter, informatics entered in daily practice of the last 20 years and several tools became essential instruments for planner and technicians [6]. Among this variety, BIM (Building Information Modeling) realizes an integrated design starting from early stages, with a set of interacting policies, processes and technologies and facing the main issues, i.e. information fragmentation during lifecycle, building performance prediction and automated assembly [7][8]. Process efficiency studies report up to 40% elimination of unbudgeted change and 80% reduction in cost estimation time with almost 7% reduction in project time [9].

In conclusion, BIM and LCA methodologies are the key for a new approach of planning and design: by technical point of view, the implementation of LCA in BIM, thanks to informatics development and availability of libraries, is within range. However, environmental impact evaluation during the early decision stages and its significance for integrated design is still a strongly debated topic.

2. State of art

When the building is not well defined, technicians are involved in order to take decisions about the overall design and select available alternatives.

As demonstrated by Basbagill et al. (2013), postponing material and thickness decisions during the design development stage is not a successful strategy in terms of environmental impact. On the other hand, an aware and timely choice of materials can significantly reduce the total GWP emissions, avoiding designers' effort on inconsequential decisions during the critical early design stages. The knowledge of material properties, building shape and orientation, for instance, can be the basis for the optimization of final energy performance [10].

In literature, several approaches and tools for LCA in BIM are available but however not all issues have been so far solved or new challenges arose. By technical point of view, the creation of such tools as support instrument for decision-making showed problems, such as the missing interoperability between BIM interfaces and environmental databases, the import of BIM information into LCA software, the complexity for many actors of treatment of a BIM model [11]. The use of IFC format has proven to be advantageous, by facilitating building description and construction industry data exchange through an open file format and neutral platform [12].

Differently, the methodological aspect is more discussed. Antón and Díaz (2014) suggest a "material-oriented" approach: the BIM library can include relevant environmental information coming from previous analyses, so that the designer will consider such performance within the ordinary material choice procedure. As disadvantage of this approach, besides the low results accuracy (e.g. transport distances measurement), LCA database implementation showed problem in terms of efficiency [13].

An alternative to this may be an environmental impact assessment during the whole planning and design process: a more accurate approach, which avoids data reentry, and realizes a real-time assessment through a three-dimensional object. Most of existing applications in literature use 3D-Cad models to be connected to an LCI database, which, in comparison to a BIM Model, are not capable to include relevant information such as recyclability, reuse and construction life span, together the with material collection [14][15].

Even though the huge potential, the combination of a BIM interface with this approach is not always effectively feasible. It has been observed, that not many standards and guidelines address demolition and aspects of refurbishment in the BIM [16]. A quick and accurate estimation of waste due to the demolition is possible only by calculating all material quantities of a building which has exhausted its service life but, even for existing buildings, this is not a direct calculation, which is a lack of accurate information that practitioners and clients face in daily practice [17].

As result of this discussion, it can be claimed that, BIM-LCA approaches, even if acknowledging the relevance of early stages, intended their application only from the early *design* phase. This because at the moment there are not available enough synergies between stakeholders, technicians and clients and none of these have achieved a full automation for calculations or information transfer between software [11][18]. As noticed by Röck et al. (2018), such application provides results and conclusions which cannot be generalized, since they depend on the quality of input data from both BIM and LCA model completeness and data accuracy [19][20].

3. Method

Within a research project "BIM based integrated planning", supported by the German Federal Ministry for Economy and Energy (BMWi), a procedure for the definition of planning and lifecycle phases has been developed [21]. As results of this, a model of concretization made of 7 phases has been realized for each of them, the information depth of BIM level and the required specifications have been collected, with particular attention to the data necessary for LCA [23].

The detail of such information depends mainly on the considered building levels: whole building, functional system, element system and component layers (see Figure 1).

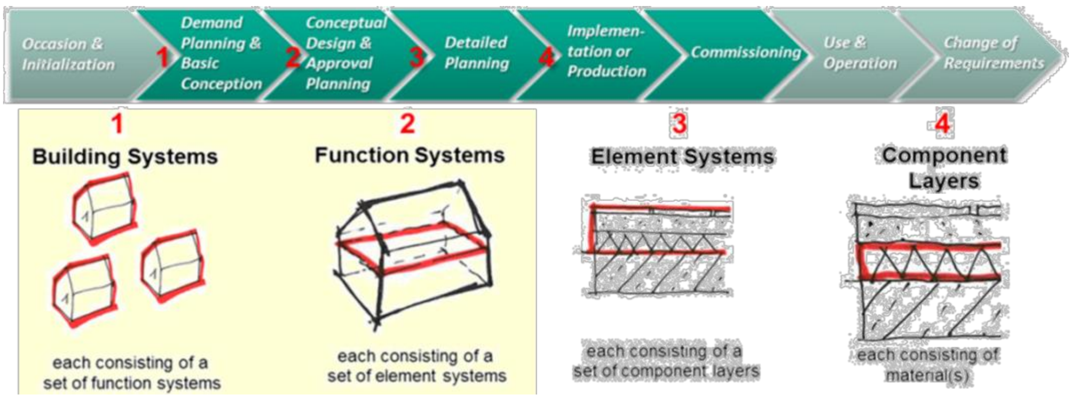

Figure 1. Building levels with reference to a model for concretization phases of planning and design process. [22]

In this section, basing on the above mentioned research project and further works [23] [24], a methodology is presented with focus on the early planning stages (phases 1-2 from the Figure 1), the involved actors and the information which is within required.

The information is *step-by-step* fragmented, reduced to the most detailed value, and converted depending on its characteristic (descriptive, quantitative, and boolean) in order to set up a full automation through informatics instruments.

3.1 Occasion and Initialization

The project starts after the initiative of an individual, who is following own personal, political or entrepreneurial goals. The main activities regard evaluation of the solution sets, basing on a series of implicit and explicit decisions and conditions. In this context, after the comprehension of the main issues and possible contributions to the project, specific solutions are considered, depending on the personal past experiences and knowledges. Such alternatives concern the whole building system, e.g. building type and construction methods (Figure 2).

The first and most important decision concerns the realization or postponement of the project, by taking into account relevant problematics (social and political) and the own experience. The functions addressed to the initiator are the research of information, the designation and experts and their corresponding commitments.

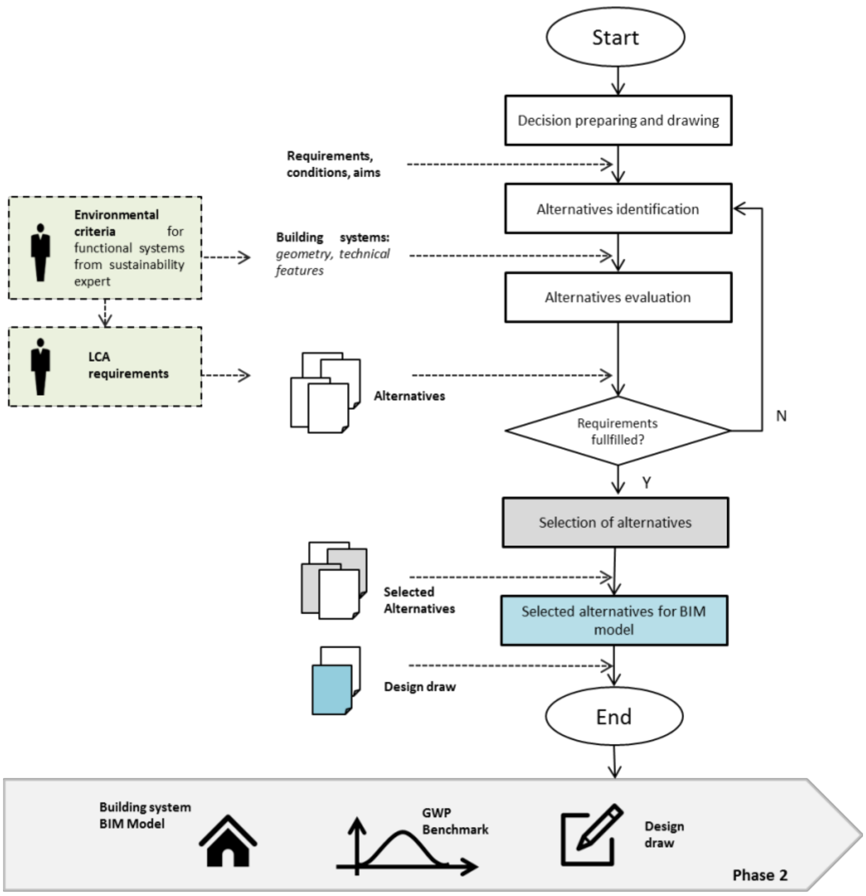

Figure 2. Stage 1: Process details and information needed [22]

The established project managers group provides general features, such as the usage type (office, residential, industrial …), category (single- or multi-family dwelling, school or university …) and location. This leads to first quantitative specifications, i.e. number of dwellings, offices, rooms, and consequently to the first evaluation of minimal using surfaces and volumes, such as mean floor area, net floor area (see f.i. ISO9837 or DIN277 standards). The plot of land location enables roughly to a hypothetic floor plant and building orientation. Furthermore, construction technologies can depend on design preferences and workforces experience as well as material availability of the neighborhoods.

As shown here, on this level, essential information is already available and a first environmental value of the whole building system can be estimated. However, this occurs *indirectly*: in fact, due to a still low workforces' awareness, sustainability problematics are not particularly taken into account unlike economic, technical and social aspects. As support during the whole project management, figures with particular sustainability expertise as wells as tools can be exploited and aims (with volunteer characters) and requirements (compulsory or guidelines suggestions, e.g. EEG for Germany) may be provided [23]. On the basis of those, alternatives can be assessed and their choice can be supported with help of environmental *Benchmarks* derived from a tool which gather in its database either available other LCA results or normative regulations. A first design draw is lastly processed, which roughly represents the building system and describes technical features only in qualitative terms, and accompanied by overall environmental impact estimation.

3.2 Demand planning and basic conception

While the first phase is focused on the building technical and geometrical specification, the following one is centered on management of financial resources and evaluation of the investment risk. The actors are called to prepare and secure a project with outlook to an upcoming investment decision. Through the involvement of the real estate industry, capital and ideas are merged and developed into a project.

Information coming from the first phase are here processed, such as plot of land, location (to be linked to permissible land for construction), infrastructure supply, permissible main use, intended real estate market and users, and further technical specifications (building structure, storeys, building orientation). In comparison with the previous stage, alternatives may be assessed by means of *function systems* level (Figure 3).

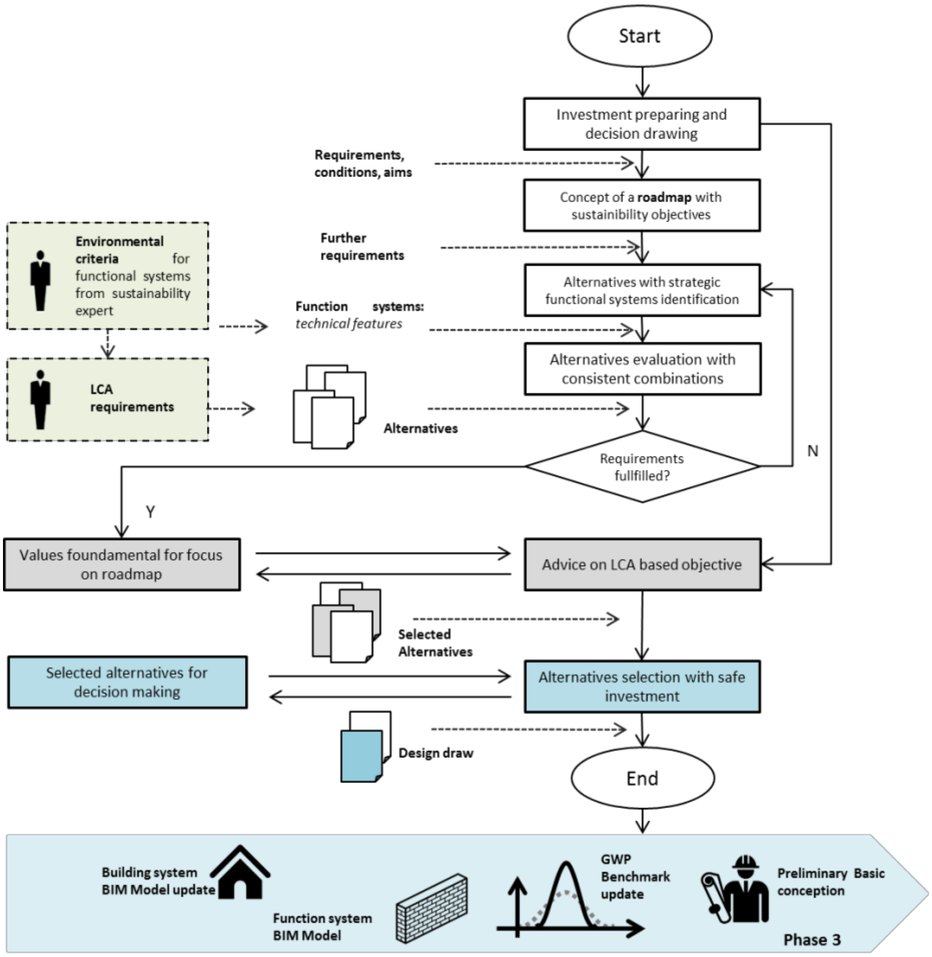

Figure 3. Stage 2: Process details and information needed [22]

Consequently, the whole building is differentiated in functional systems such as external walls, floors or roof and for each of them qualitative technical requirements are addressed (i.e. EnEV for Germany) and then connected to the already given geometry. As well as the initialization and ground concept, environmental requirements and guidelines are provided and included in a so called "*roadmap*" [21][22].

The alternatives deemed consistent with the abovementioned requirements are then evaluated and the one which guarantee a safe investment selected. As results of this process, for each functional system a BIM model is generated, the tool calculates GWP benchmarks through its database and the previous models are updated with more accurate results. The first preliminary concept design can be then presented.

4. Case study

The presented framework is applied on an exemplary multi-apartment building in Germany. With help of the online tool SBS for building sustainability evaluation, total GWP impacts have been calculated for building and functional system. An Excel tool has been set up for results collection and benchmarks calculation for alternatives comparison. The building and functional systems examples are derived from previous works and projects available in the SBS-onlinetool (www.gabi3.com) database and exploited as statistical values in order to derive Benchmarks based on typological standard. [25]

4.1 Building systems evaluation

For the initialization, the selected information cover general building features such as construction type, using type, energy standard and installation standard. Such features are the ones considered relevant for LCA and therefore their variation leads to different GWP value feedbacks. Each characteristic has been defined as specified in Table 1.

By fixing, for instance, the building use type and energy standard, different installation standard and construction types may be considered. As shown in Table 2, installation standard on this level has no relevance on the resulting GWP Benchmarks; on the other hand, the construction type can be relevant for the total potential emissions and this reduction is due to the production phase. Hence, for a multi apartment building with KfW55 energy standard, a light construction has been chosen [26]. By comparing the results with the DGNB reference for new constructions [27], the total GWP seems to be underestimated.

Table 1. Stage 1: Information needed, sources and selected example

Building system	Info	Reference	Example
General information	Building Type	Use type in according to	Multi- apartment building - Fixed
	Energy standard	EnEV, KfW, Passive house, Plus energy building	KfW55 – Fixed
	Installation standard	Low/high	Variable
	Construction type	Massive/Light	Variable
	Net surface		**707,4 m²**

Table 2. Stage 1: Benchmarks results [kg CO2/m²net surface year] [25] [27]

GWP [kg CO2 eq./m²y]	Massive Building/ Low installation standard	Light Building/ Low installation standard	Light Building/ High installation standard
Production CG 400+300 + EoL CG 300 + CG 400	5,59	1,26	5,59
Use phase KfW55	22,94	22,94	22,94
Total	***28,53***	***23,2***	***28,53***
	DGNB Reference value [NWO15(V16)] [26]		***53,11***

4.2 Functional systems evaluation: external wall

For the definition of a functional system different standard solutions of external and internal walls, floors, roofs and installation sets have been derived by simplified BIM models belonging to SBS database (see Table 3). For each of them, LCA analyses. For this case study floors, roofs, and internal walls have been fixed and external walls and installation sets varied, by taking into account that the previous analysis suggests a light construction technology for a multi apartment building and finally a new total impact due to production and end of life is calculated (see Table 5).

Table 3. Stage 2: Information needed and benchmarks

Functional system – Cost group [DIN 276]	Example	Amount [26]
Basement – CG320	Basement with overlying insulation – Fixed	294,4 m²
External walls – CG330	1) Wood Walls 2) Wood fibers	776,8 m²
Ceiling – CG350	Wood ceiling with structural beams- Fixed	588,8 m²
Roof - CG360	Slope Roof- Fixed	294,4 m²
Installation set – CG400	1) KfW55:Domestic water distribution stainless steel, Ventilation system, Composite pipe, Buffer storage ***Underfloor heating***, 2) KfW55: Domestic water distribution stainless steel Ventilation system, Composite pipe, Buffer storage***, District heating station.***	707,4m²

Table 4. Stage 2: Information needed, sources and selected example on functional system (Standard systems from previous projects [25])

Cost Group DIN276	Construction	GWP [kg CO2 eq./m²] [25]	Specification Unit [m²]
CG 320	Basement with overlying insulation	148,55	Basement surface
CG 330	1) Wood ext. walls	3,38	Ext. walls surface
	2) Wood fibers ext. walls	17,96	
CG 350	Wood ceiling with structural beams	-19,60	Ceiling surface
CG 360	Terrace Roof-	139,10	Roof surface
CG 400	KfW55:Domestic water distribution stainless steel, Ventilation system, Composite pipe, Buffer storage		net surface
	1) with *Underfloor heating*,	56,73	
	2) with *District heating station*	28,78	

Table 5. Stage 2: Information needed, sources and selected example on building system

GWP [kg CO2 eq./m²y]	Wood walls/ underfloor heating	Wood walls/ district heating	Wood fibers walls/ district heating
Production + EoL CG 400+300	3,28	2,72	3,04
	DGNB Reference value [NWO15(V16) Construction] [26]		**3,98**

Differently from the previous analysis, on this level the installation sets are more relevant for the final results, which are now provided in a more comprehensive form. The calculated benchmarks towards the DGNB reference value provided for the construction of a new residential building (NWO15 Profile) [26]: this prove the good accuracy of the results provided by SBS-onlinetool database.
On the other hand, due to a lack of comprehensibility regarding simulation data, specific installations and auxiliary energy, any further information about use phase is not given and therefore results cannot be yet enhanced.

5. Conclusion and future outlook

With the presented framework, environmental impact results can be provided already during the first decision making process and before the early design stages. Peculiarity of such framework is the necessity of sustainability expertise and respective tools supporting the project manager and providing construction alternatives and GWP values starting from the early stages. As shown in the case study section, such tools have to handle issues due to data requirement and inaccuracies. Most of them are caused by missing information about specific energy consumptions as well as refurbishment or renovation measures, which depend on the user's habits and choices and are all considerable sources of uncertainties for LCIA analyses.[18] These uncertainties have to be included in the decision making process to provide the practitioner both the sustainability feedback and the robustness of this value. Even on completion of final building design and data collection, environmental impacts cannot be still depicted by a single trustworthy value, but better by a range of values of which width or distribution depends strongly on uncertainties. [29]
Finding a solution to this matter represents indeed the next challenge: in terms of results robustness, an improvement of SBS-onlinetool can be realized in a first instance by enrichment of the available database and provision of statistical records to keep constantly up to date. Moreover, with regard to the overall methodology, more dynamic and probabilistic approaches are nowadays still on investigation. Such approaches aim to reach an environmental impacts prediction by considering of a multitude of variants and factors. Among them, the German Excellence Cluster "IntCDC" establishes research networks called to investigate innovative integrated Co-design including predictive Life Cycle Assessment, in order to achieve a real-time decision support and robust statements during the early design stage with limited environmental information basis and uncertain boundary conditions. These forthcoming improvements on LCA methodology aim to provide and to successfully communicate robust statements on environmental performance already in or before early design. Hence, through addressing the data quality and availability related issues not only in early design for LCA, some of the current implementation issues in BIM-integrated LCA may be overcome. [30]

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Connecting BIM and LCA: The Case Study of an Experimental Residential Building

Veselka J, Růžička J, Lupíšek A, Hájek P, Mančík Š, Žďára V, Široký M

Czech Technical University in Prague, Czech Republic

jakub.veselka@fsv.cvut.cz

Abstract. The aim of this paper is to present application of BIM models for the complex quality assessment and environmental analysis based on LCA. An experimental two storey building of TiCo Project representing a full scale part of a real multi-storey residential building has been used for this case study. The presented BIM model contains all relevant environmental characteristics and it will be used for environmental analysis, coordination, and operation (e.g. real-time data analysis from the sensors). Theoretical part covers development of the methodology for data transfer from BIM model to assessment scheme based on SBToolCZ, which is a national tool for building sustainability certification in the Czech Republic. Next step will be focused on describing connection of LCA and the BIM model databases and mapping data between them. Case study is focused on utilisation of BIM model with all relevant environmental characteristics for LCA analysis. All changes during construction phase and their impact on environmental analysis and LCA will be monitored and assessed.

1 Introduction

1.1 Current situation at the BIM market

Building Information Modeling (BIM) has already been widely spread and established during last couple of years at the European markets [1] [2] as well as in the Czech Republic. Markets and legislation start to be mature and ready for the BIM. In the most developed countries there is a plan of implementing BIM on the national level. For example in the Czech Republic the usage of BIM is mandatory from 2022 for the over-limit public tenders financed by the Public sector [3]. Although mentioned data [1] [2] seems positive, it is necessary to dive deeper into data. Study from the Boston Consulting Group (BCG) [4] company points out fact that with revenue of almost $10 trillion (6%) of global GDP makes AEC industry of Architecture, Engineering and Construction (AEC) one of the most important.

Another study of the McKinsey&Company [5] points out that “the world will need to spend $57 trillion on infrastructure by 2030 to keep up with global GDP growth” and also presents 5 trends which will shape construction and capital projects. Three of those trends directly contain the BIM technology (Next-generation 5-D BIM, Digital collaboration and mobility and The Internet of Things and advanced analytics respectively). The same document also says that the Construction industry is currently one of the least digitalized industries ever (worse position in the digitalization has only Agriculture and hunting).

Next important topic for further development is Facility Management (FM) perspective which also has high impact to the environment. Review of 3 Case Studies [6] from the Czech market summarizes current market development and shows possibilities of future focuse.

All mentioned analyses bring us to the conclusion that AEC industry needs a real evolution and BIM is one of the key factors on the way of digitalization.

2 Theoretical Part

2.1 BIM and LCA

Important chapter which is not yet entirely described is implementation of environmental parameters into the BIM model. This topic is widely discussed across the industry, on many various platforms e.g. Annex 72, working group under the International Energy Agency's Energy in Buildings and Communities Programme [6].

The key part always related to the model is its detail. In terms of BIM there is widely used term Level of Development (LOD) [7], standard developed by the BIMFORUM [8], the non-profit organization consists of The Associated General Contractors of America (AGC), The American Institute of Architects (AIA) and American Institute of Steel Construction and its also part of the BuildingSMART[1], the international organization developing international standards related to BIM (e.g. openBIM, Data Dictionary or data exchanging format The Industry Foundation Classes (IFC)).

The LOD in terms of incorporating environmental data can be divided in two parts:

2.2 Aggregated Data Method

Simplified method of modeling which can be widely used for comparing different material bases (e.g. load bearing system, façade etc.). The model follows LOD 200-300 and environmental data are aggregated according the whole structure (e.g. environmental values for timber wall with inserted insulation between studs is recalculated according volume of all parts). Elements which are not in the model (e.g. hangers, veneers etc.) are neglected.

2.3 Element Data Method

Detailed method of modeling which can be used for precise calculation of building's environmental impact. The model itself has to be developed in LOD 350-400 which means that it contains detailed geometrical data of the building (e.g. concrete rebar, wall studs, veneers etc.). This method is highly accurate but also time consuming. It is also necessary to keep a wide database of environmental data of used materials. Due to high detail of the model there is only minor elements neglected.

2.4 SBToolCZ

SBToolCZ is a Czech national sustainability certification scheme similar to BREEAM or LEED with focus to Czech building industry and standards. It is applicable for residential buildings, offices, schools and kindergardens. It is based on complex evaluation of environmental, social, economic and location-related quantitative and qualitative indicators. The received scores from each indicator are normalized and weighted, and the resulting score is translated into bronze, silver or gold certificate, which is awarded by independent certification bodies [9]. Schema of the SBToolCZ and its connecting with BIM models will be used in the future research.

3 Case Study

3.1 The Case Study Description

The main project objective is to develop a flexible construction system for a new generation of multifamily residential buildings capitalizing on synergy of non-bearing light timber-based structures and with a light bearing structures from high performance concrete with maximal utilization of advanced prefabrication technologies. The structural system from high performance concrete is characterized by a high bearing capacity, long lifetime, fire resistance, and favorable acoustic and heat accumulation parameters.

Timber-based structures guarantee a low carbon footprint of production, lower weight, and excellent thermal insulation of building envelope. Key issues that project addresses are development and

[1] https://www.buildingsmart.org/

optimization of both types of structures, their interfaces and coordination of prefab production of the elements and concerted fast assembly on site. Optimization in terms of environmental impacts, energy efficiency and economic feasibility is also part of the project. Load bearing system from high performance concrete and non-bearing timber-based elements fill be produced and its function will be tested per parts on special research equipment at UCEEB CTU and as a whole on a small experimental structure. Based on experience from pilot the design of all elements will be improved and verified by production of prototypes. The experimental building will be built in spring 2019 at University Centre for Energy Efficient Building (UCEEB) of Czech Technical University (CTU) in Prague. The resulting building system will become a part of portfolio of RD Rýmařov, which will sell it to developers of residential buildings in Central Europe.

3.2 The BIM Model

The digital model itself has been developed in software Autodesk Revit. This software has been chosen according the internal research which confirmed it as a leading product of the BIM world with the most advanced tools for many different trades and stakeholders on AEC market.

The case study consists of the following tasks:

- Design model in LOD 300 with applied Aggregated Data Method (described in 2.2),
- Construction Model in LOD 400 with applied Element Data Method (described in 2.3),
- As-built model in LOD 500 with incorporated all parameters needed for Facility Management (FM),
- Dashboard showing real-time data from the incorporated sensors.

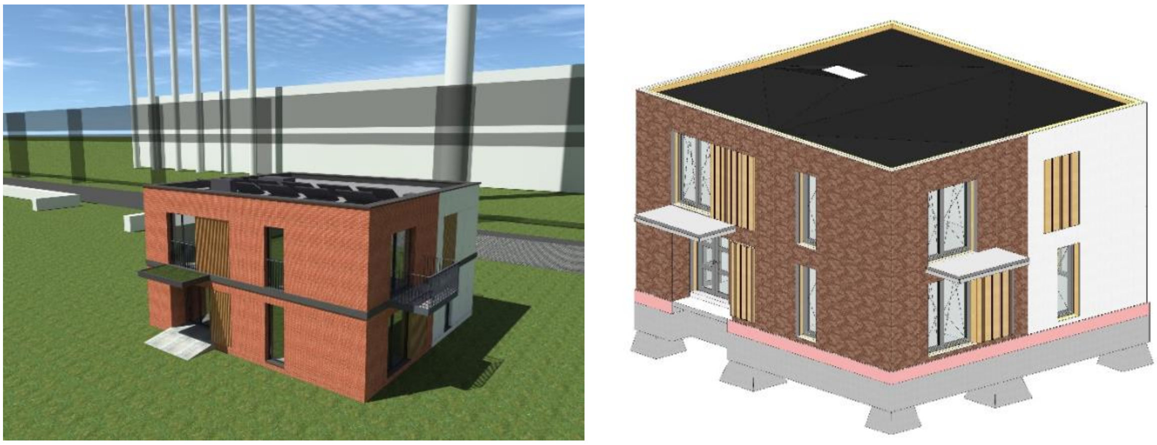

Figure 1 – Project visualization and the BIM model

Current situation described in previous section creates a perfect condition for creating the "Real BIM model" which contains all related data important for design, construction and operational phase of the project. Thanks to the TiCo project the real building will be built anyway. With the current market situation and proper knowledge there is a room for this Case Study.

3.3 Current status of the model

Currently the model is developed in LOD 300-350 and it contains all the relevant structures with relevant environmental data: Primary Energy Input [MJ] and Global Warming Potential [kg CO_2,ekv]. The environmental data has been taken out of the Envimat[2] database, the Czech catalogue of the environmental parameters of building materials.

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http://www.envimat.cz/

Material: Comments	Material: Volume [m³]	Material: Area [m²]	Material: PRIMARY ENERGY INPUT - [MJ/m³]	PEI Total [MJ]	Material: GLOBAL WARMING POTENTIAL - GWP [PEI CO_2 ekv,/m³]	GWP Total [kg CO_2,ekv]
CONCRETE	20.01	53	1211	24227	203.0	4061
CONCRETE - REINFORCED	85.48	468	6866	586933	712.0	60865
HIGH PERFORMANCE CONCRETE	13.26	101	6866	91036	712.0	9440
TIMBER STRUCTURE + MINERAL WOOL	65.98	611	1559	102866	119.0	7852
TIMBER STRUCTURE + GLASS WOOL	15.68	199	1718	26931	110.0	1724
TIMBER STRUCTURE 60/40; 420mm + AIR GAP	4.36	109	116	506	8.0	35
GYPSUM FIBREBOARD	22.12	1265	4465	98758	392.0	8670
HYDROIZOLATION	0.17	116	92964	16184	3377.0	588
BRICK VENEER	0.71	101	19861	14092	1480.0	1050
STEEL	0.08	24	189700	15746	17146.8	1423
GLASS	2.76	100	442	1218	36.0	99
THERMAL INSULATION - WOODENFIBRE	4.06	90	3682	14948	149.0	605
THERMAL INSULATION - EPS - FAÇADE	15.56	104	1903	29605	83.0	1291
THERMAL INSULATION - EPS - FLOOR	11.17	111	2365	26426	104.0	1162
THERMAL INSULATION - EPS - ROOF	37.25	116	2880	107279	126.0	4693
THERMAL INSULATION - XPS	0.86	17	3463	2989	138.0	119
SUM	**299.51**			**1159744**		**103679**

Figure 2 - Environmental impact of the building elements

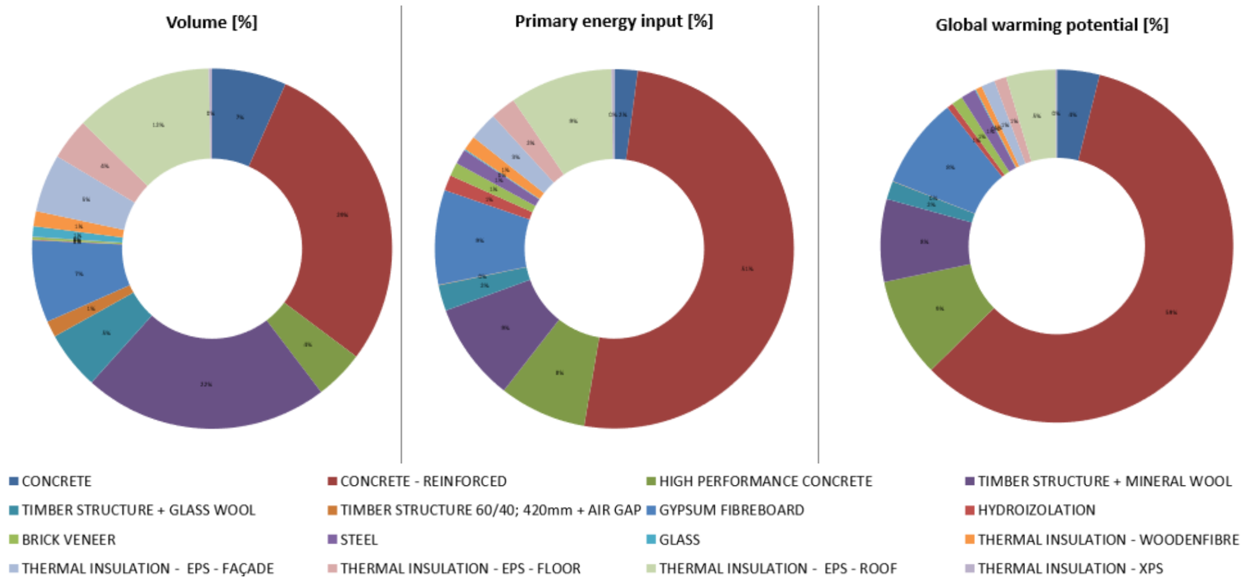

Figure 3 - Environmental data of the model

3.4 Challenges of digital model

During the modeling the team has always dealt with the following obstacles:

- Quality of the model and its LOD,
- Environmental data quality and consistency,
- Software limitations (e.g. volume deviation)..

The idea of this project part is to implement all the related date important for the operational project phase. Due to delay of construction phase this part has not been implemented yet.

4 Conclusion and the future focus

Experimental building TiCo has not been erected by the time of writing this paper yet, so only the Design Model with Aggregated Data Method of implementing the environmental data is applied. This method confirmed a wide benefit of using BIM for similar purposes because it allows simple comparison of different material bases.

Even though there are several lessons learned applicable for each project:

- Incorporating the basic environmental data is a simple process which can be replicable.
- Missing methodology and legislation describes the process of implementing environmental data into the BIM model.

4.1 Future Focus

- Incorporate the sensors data into the BIM model.
- Follow the SBToolCZ scheme and incorporate all environmental data into the BIM model.
- Create the methodology which allows replicability of gained knowledge across the market.

Acknowledgment

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Towards a Life Cycle Sustainability Assessment method for the quantification and reduction of impacts of buildings life cycle

Llatas C[1], Angulo Fornos R[1], Bizcocho N[2], Cortés Albalá I[1] , Falcón Ganfornina R[1], Galeana I[1], García-Martínez A[1], Gómez de Cózar J C[1], López Alonso S[1], Meda P[3], Mercado Martínez J M[1], Montes M V[1], Periañez Cristobal R[1], Quiñones R[1], Rojo T[1], Rubio Bellido C[1], Ruiz Alfonsea M[1], Soust-Verdaguer B[1]

[1] Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla.
[2] Departamento de Mecánica de Medios Continuos y Teoría de Estructuras. Escuela Politécnica Superior, Universidad Carlos III de Madrid.
[3] Construction Institute, Faculty of Engineering, Porto University, Portugal.
bsoust@us.es

Abstract. The construction and building sectors are one of the highest consumers of resources and energy. Literature evidences the potentialities of the design phase towards the improvement of environmental, economic and social performance of buildings. Thus, the Life Cycle Sustainability Assessment (LCSA). approach is recognized as suitable method. It is based on the "triple bottom line" principle, to calculate environmental, economic, social impacts produced by buildings during its life cycle. The present paper aims to present a methodological framework based on an LCSA, used during design stages of buildings and integrated into a building's design technology such as Building Information Modeling (BIM). A conceptual approach to conduct the data integration and a possible workflow to integrate the LCSA into BIM is proposed. The value of the present approach is the possibility to conduct quantitative environmental, economic and social assessment of buildings to guide designers to measure and predict the building's performance.

1. Introduction

The building sector is responsible, from cradle to grave, of significant environmental impacts [1]. In the European context, for example, the use and construction stages of buildings consume half of the extracted materials [2]. Moreover, it is also recognized as one of the most important waste producers, by generating one-third of the total amount [3]. Regarding this situation and given the growing demand for reducing environmental impacts of cities and buildings, the building sector also produces economic benefits [4–6] and positive impacts for the society.

The design stages of the buildings are considered as relevant in order to reduce their impacts among their life cycle [7,8]. Consequently, over the last decades there has been developed several assessment tools for design stages, mainly based on environmental aspects. The Life Cycle Assessment (LCA) is considered one of the most appropriate method to analyzes the impacts produced by buildings, mostly focused on environmental aspects [9]. The utility of LCA-based tools compared to existing Sustainable Building Certification (SBC) or Green Building Rating Systems, such as LEED [12], BREEAM [13], Living Building Challenge [14], is based on the possibility to bring quantitative assessment of building's sustainability [15] through the stages of the building's life cycle. Existing SBC are mostly based on the assessment of qualitative environmental aspects of sustainability, generally related to energy [16]. That fact evidences the scarce incidence of other sustainability dimensions, for example socio-economic aspects, such as their contribution to the employment creation in certain region or city. Furthermore, literature [7] recognizes the potentialities of the use of LCA-based methods to be integrated in building design stages. However, the main barriers over the use of LCA methods applied to buildings are related to the time-consuming process and the wide amount of data required [17], especially during the phase of Life Cycle Inventory (LCI). In this sense, several works demonstrate the viability of applying simplification strategies for buildings LCA [17–21]. It is recognized that the feasibility of using environmental assessment tools and methods, lies in the simplicity and effectiveness to verify and calculate the impacts. Malmqvist et al. [17] show the possibilities of simplifying the method without the results being substantially affected. Soust-Verdaguer et al. [22], through the analysis of simplification strategies of LCA case studies (single-family houses), underline that one of the feasible strategy to reduce effort during the LCI phase is the integration of BIM models. The strategy allows to integrate LCA into BIM methodology and helps to visualize impacts during the decision-making process. The potentialities of the integration of LCA into BIM through the development of methods and tools are demonstrated in several works [23–39]. Despite of the great amount of developments that integrate BIM and LCA, they are mainly focused on the use of Life Cycle Assessment method to assess environmental aspects. However, current situation based on "complex systems with extended and durable effects on the society" [40], requires more comprehensive and extensive strategies. Thus, the Life Cycle Sustainability Assessment (LCSA) approach aims to go beyond the limitations of the traditional LCA approach [40], by integrating environmental, economic and social dimensions. Literature review evidences that the application of LCSA into building sector is still scarce, and especially during design stages. To fulfil research gaps on this area, the present paper aims to describe a methodological framework based on an LCSA approach, used during design stages of buildings and integrated into a building's design methodology such as Building Modelling Information (BIM).

2. State of the art

This section presents a definition of the main aspects and a review of studies that integrate the LCSA approach to building products and buildings, and the implementation of LCA-based method into BIM technology.

2.1 Life Cycle Sustainability Assessment (LCSA) approach

The Life Cycle Sustainability framework aims to integrate environmental, social, and economic dimensions of sustainability and to guide the decision-making towards a life cycle perspective [41]. It is based on the formula proposed by Klöpffer (2008) [42] which introduces the application of the three techniques: (Environmental) Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA). Guinée et al. [43] understand the LCSA as a "transdisciplinary framework for integration of models rather than a model in itself" [43]. The UNEP/SETAC Life Cycle Initiative to LCSA [44] recognizes that the three techniques are based on the ISO 14040 [10] and they have similar perspectives and aims (Phases 1, 2, 3 and 4).

Previous literature review [45] evidences that its application into building sector is still scarce. However, several examples have been detected and summarized in Table 1. An example of the application of LCSA to a building product (marble slabs) is performed in Capitano et al. [46]. The study determinates in parallel the environmental, economic and social impacts produced by two existing companies' producers of marble in the Sicilian region. The authors have collected and used primary data for the impact calculation [46]. The LCA includes five impact categories: Human Toxicity Potential; Acidification Potential; Eutrophication Potential; Photochemical Oxidation and Global Warming Potential [46]. The LCC includes: Costs of extraction and production, Fuel costs (diesel and natural gas), Waste disposal costs and Electricity costs [46]. The social impacts analyzed are: total employees, women in administration, immigrants, limited contracts, unlimited contracts, health insurance, annual health check and monthly salary of employee [46]. The results obtained are reported on a desegregated manner, presenting in parallel environmental, economic and social impacts. This is due to the fact that the authors aim to acquire a transparent procedure to support decision-making into a sustainability perspective [46].

Table 1. List of LCSA studies.

References	Year	Functional unit definition	Scope of the assessment Design /Product	Data sources
Capitano et al. [46]	2011	m^3 of marble	Existing product	Primary data
Dong et al. [47]	2016	building construction project	Existing product	Primary data
Hu et al. [41]	2013	ton of materials from the EOL building	Design stage	Generic data
Onat et al. [48]	2014	national level	Existing product	Primary data
Traverso et al. [49]	2012	1m^2 of modules	Existing product	Primary data
Zheng et al. [50]	2019	1-km long pavement with one- lane (3.5mwidth)	Existing product	Primary data – secondary data

Analyzing previous studies in this field [41,46–50], one of the main barriers over the application of LCSA to buildings and building products are related to the data collection, especially for economic and social aspects. Moreover, limitations on the definition of a common functional unit for the three methods is highlighted by Zheng et al. [50]. The study considers that the "social impacts are assessed using management behavior, rather than physical quantities", due to that social impacts are not linked to the functional unit. Most of case studies [41,46–50] are based on existing products or buildings, extracted from site-specific sources (local companies or suppliers). This means that the application of LCSA requires additional efforts in data acquisition. Thus, Dong et al. [47] underline that in spite of LCSA being a relatively new technique, the S-LCA is especially the most limited part of the method. Specific research on S-LCA [51,52] underlines the difficulties on data availability about social impacts. Moreover, there is no consensus on the specific or consistent S-LCA method [52]. Regarding detected difficulties, Guinée et al. [53] highline the need to develop quantitative and practical indicators for S-LCA.

Another difficulty was found over the communication of results and the effective integration of environmental, economic and social impacts in the assessment process. Difficulties on weighting and calibrating indicators in order to support the decision-making stages have been identified in [46–50]. Moreover, it is concluded that the use of LCSA frameworks is still infrequent in building sector, especially focused on guiding the design stages and assessing scenarios for sustainability. Most case studies [46–50], based the LCSA application on existing products or buildings, excepting Hu et al. [41]. Considering this context, the development of tools and methods focusing on design stages of buildings is becoming an opportunity. However, this type of tools should deal with uncertainty, underlined by Guinée et al. [53] as one of the three most crucial challenges to be addressed by the LCSA, along with variability and the feasibility to obtain reliable results.

2.2 BIM methodology and LCA integration

During the design stages of buildings, it is expected that the BIM methodology can integrate a great amount of information about the building, guide designers on a user-friendly way, and reduce time and effort during design process. Regarding the integration of LCA and BIM, it is expected to be automatic, user-friendly, useful during the design stages, and provide reliable results [38]. Considering previous research on this field [38], it may be concluded that one of the most relevant challenges of the integration of life cycle perspective into BIM methodology is the interoperability [25]. This means that the ideal workflow should provide the most automatic interaction between the BIM model and the data about environmental, economic and social impacts. Several examples on how it can be conducted are detected. Röck et al. [31], for example, to calculate embodied environmental impacts, solved the link LCA and BIM as a simple product between the total area of building element obtained from the BIM model and the environmental impact values from the LCA database. Soust-Verdaguer et al. [54] proposed a BIM-based LCA method to compare the environmental performance of envelope alternatives during the life cycle. The workflow is based on integrating the automatic bill of quantities (extracted from the BIM model) with various documents of supplementary data, before conducting the environmental impact calculation. Furthermore, Shin et al [24], to conduct simultaneously LCA and LCCA during design stages, required several design documents to conduct the existing two-dimension-based quantity calculations. The authors evidenced that the process requires a large amount of time and errors occasionally result [24]. Case studies analysis conclude that the more complete and complex data structure and information provide, the more difficult to automatize the integration of LCA and BIM.

Table 2. List of LCA-based studies integrated in BIM technology.

References	Year	Design stage	TBL (environmental, economic, social) dimensions of sustainability
Basbagill et al. [34]	2013	Early design stage	Environmental
Peng [55]	2014	Detailed stage	Environmental
Röck et al. [31]	2018	Early design stage	Environmental
Shin et al. [24]	2015	Detailed stage	Environmental and Economic
Santos et al. [56]	2019	Early design stage and Detailed stage	Environmental and Economic
Soust-Verdaguer et al. [54]	2018	Detailed stage	Environmental

Previous research on this field [38] recognized that one of the most important uses of BIM models in the LCA application is to obtain the bill of material quantities. This means that exists a direct relation between the material quantification of the building and the environmental impacts that those materials and process produce. However, regarding the integration of social aspects other difficulties are identified. Specific S-LCA literature [51] recognizes that one of the most relevant difference between LCA and S-LCA is that LCA mainly focuses on collecting physical aspects of a product, and the S-LCA needs to collect additional information about organizations aspects along the chain of production.

Moreover, literature review (see Table 2) evidences the scarce existence of tools or methods, that develop LCA-based studies integrated in BIM technology, nor based on "triple approach" (environmental, social and economic) neither based on the quantification of impacts produced by buildings during their life cycle, that can be used to guide decision-making during the design stages. Considering detected gaps on literature, this paper presents the first steps towards the definition of a conceptual framework based on LCSA of buildings integrated to BIM methodology. The paper proposes methodological considerations to use BIM models to conduct LCSA, by combining LCA, LCC and S-LCA methods.

3. Description of the method

This section aims to provide a general description of the main methodological aspects to be considered to conduct LCSA during design stages of buildings, and a possible workflow. It also aims to identify the main difficulties and challenges towards the interaction of LCSA into BIM methodology.

3.1. Methodological considerations in LCSA

The proposed conceptual method was based on UNEP/SETAC Life Cycle Initiative to LCSA [44], which includes the ISO 14040 phases (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation. The approach also complies with the standards on environmental, economic and social assessment of buildings ISO 21931-1[57] and ISO 21931- 2 [58], LCA of buildings EN 15978 [9] and EN 15804 [59], LCC of buildings ISO 15686-5 [60] and UNEP/SETAC Guidelines of S-LCA [51].

Goal and scope definition: Considering previous research on this field [49], the proposed LCSA approach integrated the implementation in parallel of the three methods (LCA, LCC and S-LCA). The use of a "common goal and scope" [44] was proposed. The method considered the UNEP/SETAC recommendation for the definition of a functional unit and the system boundary definition. The functional unit was performed describing the technical utility of the product and the product's social utility [44]. The system boundary comprised relevant unit processes, at least for one of the methods (LCA, LCC, S-LCA) [44].

Life Cycle Inventory: The inventory analysis phase was supported using the BIM model and the interaction of environmental, economic and social data about the building. Following the recommendations of UNEP/SETAC [44] the LCI "compiles exchanges between unit processes and organizations of the product system and the external environment which lead to environmental, economic and social impacts". Thus, it was suggested that the "unit process" has a direct correlation between environmental, economic and social aspects, such as shown in Figure 1.

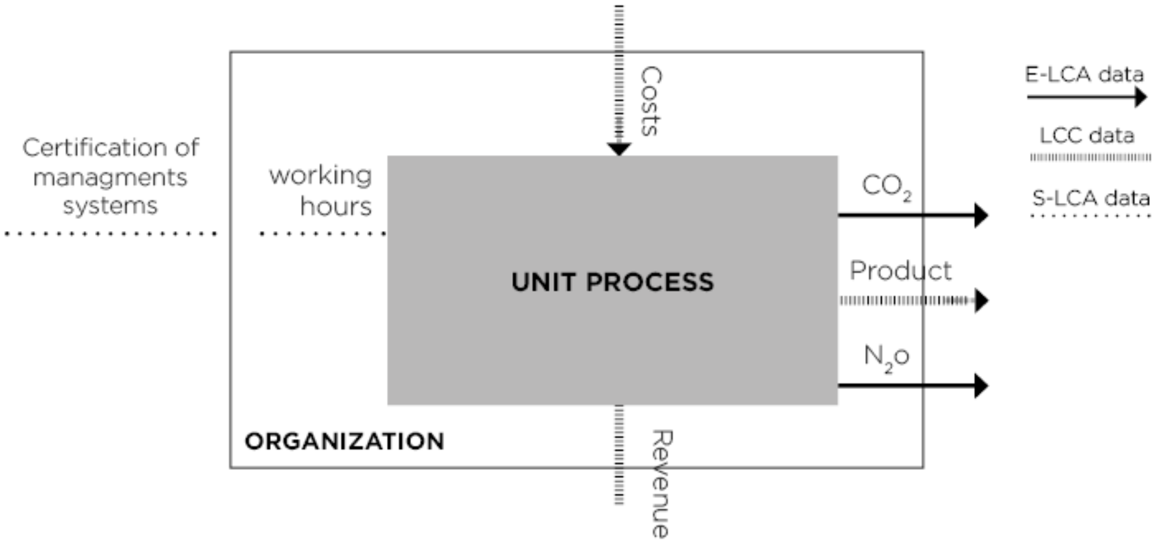

Figure 1 Scheme of the interaction of environmental, economic and social aspects of unit process. (Source: based on [22]).

Life cycle Impact Calculation: The classification and characterization steps were developed following UNEP/SETAC [44] recommendations. Thus, to deal with possible differences in characterization models of impact categories and impacted environments, a combined framework for impact assessment based on the individual S-LCA, LCC and LCA was performed [44].

Interpretation: The method follows the UNEP/SETAC [44] recommendation of combining environmental, economic and social aspects. This strategy can provide designers a sustainable assessment of the building and help decision-making during design stages.

3.2. BIM model to LCSA

The present conceptual framework aims to get the most out of the BIM model (geometry and information) to conduct the LCSA calculation, in order to reduce user manually entering data and reduce effort in data acquisition. Regarding that one of the underlined limitations of BIM to conduct LCA is the limited database [55], the proposed structure integrates a *TBL / sustainability* database about the building with the BIM model. It was founded on previous research [54,61–63] based on the integration of LCA into BIM methodology and the design process of buildings in BIM.

3.2.1 Phases of the method. Following, a possible three steps workflow (see Figure 2) to conduct a LCSA linked to BIM methodology is presented.

Step 1: BIM model. The proposed method started by defining the template, which "helps designers to derive standardized information and outcomes in a consistent work environment" [64]. This step aimed to provide a reliable and normalized structure to build up the BIM model. This step also aimed to provide designers the possibility to integrate different alternatives or scenarios in the model.

Step 2: **LCSA calculation.** This stage was based on the **interaction** between the **normalized BIM model** with *TBL / sustainability* database, which contains the environmental, economic and social impacts data following the Guidelines of LCSA [44] (Figure 1).

Step 3: Communication of results. This step was focused on the visualization of results, according to a normalized structure which aims to organize results and help designers to optimize the model. To provide an automatic optimization of the BIM model, a simultaneous interaction between the first step and the last one was performed.

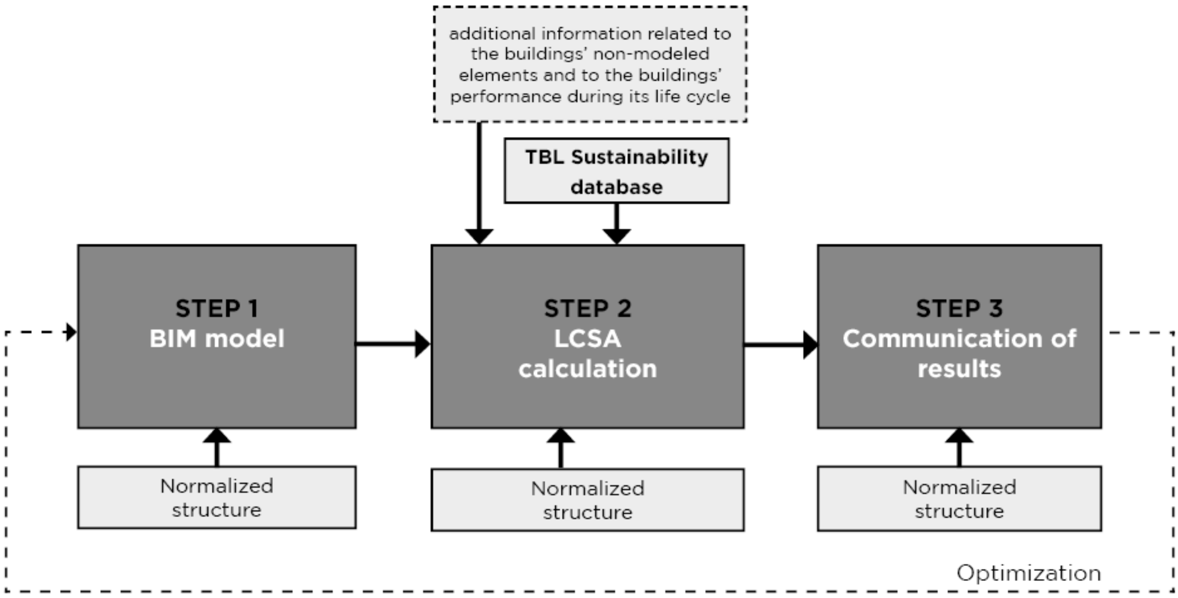

Figure 2. Scheme of the proposed workflow.

4. Discussion

From the literature review and the proposed framework, the following limitations, challenges and resulting research gaps have been detected.

4.1 Limitations on conducting LCI and LCIA

Regarding the integration of the BIM model (bill of quantities) and the implementation of LCI using the structure based on the LCSA unit process approach (Figure 1), it can be problematic in the terms described by Hu et al. [41]. The correlation between environmental, economic and social dimensions of the unit process can neither be linked with the unit process nor with the functional unit [41]. Hu et al. [41] underline that not all the costs (e.g. overhead, profit and loss) can be directly linked with the unit process as well as the qualitative SLCA indicators. The incapability to link the S-LCA assessment to the functional unit is also discussed in the S-LCA specific literature [52]. A possible solution to address the underlined difficulty could be to limit the use of the unit process and the selection of indicators to those that can be integrated in the triple approach (environmental, social and economic), and verified for the case of building design.

4.1.1 Data availability and design-oriented benchmarks. The lack of available S-LCA data is an underlined limitation [47]. Dong et al. [47] propose as a possible solution, to establish a sector-based database of S-LCA, to collect primary data. Moreover, it is also noted that the emerging use of this type of sustainable assessment tools and methods (integrating environmental, economic and social dimensions) can be a powerful tool to improve the performance of buildings, thus the development of benchmarks for guiding designers is recommended. Recent research [116] examines the need of benchmarks and reference values to guide and support decision-making on building design stages. In this sense, the present method also considered the integration of benchmarks and reference values adapted to regional and national scenarios.

4.1.2 Communication of results. The difficulties of integrating environmental, economic, and social aspects in the communication of results were detected. Finkbeiner et al. [65] underline that LCSA requires appropriated multi-criteria evaluation strategies. Life Cycle Sustainability Triangle and the Life Cycle Sustainability Dashboard are proposed as approaches to address this challenge [65]. Thus, it is needed to verify them into building design stages. It is also needed to establish effective strategies focused on helping designer during decision-making.

5. Conclusions

This paper presented the first steps towards the development of a method to automatically perform LCSA calculations during design stages and that uses the potentialities of the BIM methodology to quantify and reduce environmental, economic and social impacts of buildings. In future work, this LCSA framework will be verified in building applications, in order to determine its accuracy and reliability for decisions-making during building design stages.

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Digitalization of building LCA and international activities – in the context of German assessment system for sustainable building

Brockmann T

Head of Division II Construction and Environment, Federal Institute for research on Building, Urban Affairs and Spatial Development BBSR, Germany

tanja.brockmann@bbr.bund.de

Abstract. In this paper it is shown how digitalization and the establishment of an online infrastructure for life cycle assessment (LCA) in the context of the assessment system for sustainable building (BNB) by the German government forms starting point for an open international data network, as brought forward by the activities of InData ("International Open Data Network for Sustainable Building"). The establishment of the ILCD+EPD data format for EPD, the provision of interfaces, the development of workflow structures, guidelines and rules, which are openly published, internationally allow to access data from several databases. All these aspects are subject of the InData activities, and are decisive for a harmonization of LCA for sustainable building. With this concept of digitalization the propagation of the use of environmental product declarations (EPD) in building LCA was enhanced, and also new applications for using EPD data are offered, e.g. in BIM or other context.

1. Introduction

Nowadays the climate change is widely recognized. It is the motivation for manifold international, European, and national policy strategies regarding CO2-reduction, energy and resource efficiency, all of these are aspects of sustainability. As a consequence, building certification systems for sustainable building have been established worldwide (Figure 1).

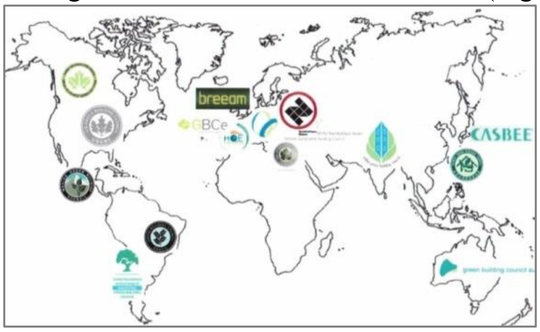


Figure 1: Building certification schemes for sustainable building worldwide.

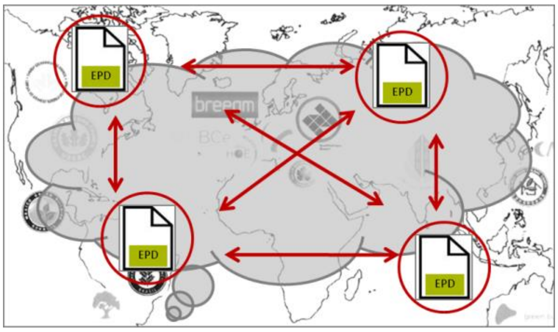


Figure 2. Integrated communication of EPD data via digitalization.

In Germany, Sustainable Building is part of the National Sustainability Strategy with the Guideline for Sustainable Building and the Assessment System for Sustainable Building (BNB) being most essential for the construction sector. The government takes the responsibility and brings forward sustainability by establishing BNB as a binding instrument for federal buildings. All information and tools are offered with a high transparency in order to diminish barriers. Political programs and support is considered as very helpful, also for the definition of responsibilities. Experience in Germany has shown that the centrally bundled provision of data and tools by the government is a valuable instrument for a wide application of LCA at building level and the realization of sustainable buildings.

2. BNB

The sustainability of a building under the BNB principles takes into account Ecological, Economic, and Socio-Cultural aspects in equal parts, additionally regarding Technical and Process Quality for buildings. Particularly with respect to ecological quality, that is, when considering the impact on the global environment, LCA forms an essential part of the overall assessment (Figure 3). The primary energy demand and effects of the building on the global warming, ozone depletion, photochemical ozone creation, acidification and eutrophication potential are determined, taking into account the life cycle over the chosen time period of 50 years.

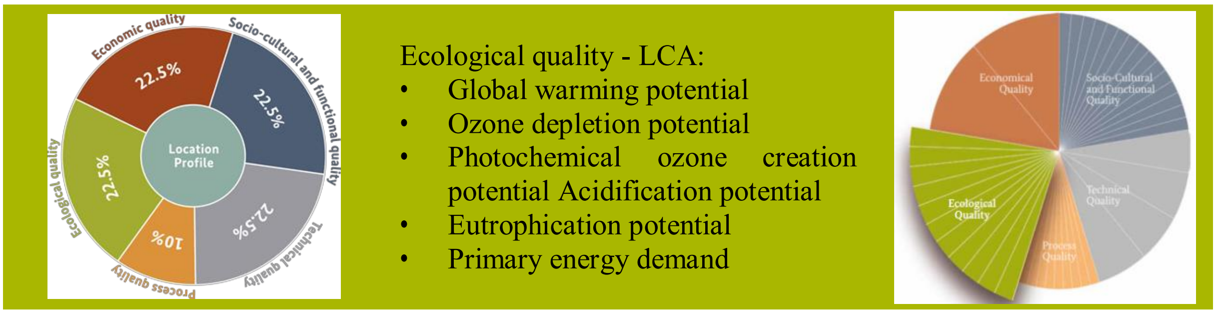


Figure 3. Considered dimensions of sustainability within BNB.

2.1. BNB tools

For choosing suitable building products and constructions BNB provides ÖKOBAUDAT with basic data for life cycle analysis at building level with the online tool eLCA. All provided tools are web-based, cost-free, open-source based, and publicly available; for all of them an English version (or other information) is given. The tools are initiated and maintained by the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR), a research Institution under the portfolio of the Federal Ministry of the Interior, Building and Community (BMI) [1, 2].

2.1.1. The ÖKOBAUDAT platform. It is a platform with data, information, and links related to the LCA of construction works. At the platform's core is the online database with LCA datasets on building materials, construction, transport, energy and disposal processes. ÖKOBAUDAT is provided already since 2009, and it is available for everybody interested in an ecological evaluation of buildings with a consistent database. Search- and filter-functionalities allow browsing relevant data for chosen materials or products directly in the online database.
Currently, ÖKOBAUDAT provides more than 1,200 datasets (about half of them are generic data) on all important construction product groups. Since 2013, it comprehensively meets the demands of European Standard EN 15804.
ÖKOBAUDAT data are used nationally and internationally by other certification schemes, LCA tools, BIM applications, or other. All ÖKOBAUDAT data are quality checked. The *ÖKOBAUDAT Manual* [6] contains technical and formal information on the ÖKOBAUDAT database.

2.1.2. eLCA software for building life cycle assessment. With the online tool eLCA the environmental effects of buildings can be easily determined taking into consideration the entire life cycle [7]. The basis is the calculation rules of BNB which are linked with the ÖKOBAUDAT data.
The core of eLCA is the component editor ("Bauteileditor"). The users can model their building

components in a very user friendly way. The dynamic graphic displays the building components with its material layers and enables the user to visually inspect the input data (Figure 4). The results can be directly compared with the benchmarks of BNB. eLCA presents the calculations transparently, and thereby enables detailed analysis of the results (Figure 5).

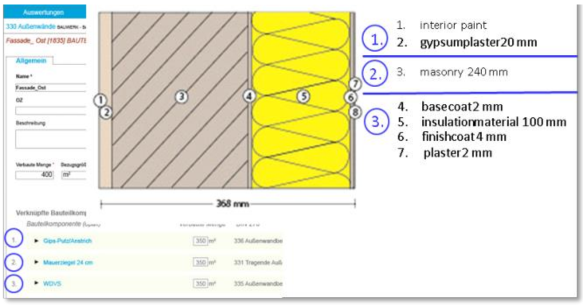


Figure 4. Dynamic graph – visual check input parameters.

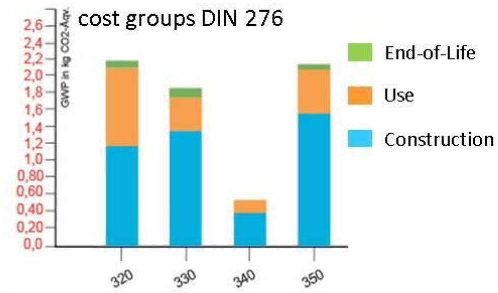


Figure 5. Analysis of eLCA results.

eLCA is a central instrument in the digitalization process as there is internal and external data transfer to and from the tool. Besides LCA, the instrument is used for other BNB criteria, like life cycle costing (LCC), transport calculations, and waste/recycling with digital data exchange.
It also imports building components from external software applications e.g. used for German (bindingly required) energy performance certificate for buildings ("Energieausweis"), and exports data/results to subsequently used applications.
Data transfer to/from BIM applications also is possible, and will be further developed in ongoing (research) projects.

3. Digital LCA infrastructure within German BNB

Reasons to digitalize the LCA infrastructure within the context of BNB were to improve all data related workflows, assure independency, and reduce cost for the production of building LCA.

In earlier stages ÖKOBAUDAT consisted of zip.files, and LCA sometimes was based on excel calculation routines. With a growing amount of data and data providers suitable workflows had to be developed. Also, the BMI/BBSR decided not only to offer online data transfer via ÖKOBAUDAT, but also to publish an independent building LCA calculation tool, eLCA.

Also, there already was the vision of an open international data network and to establish an integrated communication of EPD data and information. Standardized EPD were produced internationally, but due to the format (often pdf.file) they could not be used directly e.g. for LCA calculations.

A digital data format and interfaces were the precondition for these online structures. Within the digitalization process, most decisive was the development of a machine readable data format for EPD, i.e. the ILCD+EPD data format. This forms the basis for most other related activities.

3.1. LCA tool chain

BNB established a complete digitalized LCA 'tool chain'. It starts with the basic material data from EPD, which are imported in the online database ÖKOBAUDAT, exported from there to eLCA, which results are used for the final evaluation with bronze, silver, or gold sustainability certificate (Figure 6).

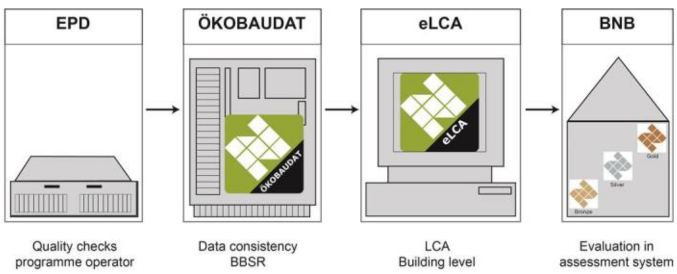


Figure 6. Digitalized tool chain LCA German BNB.

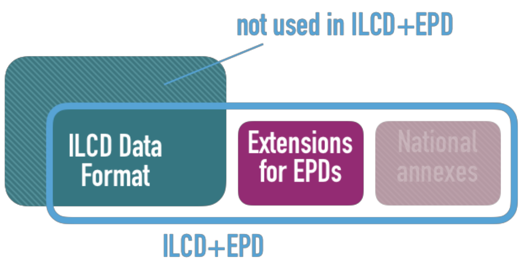


Figure 7. ILCD+EPD data format.

3.2. Technical Aspects
For a better understanding of the digitalized LCA structures the technical aspects are described.

3.2.1. Data format
The ILCD+EPD data format (short for 'ILCD data format with EPD extensions') is a technical means for transporting information associated with an EPD in a structured way. It is based on the established ILCD data format created by the European Commission [8]. It does not use the entire extent of the original ILCD format, but only those parts which are necessary and suitable for describing EPD data, complemented by additional EPD specific information that was not foreseen in the original ILCD format (Figure 7). The information is published in the *Table of Definitions ILD+EPD data format, CPEN2018* and corresponding *FAQ-document* [6]. The format structure allows for national annexes, where e.g. metadata can be integrated. Data format as in ÖKOBAUDAT is fully compatible with InData (Table 1).

3.2.2. Databases. In technical terms, the ÖKOBAUDAT database is based on the software soda4LCA [9].

3.2.3. Interfaces. The ÖKOBAUDAT is equipped with a standardized interface (API – application programming interface) for data exchange with other applications and software tools with the corresponding authorisations. The API documentation is provided in HTML and PDF formats in the zip.file *Developer documentation* [6].

3.2.4. Data supply for ÖKOBAUDAT. One of the decisive advantages of the digitalization is that now for all data providers an online data transfer into ÖKOBAUDAT is possible. There are essentially several ways of data import.

Import via EPD Editor
The currently published open source software, the EPD Editor [10], was developed on behalf of and financed substantially by BMI/BBSR. On the basis of existing EPD (e.g. pdf.format) with this software EPD datasets can be transformed/modelled in the ILCD+EPD data format with manual input, and then imported into ÖKOBAUDAT. A special feature of the tool is that datasets can be created in several languages and then offered in bi- or multilingual version. Currently the EPD programs ift Rosenheim, Bau EPD, kiwa, and Thünen Institut with representative average datasets, use the EPD Editor for data creation and transfer. For the *EPD-Editor manual* [6] and other support see website ÖKOBAUDAT/downloads.

Direct import via an interface
Data supplier can import their EPD/LCA datasets directly into ÖKOBAUDAT online from their database systems via the interface. Currently, the EPD program IBU and thinkstep with generic data use this option.

Validation tool
Before datasets are imported, which way ever, data providers must check their data with the validation tool [11]. Data are validated regarding data format, completeness, and product category allocation. The tool was developed for BNB and is regarded as highly user friendly and intuitive. It runs on a standalone, cross-platform basis. Instructions are given in *Technical Validation of datasets* [6].

3.3. Data quality management - ÖKOBAUDAT

While EPD programs publish several EPD types, e.g. differing in referenced standards (EN 15804, ISO 21930) [3, 4], background database (Gabi, ecoinvent), and depth of information (core EPD, program EPD), addressed location etc., the specific aim of ÖKOBAUDAT is the provision of data for building LCA. The results are related to benchmarks and are used for evaluation and comparison within certification schemes. For this application a high level of data quality and consistency is decisive. Therefore, the data quality management is an essential part of the LCA infrastructure. It comprises requirements regarding data format **and** data quality, in terms of EPD programs, processes and workflows.

3.3.1. Process of data acceptance. The process of data acceptance is as follows:
1. Send *Application form* [6] including self-declaration about compliance with requirements
2. Check of data provider (program and provided documents) by BMI/BBSR
3. Approval of data provider
4. Data supply to inbox of ÖKOBAUDAT
5. Plausibility checks (e. g. sample testing of data)
6. Full approval (data provider + data)
7. Publication of data in ÖKOBAUDAT

3.3.2. Requirements data provider. To ensure data quality in ÖKOBAUDAT, the data providers are checked in terms of meeting the requirements. Hence, they are asked to provide the following information / documents:
- Self-declaration stating conformity with relevant standards (e.g. EN 15804) and *Principles for acceptance of LCA data in ÖKOBAUDAT* [6]
- Access to program rules and PCR documents
- List of the members of the PCR review panel
- List of verifiers, description of the requirements for the verifiers and verification process
- Consent of the owner of the datasets for use in ÖKOBAUDAT

3.3.3. Requirements data format. To ensure compliance with the data format the following criteria need to be regarded:
- Delivery of data in ILCD+EPD data format
- Use of validation tool before data delivery
- Delivery of data for plausibility checks (sample testing)
- Validity of data

3.3.4. Quality aspects eLCA

The eLCA calculations are in line with quality assurance as the application of eLCA offers high transparency and consistency of calculations. Pre-configurations of data (e. g. if EPD datasets only offer production phase information, i.e. modules A1-A3, datasets for use phase and end-of-life scenarios need to be assigned), construction element templates, frontend for data input, and graphic presentation of results contribute to quality. Also, interfaces allow using synergies by importing building components from other (energy) calculation software, which also minimizes sources of errors by avoiding manual data input. Another aspect is ongoing optimisation by users' feedback.

3.4. BIM

As already mentioned data format and digitalized LCA structures allow to connect with BIM applications. BMI/BBSR currently is analysing suitable workflows, and further developments in ongoing (research) projects. As BNB has to be applied for federal buildings in general, relevant developments need to be aligned. As a public institution usually predominantly open source and regulations applicable for all stakeholders will be supported. BBSR is involved in national and international standardization works regarding BIM. As being part of InData which co-operates with

ECO platform, which both aim at digitalization and use of EPD for BIM, BBSR will support international harmonization of these processes.

4. International activities

International activities of BMI/BBSR aim at supporting sustainable building. For this reason, it is involved in national and international standardization works. It organizes sessions during (SBE and WSBE) conferences. In respect to building LCA, from beginning on, there was the vision of digitalization for an integrated international communication of data and information to enhance application of building LCA (Figure 2). This is an important motivation for the engagement in InData.

4.1. InData

InData was initiated after important talks/sessions at WSBE 2014 in Barcelona, and is chaired by the BBSR. The mission of InData is to establish an open web based international data network structure for EPD/LCA data using a common data format and open source software, as formulated in the *Decalogue* [6]. Within this network, data for specific purposes shall be identified by filters and easily implemented in applications. InData is an informal, non-profit working group of interested stakeholders who support the stipulated mission. It aims at establishing best practice for providing digitalized EPD as a quality source of verified EPD/LCA data for BIM, as for building LCA and other relevant applications.
With the participating members it represents important EPD programs and covers a significant amount of EPD (Figure 9). From 2014 with about 1,000 globally registered EN 15804 conform EPD it grew to about 6,000 in January 2019 [12]. With this, the interest in using digitalized structures is growing. Another reason for interest in InData is the growing amount of BIM applications in the construction sector which implies a strong demand to connect EPD data with BIM based building models. As InData is offering a platform for developing digitalization and harmonized structures, more stakeholders get involved. Starting with 6, now 12 nations are involved.

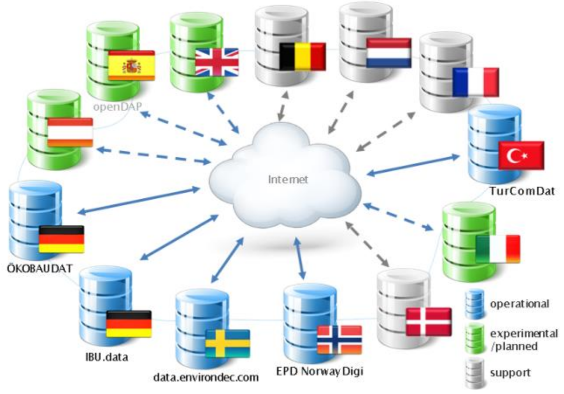
4.1.1. Open Network. InData bases its activities on the already existing ILCD+EPD data format, as this offers a high flexibility for possible adaptions, and allows open access to data, while maintaining individual ownership. Anyhow, the use and development of the format as such is to be seen independent.
The idea of InData is to represent defined data quality and consistency. Thus, it decided to define a InData compliance. Within the open data network only InData compliant data will be published. This means that most participants probably will only share certain parts of their databases within the InData network, (e.g. only English is compliant). Only those members who commit (by self-declaration) to meet InData compliance will be allowed to share data within the InData network.

4.1.2. InData compliance. InData compliance comprises common commitment about the data format **and** rules. Currently, it refers to construction products and European Standard EN 15804 (CPEN2018), but it is flexible for development and definitions of compliance for other products and standards. Actually, InData already is defining a compliance level for the amendment EN15804:A2. [5].

a) *Technical*
   In Data defined a common core of information, i.e. the list of addressed elements of the data format, the definition and explanations of these, and stating mandatory data fields (Table 1). These commitments of harmonization between the international stakeholders are published in the *Table of Definitions ILD+EPD data format, CPEN2018* and corresponding *FAQ-document* [6].
b) *Compliance Rules*
   The compliance rules *InData compliance – core rules and requirements* [6] address the data quality, which is mainly used in the sense “fitness for purpose”. With a high transparency and

given information about the delivered data the users will be enabled to filter the adequate data for their specific purposes. Anyhow, common basic rules are described, for EPD data (data format, standard EN 15804, verification, language, validity of data, product category structure, background databases, life cycle modules, and scenarios), data providers (responsibility on datasets, acceptance criteria, validation of data), and EPD programme operators (e. g. verification aspects).

4.1.3. Currently in use. Following BMI/BBSR with ÖKOBAUDAT, InData participants brought ideas to practice and now, are ready to contribute to the data network: IBU Germany with IBU.data, EPD International Europe with data.environdec.com, Metsims Turkey with TurComDat, and EPD Norge Norway with EPD-Norge Digi (Figure 8). It is a great success that these stakeholders were able to set up these databases structures on basis of the openly published information and the given open source structures, with only very little additional support from experienced experts. Further stakeholders are currently setting up further databases and corresponding structures.



InData = member, permanent guest, interested stakeholder.

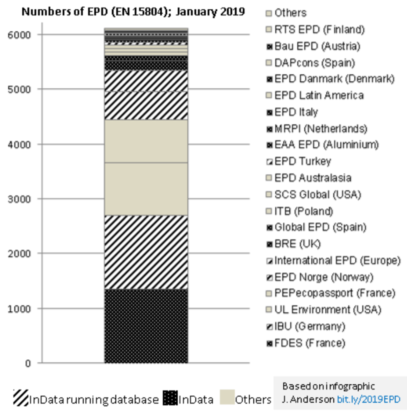
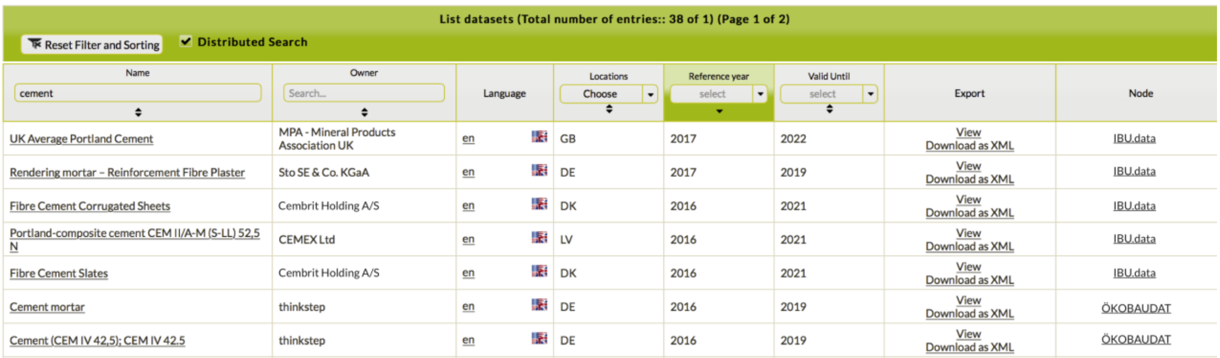


Figure 8. InData Network - participating stakeholders. **Figure 9.** Represented EPD by InData.

4.1.4. Website. The InData website offers general information about InData, but the core element will be the browsing of InData compliant data, offered by the participating international stakeholders. Data and technical structure are ready for the publication of the data. As compliance rules are still on the way, the data will be published in a next step, after approval of these rules. Then, the data will be accessible in a table with user friendly search and filter functionalities (Figure 10).

Search results License conditions of the individual data providers apply. Data resale prohibited



List datasets (Total number of entries:: 38 of 1) (Page 1 of 2)

Reset Filter and Sorting ✔ Distributed Search

Name	Owner	Language	Locations	Reference year	Valid Until	Export	Node
cement	Search...		Choose	select	select		
UK Average Portland Cement	MPA - Mineral Products Association UK	en	GB	2017	2022	View Download as XML	IBU.data
Rendering mortar – Reinforcement Fibre Plaster	Sto SE & Co. KGaA	en	DE	2017	2019	View Download as XML	IBU.data
Fibre Cement Corrugated Sheets	Cembrit Holding A/S	en	DK	2016	2021	View Download as XML	IBU.data
Portland-composite cement CEM II/A-M (S-LL) 52,5 N	CEMEX Ltd	en	LV	2016	2021	View Download as XML	IBU.data
Fibre Cement Slates	Cembrit Holding A/S	en	DK	2016	2021	View Download as XML	IBU.data
Cement mortar	thinkstep	en	DE	2016	2019	View Download as XML	ÖKOBAUDAT
Cement (CEM IV 42,5); CEM IV 42.5	thinkstep	en	DE	2016	2019	View Download as XML	ÖKOBAUDAT

Figure 10. Screenshot browsing in InData network with search and filter functionalities (preview)

4.1.5. International co-operations. As InData committed to base its activities on already existing methods and standards it co-operates with ECO platform, the umbrella organization for EPD program operators. ECO platform offers a coherent framework, and it harmonizes activities on EPD, like e. g.

verification procedures and other processes. Harmonized rules will be regarded within InData. Also, ECO platform support InData with digitalization and thus, use of EPD for BIM and other applications. Exchange of both initiatives is given by joint international meetings.

5. Summary and Outlook

With establishing the digital infrastructure for building LCA the German government offered the basis and starting point for international activities which support the propagation of sustainability in the construction sector. The open access to quality-checked data and tools diminishes barriers and enhances harmonization. Decisive was the digitalized EPD format ILCD+EPD. Workflows, tools, user friendly features, and rules are further developed and enhanced continuously within multi-lateral co-operations, nationally and internationally. Digitalization not only improves quality, but also it allows for manifold further developments in future, especially as being open source based. Further developments for the optimization and use for BIM will be the issues in the coming working process, at national and international level. Anyhow, the participation and provision of already running databases according to offered data format and open source structures is considered as a great access for both, German LCA infrastructure as a national forerunner, and InData initiative as an international platform, and distributor of the ideas.

Acknowledgements

The mentioned developments were carried out in research projects within the research program Zukunft Bau run by BMI, in which amongst others, thinkstep, IBO, KIT, greendelta, okworx, and Online Now!, were involved. Especially to acknowledge are the valuable contributions to this paper by Hildegund Figl (IBO), and Oliver Kusche (okworx).

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Table 1. ILCD+EPD data format (m = mandatory field InData compliance CPEN2018)

Field name (EN)
Process information
Key data set information
UUID of data set^{m}
Name^{m}
Classification^{m}
General comment on data set
Data set LCA report, background information
Generic data uncertainty loads
Description of generic data uncertainty loads
Scenarios
Scenario
Name
Default
Group
Description
Modules
Module
Name
Product system ID
Quantitative reference
Reference flow(s)^{m}
Functional unit, production period, or other parameter
Time representativeness
Reference year^{m}
Data set valid until^{m}
Time representativeness description
Geographical representativeness
Location^{m}
Geographical representativeness description
Technological representativeness
Technology description including background system^{m}
Technical purpose of product or process^{m}
Pictogram of technology
Flow diagramm(s) or picture(s)
Modelling and validation
LCA methodology report^{m}
Subtype^{m}
Data sources, treatment, and representativeness
Data sources used for this data set^{m}
Use advice for data set^{m}
Validation
Type of review^{m}
Review details
Reviewer name and institution
Complete review report
Compliance declarations
Compliance system name^{m}
Administrative information
Data entry
Time stamp (last saved)^{m}
Data set format(s)^{m}
Data entry by
Publication and ownership
Date of last revision
Data set version^{m}
Issuer^{m}
Registration number^{m}
Owner of data set^{m}
Copyright^{m}
Exchanges
LCIA results
Indicator^{m}
Module/Phase^{m}
Scenario
Value^{m}
Unit^{m}
Material properties^{m}
Environmental indicators
Indicators of life cycle
Use of renewable primary energy (PERE)^{m}
Use of renew. primary energy resources as raw materials (PERM)^{m}
Total use of renewable primary energy (PERT)^{m}
Use of non-renewable primary energy (PENRE)^{m}
Use non-renewable primary energy as raw materials PENRM)^{m}
Total use of non-renewable primary energy resource (PENRT)^{m}
Use of secondary material (SM)^{m}
Use of renewable secondary fuels (RSF)^{m}
Use of non-renewable secondary fuels (NRSF)^{m}
Use of net fresh water (FW)^{m}
Hazardous waste disposed (HWD)^{m}
Non harzardous waste dispose (NHWD)^{m}
Radioactive waste disposed (RWD)^{m}
Components for re-use (CRU)^{m}
Materials for recycling (MFR)^{m}
Materials for energy recovery (MER)^{m}
Exported electrical energy (EEE)^{m}
Exported thermal energy (EET)^{m}
Indicators of the impact assessment
Global warming potential (GWP)^{m}
Depletion potential of the stratospheric layer (ODP)^{m}
Formation potential of tropospheric ozone (POCP)^{m}
Acidification potential of soil and water (AP)^{m}
Eutrophication potential (EP)^{m}
Abiotic depletion potential for fossil resources (ADPfossil)^{m}
Abiotic depletion potential non-fossil resources (ADPnon-fossil)^{m}

Computer-aided supporting tool for LCA evaluation of energy efficiency of the buildings – assessment method and case studies

Domjan S, Arkar C, Medved S

Laboratory for Sustainable Technologies in Buildings, Faculty of Mechanical Engineering, University of Ljubljana, Aškerčeva 6, 1000 Ljubljana, Slovenia

suzana.domjan@fs.uni-lj.si

Abstract. In the paper methods and the development of computer tool for the comprehensive life cycle assessment evaluation of the new or renovated buildings is presented. To support decision making process, computer tool was developed and consists of two computational units: the building description unit (BDU), and the life cycle assessment tool (Etool). BDU enables the determination of energy needs and final energy demand for the operation of EPBD systems. For the purpose of environment impact assessment, the life cycle inventory database is integrated into the BDU. Data are exported to LCA evaluation tool E^{tool} that include two assessment modules: life cycle environmental impact module for mid-point and end-point assessment taking into account impact groups and damage factors from IMAPCT2002+ and ReCiPe methods and life cycle costs assessment module for evaluation of costs optimal values of energy efficiency measures for nearly zero energy buildings (nZEB). In the paper case studies are presented and discussed. The results show that energy use has dominant influence on buildings' environment impacts and that life cycle cost analysis show optimal thermal insulation thickness higher than required in current regulative.

1. Introduction

The Energy Performance of Building Directive (recast) (EPBD recast) [1] introduced targets for nearly Zero Energy Buildings (nZEB) in the form building minimum energy efficiency criteria. Directive also required that minimum energy efficiency criteria must be required in the way to be cost-effective. The experts involved in building planning and renovation encounter this challenging task in the early stage of planning. In addition to the relevant multidisciplinary knowledge on life cycle assessment (LCA), a simplified computational tool to verify the early phase decisions is needed to meet the requirements of EPBD [2]. Such computer tool is presented in this paper

2. LCEA, LCIA and LCCA computer tool structure

Computer tool for life cycle energy efficiency (LCEA), environment impact (LCIA) and life cycle cost assessment (LCCA) has two calculation units: the building description unit (BDU) and LCA evaluation unit (E^{tool}) as it is shown in Figure 1. The BDU is based on the national building labelling software tool KI Energija [3] developed by Knauf Insulation company and authors of the presented article, meanwhile the E^{tool} was custom made in MS Excel environment.

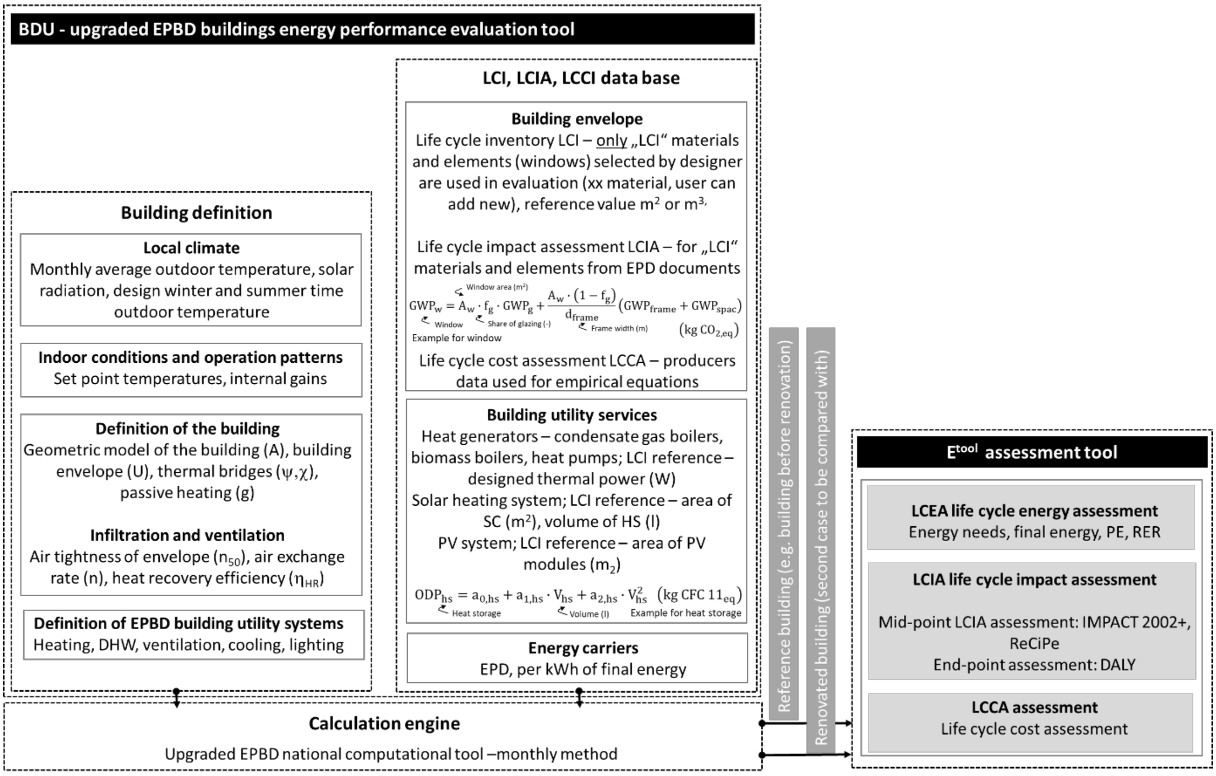

Figure 1. Structure and interactions between BDU (upgraded EPBD national certificated software tool) and life cycle assessment tool (E^{tool}).

2.1. *Upgrading the BDU for life cycle assessment*

EPBD evaluation software tool was upgraded by creating additional database files marked as “LCA” that includes life cycle inventory (LCI) data. If the designer chooses the material, the building structure or the building service system component from “LCA” database, additional inventory data for LCIA and LCCA is created in the BDU.

2.1.1. Life cycle energy assessment (LCEA). Monthly method is used for determination of energy needs for heating and cooling [4], [5], and other EPBD supporting standards were used for final and primary energy evaluation. Yearly value of energy demand is used to determine non-energy related variables such as emissions of pollutant equivalents or energy carriers’ costs.

2.1.2. Life cycle environment impact assessment (LCIA). The environment impact indicators were chosen according to the public available data sources. Because of that, basic indicators presented in Environment Product Declarations are used. Data from public open database like Ökobaudat [6], Environdec EPD Database [7], Eco-Platform [8] and IBU [9] and manufactures data (i.e. Knauf Insulation [10]) were used to create data that are integrated in the BDU. LCIA is performed in three phases – through classification, characterization and normalization. In the classification phase material and energy flows as well as emission of pollutants equivalents related to “LCA” marked building elements and energy carriers, are summarized during user selected assessment calculation period into seven pre-selected impact categories. Values are presented as physical quantities (e.g. kg, MJ). In the characterization phase sum of environmental impacts expressed by equivalents (e.g. AP or EP) are weighed by impact factors (e.g. global warming potential GWP_{100} of particular greenhouse gas) and classified into several damage categories. As most common used, damage categories included in IMPACT 2002+ [11], [12] and ReCiPe [13] method can be evaluated in E^{tool}. By normalization, impacts of analysed building (reference and designed one) are compared to the total environmental impacts in the reference system (e.g. European Union) and total impacts are normalized to total number of inhabitancies in the system (410×10^6 in EU). By grouping and weighting, end-point in form of single score environmental impact can be evaluated by Eco Points per year (PT/y). All indicators are presented in the way that show contribution of each group of "LCA" elements (energy carrier, materials, and building service systems).

2.1.3. Life cycle cost assessment (LCCA). The important requirement of the EPBD recast is that EC Member States must set minimum requirements for energy performance of buildings in such a way that a cost-optimal solutions are provided. In order to assess the cost-effectiveness of measures, life cycle cash flow is shown in E^{tool} determined by discounting costs and savings. Guidelines accompanying Commission Delegated Regulation [14] that suggested macroeconomic annual discount factor (3%) and predict the annual increase in energy carrier prices (2.8% for natural gas and light heating oil prices, 2% for coal and 9% increase of electricity price) for the period until 2030 were taken into account. Annual cost of maintenance of technical systems is assumed to be between 2% and 5% [15]. The residual value of the measures is determined on the basis of the expected lifetime of the measures [16].

2.2. *LCA evaluation tool E^{tool}*
Data determine in BDU needed for LCEA, LCIA and LCCA life cycle assessment are automatically transferred in form of inventory database to E^{tool} for two project, one of which is selected as a reference. Among others, E^{tool} display LCA metrics shown in Fig. 2 (LCEA), Fig. 3 (LCIA) and Fig. 4 (LCCA).

Figure 2. LCEA metrics displayed in E^{tool} shown nZEB indicators, energy carrier demand, embodied energy and emissions of greenhouse gasses; two project can be compared at the same time.

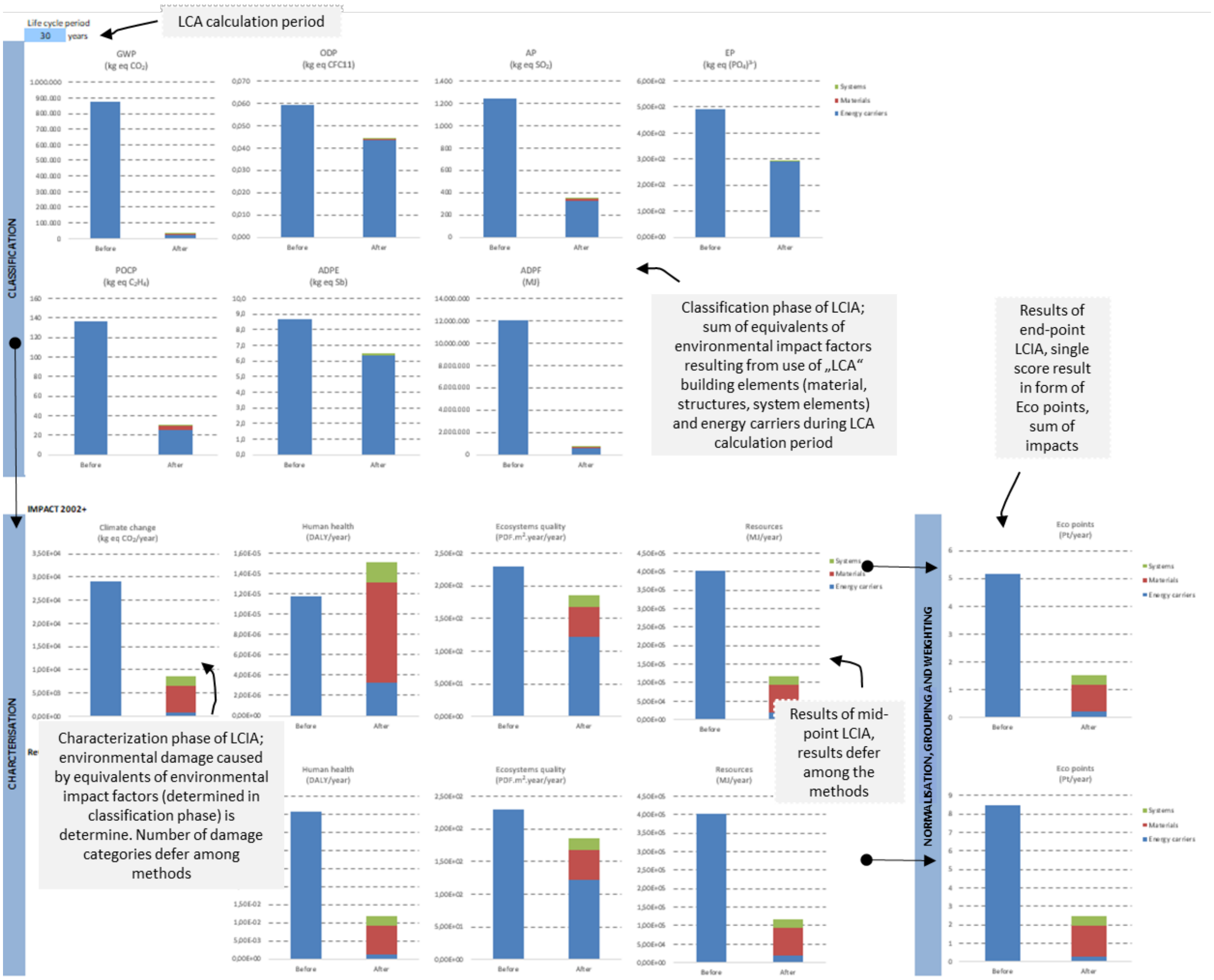

Figure 3. LCIA metrics displayed in E^{tool} as mid-point and end-point assessment.

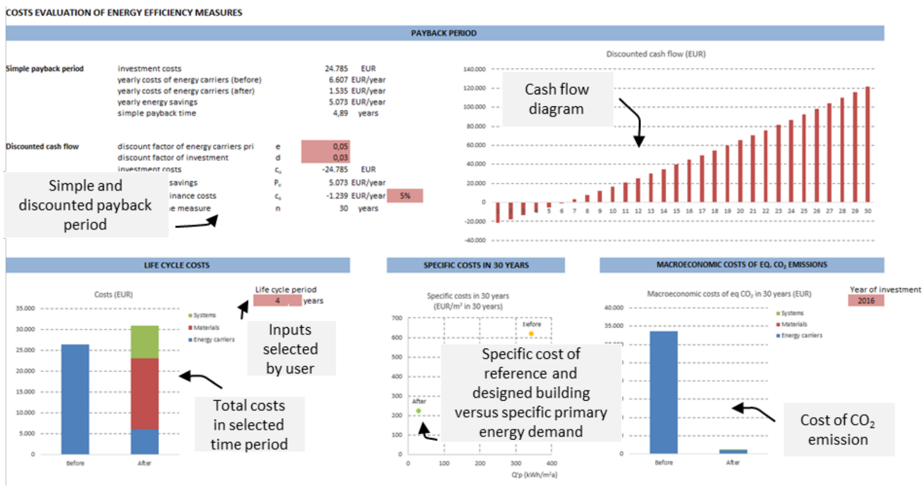

Figure 4. LCCA metrics displayed in E^{tool} showing cash flow diagram, LCC and cost of CO_2 emissions.

3. Study Cases

3.1. *An integrated assessment of the effects of energy retrofitting of a public building*

An example of an analysis of the energy retrofitting measures of a larger hospital in Ljubljana is presented (Fig. 5). The facility is heated by district heating system. District heat is also used for the DHW. Conditioned area of the building is 7405 m^2, energy needs for heating Q_{NH} 1.195,457 kWh/a and primary energy needed for operation of the building Q_p 1.865,362 kWh/a. Proposed and analysed measures are replacement of windows (U_w 3 W/m^{2}K → 1.1 W/m^{2}K), thermal insulation of the facade (U_{wall} 1.3 W/m^{2}K → 0.168 W/m^{2}K), and thermal insulation of the ceiling to unheated attic (U_{roof} 0.957 W/m^{2}K → 0.094 W/m^{2}K).

Figure 5. Hospital building in Ljubljana.

After the energy retrofitting, the specific energy needs for heating will be reduced by 75% (Q'_{NH} 161 kWh/m^{2}a → 39 kWh/m^{2}a), the final energy by 68% (Q'_f 220 kWh/m^{2}a → 70 kWh/m^{2}a) and the required primary energy for the operation of the building by 58% (Q'_p 252 kWh/m^{2}a → 107 kWh/m^{2}a). With a lower use of district heat (coal fired, 1,380 MWh/a to 320 MWh/a), CO_2 emissions will decrease by 345 tonnes per year, meanwhile emissions of $CO_{2,eq}$ will be lowered by 85 tonnes in the first year and by 270 tonnes every year after (Fig. 6).

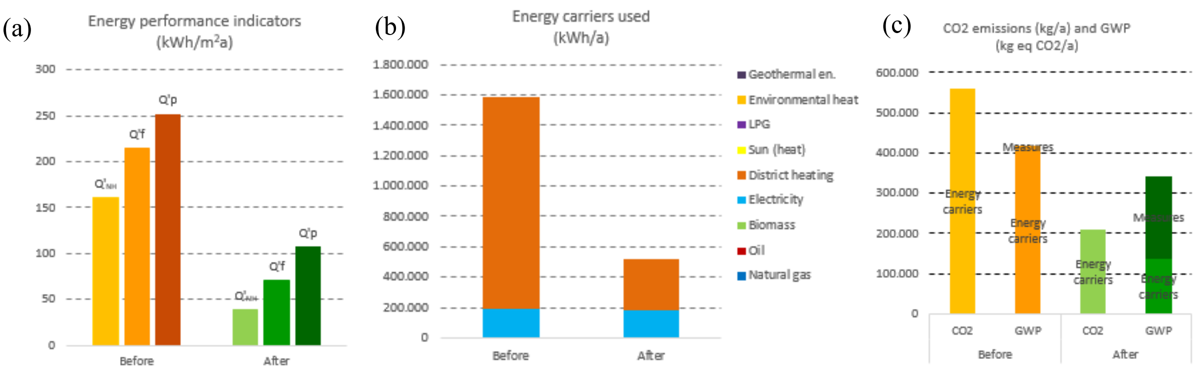

Figure 6. Results of LCEA: energy performance indicators (a), energy carriers (b) and CO_2 and GWP emissions (c) for reference project (before == existing) and retrofitted building (after).

The embodied energy of all energy efficiency measures (760 MWh) is lower than decried yearly energy demand (1040 MWh/a) for operation of the building indicating short "energy payback" period.

The operation of the reference building causes 0.58 DALY, while the retrofitted building will cause 0.48 DALY the first year, and 0.19 DALY/a in the following years. The number of Eco Points after retrofitting resulting from the use of energy carriers will be reduced from 68 Pt/a to 59 Pt/a in the first year and to 24 Pt/a in the rest of the calculation period. The investment payback time will, taking into account discount factors, d 3% and e 2.8%, and maintenance costs of approximately 0.5% per year, approximately 16 years. The cost of district heating and electricity for the operation of heating systems, DHW, ventilation and lighting will be reduced from the current 391 €/m^2 to 268 €/m^2 of the conditioned building area.

3.2. *Selecting technologies for nearly Zero Energy Building (nZEB)*

Passive reference building (A_u = 92 m^2, Q'_{NH} 11.9 kWh/m^{2}a) with pellet boiler and 600 l storage for heating and 300 l for DHW will be compared with following options: case 1: heat pump (A-W, 5 kW, heat storage 300 l), case 2: NG condensing boilers and solar heating system (SC 7.5 m^2, heat storage 300 l), case 3: NG condensing boiler for heating and DHW and 1.75 kW$_p$ grid connected PV power plant. Amount and structure of energy carriers is shown in Fig. 7.

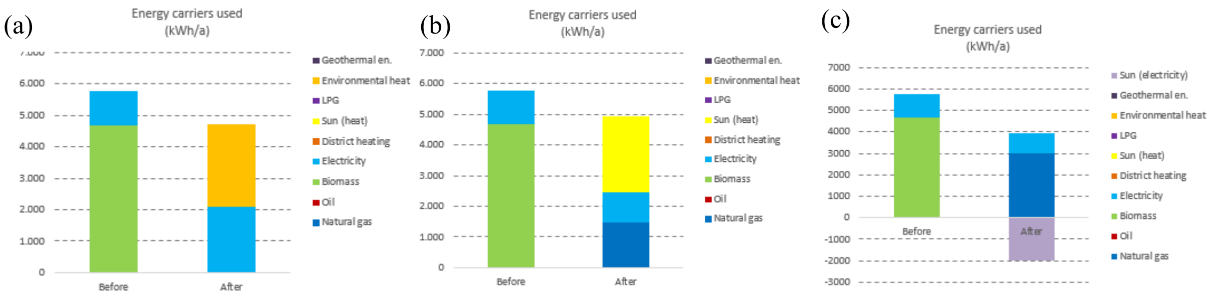

Figure 7. Amount and structure of energy carriers for reference case (before) and for the case 1 (a), the case 2 (b) and the case 3 (c).

Annual CO_2 emissions, calculated by the factors defined in Slovenian national legislation [17], are highest for the case 1 (1150 kg/a), and the lowest for the case 2 (750 kg/a). In all three cases, CO_2 emissions are higher than in reference case (as biomass is CO_2 neutral). Comparing GHG emissions (GWP) shown that the case 1 is the best solution due to the lower use of energy carriers and the high share of RES in the electricity mix in last years in Slovenia (Fig. 8).

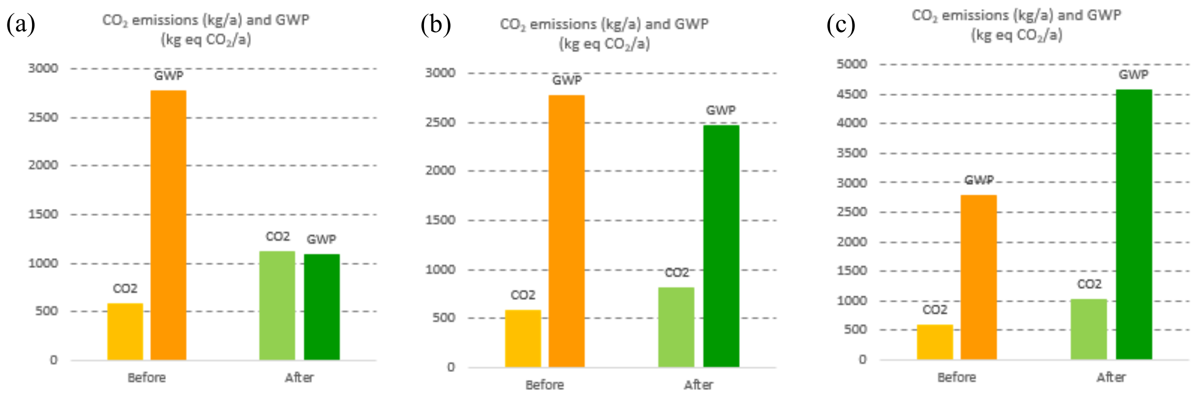

Figure 8. Annual CO_2 and GWP emissions for reference building, the case 1 (a), the case 2 (b) and the case 3 (c).

In comparison with the reference case (0.445 Pt/a), Eco Points in the first year of operation of the building would be more than a half lower for the case 1, approximately the same for the case 2 (0.425 Pt/a) and significantly higher for the case 3 (0.88 Pt/a), which is predominantly influenced by the environmental pressures caused by the use of materials and the production of system elements (Fig. 9). After the first year of operation, damage to the environment is caused only by the use of energy carriers, and the relationship between the cases is changing. The lowest number of Eco Points is typical for the reference case (0.075 Pt/a), the environmental impacts of the case 1 and the case 2 are quite similar (0.11 Pt/a, 0.12 Pt/a), while the number of Eco Points for the case 3 is almost doubled (0.19 Pt/a).

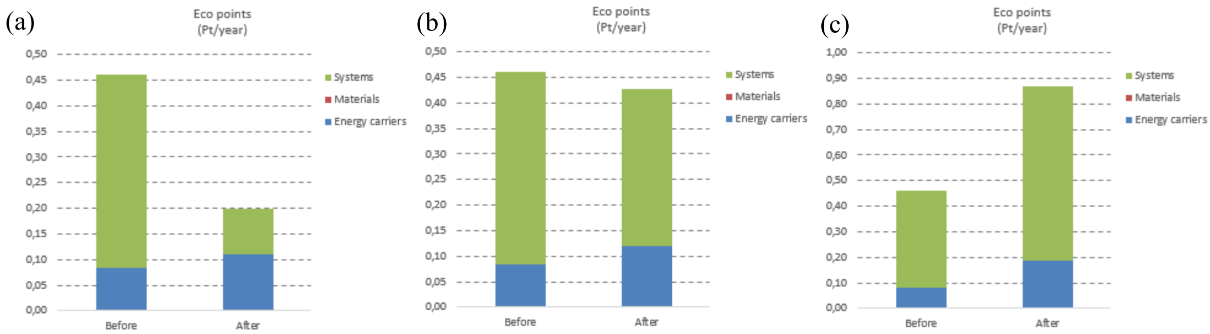

Figure 9. Eco points for the first year of operation for reference building and the case 1 (a), the case 2 (b) and the case 3 (c).

LCCA shown that costs are almost identical for the reference case (€ 18,200), the case 2 (€ 18,100) and the case 3 (€ 18,200), meanwhile life cycle costs are lower by 17% (€ 15,200) in case of the case 1. The total costs of the investment and the energy costs are roughly equal for the case 1 and 3, whereas for the case 2, the investment cost is 2/3 of the total cost of reference case over a 30-years period.

3.3. *Envelope energy retrofitting optimization of a multi-family building*

Study case of energy retrofitting of the envelope of multi-family building in Ljubljana with conditioned area of 1950 m^2 (Fig. 10). Building is connected to district heating system. As a reference project we took existing building, without thermal insulation and with old wooden frame windows (U_w = 3.0 W/m^{2}K). Energy needs for heating are 147.7 kWh/m^{2}a.

Figure 10. Multi-family building in Ljubljana.

Thermal insulation thickness was optimized on the basis of cost-effectiveness in the 30 years calculation period. The optimum thickness of 25 cm results in maximum specific cost saving 52 EUR per m^2 of useful area. Macroeconomic costs of $CO_{2,eq}$ emissions are lowest at much thicker thermal insulation layer, from which it follows that common practice to limit the grants with the thickness of the thermal insulation or with the U-value of the building structure is not adequate (Fig. 11a). LCA cost optimization of windows replacement shows that windows with double glazing are more cost effective and provide the same decrease in specific primary energy needed for the building operation (Fig. 11b). Macroeconomic greenhouse gas emissions costs indicator also gives priority to this technology.

(a) (b)

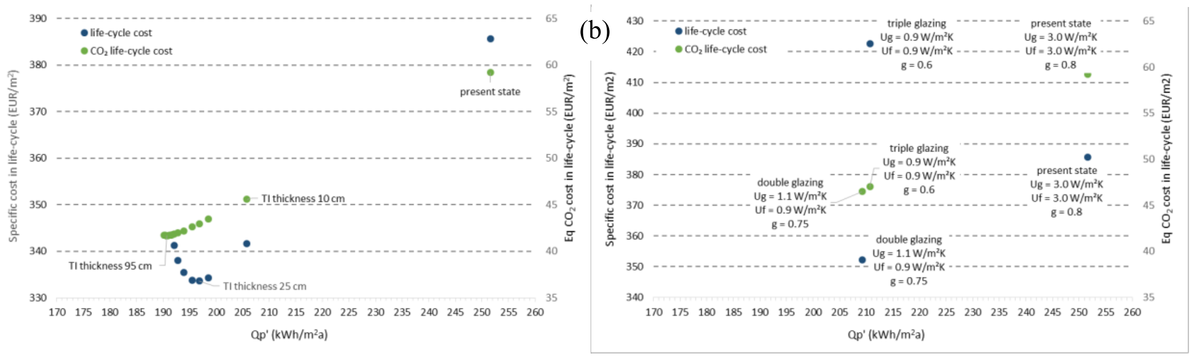

Figure 11. LCA thermal insulation thickness and window technology optimization on the basis of the life cycle specific costs.

4. Conclusions

Complex LCA evaluation computer tool was developed at the Laboratory for Sustainable Technologies in Buildings at the Faculty of mechanical Engineering (University of Ljubljana). Tool is divided into two connected units that enable life cycle energy efficiency (LCEA), environment impact (LCIA) and life cycle cost (LCCA) assessment. As life cycle environmental impacts assessment methods are not widely used, even sense of EPD is difficult to explain and number of assessment modules are more or less limited to A1-A3 and because life cycle assessment is accompanied by a number of prediction uncertainness, the authors of this article see the importance of a developed LCA computer tool primarily in education and learning assessment methods and sustainability of buildings. This is easier when methods are introduced through case studies and effect of the design decisions are promptly compared.

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Information management throughout the life cycle of buildings – Basics and new approaches such as blockchain

Ganter M[1,3], Lützkendorf T[2,3]

[1]Student, Karlsruhe Institute of Technology, Karlsruhe, Germany
[2]Head of Chair, Chair for Sustainable Management of Housing and Real Estate, Karlsruhe Institute of Technology, Karlsruhe, Germany
[3]Centre for Real Estate, Kaiserstraße 12, 76131 Karlsruhe, Germany

manuel.ganter@student.kit.edu

Abstract. Ensuring sustainability for real estate is subject - among other aspects - to building related information. This information needs to be stored and updated continuously throughout the life cycle of a building. A delivery to buyers, tenants, consultants or other actors must be possible at any time. However, in most cases transactions cause significant loss of information while the issues associated with the "building passport" approach remains unsolved to date. Considering the long service life of buildings, various questions arise: (1) How to support data generation and storage within the life cycle and how to encourage actors to compete? (2) How to assure a high data quality and how to store it over a long period of time? (3) How to assure that all data users can track down the data owners at any point of time to manage compliance and legal issues? (4) Are there any new business models or new scopes for designers or other service providers? Information needs of actors along the life cycle are analysed and new information technologies (e.g. blockchain) are discussed. A relation to Building Information Modeling (BIM) is shown. Potentials of enhancing existing approaches regarding documentation retracing and accessibility of building and life cycle related information by using new technologies and IT are discussed; benefits of using a blockchain based system is pointed out by referring to existing pilot projects and first examples. Solution approaches for building passports are shown.

1. Introduction

The implementation of principles of sustainable development in design, construction, and use of buildings requires that the economic, environmental, and social impacts of each decision are taken into account. This demands a reliable and comprehensible basis for decision-making. The collection, processing, interpretation, transformation and communication of suitable information that supports decision-making thus becomes an essential prerequisite. In particular, the increasing adoption of life cycle analysis with its quantitative methods of life cycle assessment and life cycle costing, which is used to support design and investment decisions, requires a considerable amount of data. This also applies to the economic valuation, risk assessment and due diligence of buildings, which incorporate sustainability aspects to a greater extent than in the past. This requires the exchange of information between actors, the configuration of information flows along the value chains, appropriate information management and the application and further development of data processing systems. Indeed, information forms an essential basis for decision-making, but also legal and economic consequences are associated with it.

The "value" of information is growing, as is the risk of dealing with false or incomplete information. At the same time, it is a special feature of buildings that information must be stored over long periods of time and partly updated or supplemented. This raises a number of questions: (1) How to support data generation and storage within the life cycle and how to encourage actors to compete? (2) How to assure a high data quality over a long period of time? (3) How to assure that all data users can track down the data owners at any point of time to clarify on compliance and legal issues? (4) Are there any new business models or new scopes for designers or other service providers. These questions are explored in the present article.

2. Current trends in the demand for building-related data

At present, several developments can be identified that will lead to an increase in the demand for building and life cycle related data. These are among others:

- The introduction of level(s) [1]: The European Commission (EC) has developed the basis for a reporting instrument which serves to present and communicate sustainability-relevant features and characteristics of buildings. This is currently being tested. Among other things, the instrument deals with the effects of sustainability-relevant features and characteristics on the value of real estate and its development as well as the associated risks. For the first time, through the introduction of an indicator dealing with value creation and risk factors – namely indicator 6.2 – an attempt is made "to provide information on the reliability of the underlying data and calculation methods on which a reported performance is based."[1] This points to the need for a transfer of information from sustainability assessment to valuation and risk analysis with simultaneous quality control.

- The development of a taxonomy to record and evaluate the contribution of real estate projects to sustainable development [2]: The EC has launched an initiative on "Sustainable Finance." One sub-aspect is "green finance". The aim is to channel financial resources towards projects that contribute to sustainable development, particularly in the area of climate protection and resource conservation. This implies that in future banks will need reliable information on whether and to what extent a to-be-build or to-be-renovated real estate has an above-average environmental performance for project financing. This is to be achieved by means of a taxonomy that summarizes sustainability-relevant information in a form that can be interpreted by banks.

- New approaches for the development of lifecycle-accompanying object documentation in the form of building passports or building files [3]: In a current Global ABC initiative, an attempt is once again being made to agree on a format for the collection, administration and communication of building data that is required during the lifecycle by owners, administrators, experts or third parties. This is a continuation of efforts, in some cases lasting decades, to introduce building passports, which have not yet led to a result so far.

- The results of BAMB [4]: One of the main proposals resulted from a recent research project funded by the EU is the documentation of the material composition of buildings in the form of material passports. Further research projects go in a similar direction. There is a close connection with the goals of a circular economy.

- New guideline for waste audits before demolition and renovation works of buildings [5]: The guideline plans the compilation of information on the type and quantity of materials used in the building and on recycling possibilities in preparation for dismantling or conversion work. This can be facilitated by taking over information from the design phase of buildings.

It becomes clear that the requirements for object data are currently growing, not only in terms of type and scope, but also in terms of quality, reliability and traceability. Thus, the following requirements for building- and life cycle-related data can be formulated. In particular, data should

a) meet the information needs of actors on selected occasions in the life cycle of buildings,
b) be extracted/processed to the extent possible from information already generated during design, construction and management processes in order to save time and money,
c) be permanently available - here in terms of lifecycle support -, including their history,
d) be updatable / overwritable and expandable, with the respective history,
e) be clearly assigned to a data source/author who vouches for the correctness of the information and assumes a corresponding liability,
f) be machine-readable / processable (e.g. BIM-compatible / BIM-able), and
g) be (globally) accessible when access conditions are met.

The listed requirements are important for different types of information. These are presented in Table 1 including a distinction between static and dynamically generated data.

Table 1. Selected types of information to manage in the life cycle of buildings (Lützkendorf)

Type of information	static	dynamic
Information on location and land	X	(x)
Excerpt from the land register	X	(x)
Approval documents (e.g. building permit)	X	(x)
Planning documents incl. drawings - new building/updated (a)	X	(x)
Image documentation		X
Expert reports (e.g. subsoil reports)	X	(x)
Participants in planning incl. contracts - New construction	X	
Participants in the execution incl. contracts - New construction	X	
Acceptance protocols and warranty periods - New construction	X	
Bill of materials – New construction/ updated	X	(x)
Cleaning, maintenance, repair instructions (e) – New construction/ updated	X	(x)
Energy performance certificate (always latest version)	X	(x)
Information on environmental and health compatibility (b)	X	(x)
Information on technical quality (c)		
Other certificates (e.g. sustainability certificate) - New construction	X	
Insurance documents		X
Usage data (Energy, Water)		X
Usage costs		X
Status of the maintenance reserve		X
Documentation of maintenance activities		X
Indications of possible pollutant inputs from use (d)		X
Documents for reconstruction, (various, see new building)		X
If available, Leasing contracts (e.g. green lease)		*X*

(a) Incl. references to won competitions
(b) Incl. risks to local environment and health, with regards to the carbon footprint
(c) In particular with respect to stability, sound insulation & room acoustics, fire protection, moisture protection, thermal comfort in winter, thermal comfort in summer, visual comfort, accessibility, flexibility, rebuildability, deconstructability, recycling friendliness.
(d) e.g. for the use of buildings for chemical cleaning, industrial buildings, etc.
(e) *Incl. indication of cycles*

From Table 1 it becomes clear that some documents created during the design phase must be updated and supplemented during the further use of the building. On selected occasions (e.g. lending, insurance, valuation, transactions), the information contained is passed on to third parties (e.g. valuers, insurance brokers, buyers) and used by them. Figure 1 shows examples of such information flows.

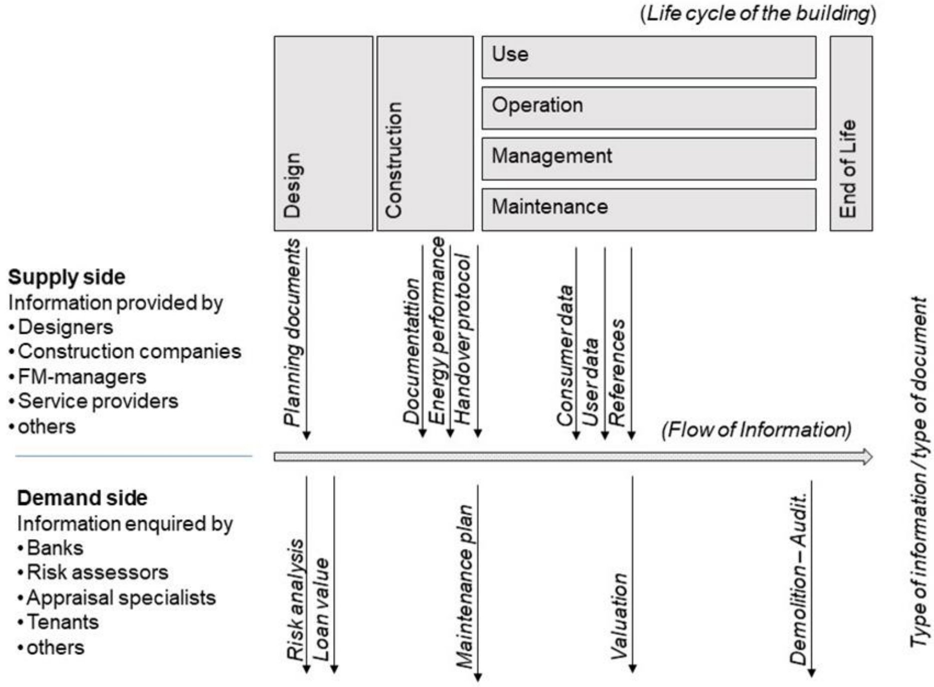

Figure 1. Selected types of information flows in the life cycle of buildings (Lützkendorf)

"*Globalization*" also leads to transactions in the real estate industry that are far away from traditionally known submarkets and thus to the need for reliable data on properties and market conditions at other locations. Ultimately, the trend towards "*Digitization*" offers solutions. To answer the above-stated questions, the possibilities offered by current IT solutions, such as BIM, databases/clouds and blockchains are discussed in the following.

3. Brief introduction of solutions

3.1. Building information modelling (BIM) and BIM Level

BIM – a virtual model as the digital twin of a building – is an approach to support documentation and information flows during the entire real estate life cycle, from the early stage of conception through the more detailed design stages and the construction process (where it enables all parties to work on a shared model) and up to the operation and management of the complete building and its final deconstruction. The concept has been around for years; however, it had a major focus on the design and construction phases [6]. Since all building- and material-related information is stored in a central location from the start of the design phase, BIM shows great potential for embodied and whole life carbon calculations, especially in the early design stages [7]. To speed up and support the process of implementation during all phases of a real estate life cycle, the so-called BIM Levels were introduced to give an assessment of the current implementation status of a model (referred to as maturity of a model). While Level 0 indicates that there is no collaboration and most information exist in printed or electronic printed 2D drafting, Level 1 includes first 3D CAD concept work, CAD standards, and file sharing over a common file sharing system. Level 2 is the first system with advanced knowledge and information transfer with implemented workflows between serval parties. The final level, Level 3, which is not fully defined yet, is considered as being a fully digital knowledge and information transfer characterized by full transparency and based on a single model shared between all participants.

In addition to the introduction of the above-mentioned BIM-Levels to describe the maturity of a model there are seven, so called "dimensions", which describe how the included data is linked with each other. While all dimensions up to dimension 4 relate to data about the construction object and the construction sequence (compare to "design" and "construction" in figure 1), dimension 5 to 7 add additional information (everything following the construction phase in figure 1). Particularly dimension 5, the cost analysis, and dimension 6, the sustainability evaluation, are relevant when it comes to taking BIM further than the construction phase towards lifetime documentation and facility management. Existing literature shows benefits of using BIM as a facility management tool [8] but they clearly indicate that there are some open issues, as stated in section 2 of this paper. A lot of data such as energy consumption, maintenance or leasing contracts is dynamically generated and must be therefore frequently updated during the life cycle. This requires clear roles and responsibilities among the different involved actors.

3.2. Clouds and databases

The concept of a database is nothing new, however, new possibilities of storing information globally accessible in clouds, including change histories, made it an attractive solution to storing information over the entire life cycle. Cloud based offers for real estate documentation are already available, including features such as valuation, data transfers to other users and active real estate management. Cloud and database solutions are the most popular solutions these days. However, it is important to distinguish between the stored data types. Some use digital databases for storing electronic print documents which are not (or only partly) machine readable, while others use it to store data, which is fully machine readable and ready to be processed. The later solution is the more advanced and complex solution, as it enables data-driven analysis without any human interaction. In order to get to this point, it is a key success factor to reliably transfer print information such as paper scans into machine readable data. There are a few solutions in the market already, but they all include manual support and are not very reliable yet [9].

Since BIM models can also be managed on servers or in clouds, it is difficult to make a clear distinction between these two technologies.

3.3. Blockchain

Thanks to the strong development of Bitcoin [10], there has been a lot of attention to the topic of blockchain. A blockchain can be understood as a decentralized database whose entries are immutable [11]. Blockchains can be categorised in two major categories: "*Public Blockchains*" where everyone can compete, validate, and look at all transactions, and "*Private Blockchains*" where an invitation is required to contribute to the network. During the past year a new category has been forming called "*Hybrid Blockchain*." Hybrid Blockchain consists of private ledgers which are all registered in a public blockchain. This joins the benefits of both, full transparency and immutability from public ledgers and data privacy from the private ledgers [12].

The major benefit of this technology is the possibility of performing transactions without any trusted parties or middle man. Object of a transactions can be anything from cryptocurrencies like Bitcoin to properties or simple data. Once a transaction is validated, it is consolidated with other transactions to build a new block. To ensure that manipulation in the blockchain is prevented, a process called "hashing" is used compressing the content of the block into a string of a set length. The major benefit of hashing is that the output of the algorithm changes entirely, if a single character of the input is changed. As the hash of every block also contains the hash of its predecessor, it is assured that, if a block is manipulated, the error will cascade down through all blocks which have been added after it, revealing the fraud. In order to manipulate a transaction, one would therefore have to manipulate every single copy of the ledger at the same time, which is impossible.

To finally add the new block to the existing chain and distribute it across the network, a consensus protocol is used. There are different implementations such as the proof-of-work or the proof-of-stake, all having in common to achieve a consensus between all users across the network about what the truth is and whether a block can be added or not [13]. In the current market, there is only a limited offer of solutions based on blockchain. The current development is mainly driven by two types of companies, on one hand, big software enterprises and, on the other hand, small startups with a major focus on real estate.

4. Discussion

The discussion addresses the questions raised in the introduction. Among other things, it is discussed whether and to what extent job-sharing approaches between different IT solutions can be developed.

4.1. How to support data generation and storage within the life cycle of the building and how to encourage actors to compete? (1) Addressing data requirements a) and b) in section 2 of this paper.

Data generation, as the start of the data life cycle, is one of the most crucial points of data management since this sets the base for all further activities, such as data interpretation and data transfer.

When it comes to the question of where and when to register a property in a blockchain or a cloud, a potential link to BIM can be seen. As BIM is currently mainly used during the design and construction phase – the start of every real estate life cycle – this could be a promising entering point. BIM up to Level 2 and dimension 4 covers all relevant information, such as plans, materials used and contractors involved in the construction process. Once the construction process is completed, the BIM Model could - from the point of view of the authors - be transferred into a Blockchain assuring that no information gets lost. At the same time, it builds a framework for future information flow (compare figure 1) within the remaining life cycle of the real estate. To ensure a smooth transition, industry standards like the IFC (Industry Foundation Classes) [14] are of great help. To assure the usage of a format like this, political support in the form of setting requirements for minimal information which must be provided when transferring an object would be of great use. A further potential tool to assure information content and format standards could be based on the building passports, a certificate which is used to describe all relevant properties of a real estate. To support that data security during the construction process, it is also possible to link the blockchain to a BIM model as a backbone. [15] shows an interesting approach where all new information of a model update is consolidated in a new block, which is then added to the blockchain. This would lead to two major benefits: 1) The transition process from BIM to blockchain will be easier and more efficient and 2) data security can also be assured during the construction phase of a real estate.

Once the information is stored in a blockchain, an open question is how to convince property owners and property users to compete on keeping and updating all relevant information in a blockchain. For both sides, the most important requirement will be an easy-to-use and intuitive interface to make it as simple as possible for all users to compete. This is a very crucial point as this will be the first hurdle to take for users. The second major requirement is the verification process. Standard concepts such as the proof-of-work or proof-of-stake are based on monetary incentives for the miners to validate the added information [16]. When applying this concept to real estate documentation, the question of who will be the actor paying out incentives arises. In an ideal case, which assumes that a buyer is willing to pay a premium for a property if the data is complete and of good quality, the property owner could have this interest to pay for up-to-date information. However, looking at the current market situation, there are a lot of unexperienced actors who are not aware of the importance of good documentation. A lot of transactions are based on incomplete information with further data loss. Hence, one must find another compelling way to convince owners to compete. Only if banks and insurance companies demand consistent data more than before and make conditions more dependent on it, as it is intended with the new approach of taxonomies, the "value" of information will become clear and the willingness to pay for good information will increase.

For data transfer from BIM to a cloud the transition is a lot easier to realize as no incentives or validations are required. In some cases, the original BIM model is even created and stored in a cloud environment right from the start [17]. Depending on the database structure, the BIM model could be included as the main structure of the data set or as part of additional information.

4.2. How to assure a high data quality over a long period of time? (2) Addressing data requirements c) and d) in section 2 of this paper

Data quality is one of the most important requirements when it comes to storing information along the life cycle of properties. Blockchain and its characteristics mentioned in section 3.3. can be a key success factor to improve the data quality of real estate information. Once information is included into a block of a blockchain, it can neither be changed nor deleted or lost leading to assured data consistency and quality. As an actor, who requires information, it will therefore be possible to search the blockchain for the information he/she needs, knowing that there is no risk of losing any information which has been added.

Depending on how a database or cloud is used, it could also lead to high data quality under the precondition that a change history can be stored, showing when information has been changed and what the initial value was. The major problem is that in these systems there is always an administrator who has full access and change authority. Therefore, the scenario of an actor manipulating information, e.g. in order to achieve a higher selling price, is something to keep in mind. In other words, it is not impossible to change information or delete change logs. Nevertheless, if industry standards such as the building passport would set the minimum information requirements which have to be documented this technology provides a solid data quality. The data quality of BIM is strongly dependent on the different models and the implemented dimension. Since there are no industry standards or minimum requirements yet, the data quality can be different in every model. In existing literature such as [18] the authors propose an interesting data standard as a combination of GIS proven data quality standards and ISO/TS 8000-1:2011 with focus on data provenance. By focusing on data completeness, metric accuracy, thematic accuracy, temporal accuracy and logical consistency the stored data would meet the required data quality over a long period of time. However, this would need to be ensured on a technology level, allowing to add information only if all standards are fulfilled. As of today, the current systems still do not have such capabilities and bear the risk of manipulation through the system administrator.

4.3. How to assure that all data users can track down the data owners at any point of time to clarify on compliance and legal issues? Addressing data requirements e) and f) in section 2 of this paper

Another useful characteristic of the blockchain technology is that at every point in time information can be tracked down to its owner/adder. In terms of compliance issues, this is a significant benefit when it comes to storing real estate information. A common issue is that there is no clear ownership for existing information. This causes problems when it comes to wrong information or bad decisions based on wrong information. Using blockchain to store all information would overcome this issue, always allowing to reach out to the data owner to clarify in case of uncertainty [19].

In most of the current cloud solutions an owner tracking including a change history is possible. Usually the history is even part of the user interface ensuring great visibility of the data ownership.

According to the data standards for BIM proposed in 4.2., a data owner and change log tracking is also possible in BIM models, given that it is supported on the technology level.

In all three cases, an open question which would need further investigation and research is how to handle the data ownership during transactions. As of now it is not clear whether the data ownership and data responsibility will be transferred to the buyer or stick with the actor who added the information to the blockchain in the first place.

4.4. Are there any new business models or scopes for designers or other service providers?

Thanks to the immutability of blockchain, a potential use case for blockchain is the creation of a blockchain based land registry. Sweden has been running a successful trial since 2016 with the target to extend and fully cover all properties in Sweden [20]. Furthermore, blockchain enables the tokenisation of properties which opens the opportunity to invest in pieces of properties, making it more affordable for everyone and not only actors with major liquidity [21]. Together with smart contracts, blockchain can also be used to manage properties and automate processes like maintenance work, rental payments and even contract management [22]. For designers and architects, it will be increasingly important to adapt to the current technology standards and build up expertise with the new tools. Design models should be offered as integrated solutions in currently existing industry standards to remain competitive.

The answers to the questions raised show that the IT fundamentals are available for improving information management throughout the lifecycle. Furthermore, a division of labour between the use of BIM in the design phase and systems for managing data over the life cycle are emerging. In the competition between these systems, it remains to be seen if this division of labour will succeed or if individual IT approaches will develop into complete solutions for the generation and management of "life cycle data", a term which was characterized in the context of a major project [23].

5. Use case and recommendation for action

For providers – e.g. prefabricated house manufacturers, who already hand over a house file to their customers today – there is the possibility of a permanent administration and provision of information. Using solutions available on the market (e.g. see [24] or [25]), the information types shown in chapter 2 can be stored with clear structure in a blockchain. In this case, the blockchains primary function is a database, which is forgery-proof and loss-free. Data such as information on materials used or the exact position of cables and pipes, which are often lost, are thus reliably stored. If a building is sold at a later date the buyer can see which materials were used in the construction and where pipes or cables are located for possible reconstruction work. Furthermore, a documentation like this is the starting point for blockchain-based real estate transaction [26] where the asset works as a digital security unit (DAI) [27].

Section 2 of this paper showed that the demand for building-related life cycle data is currently growing. This applies not only to new players (e.g. banks) on the demand side and the growing urgency and relevance (effects on property value and financing), but also to new occasions (deconstruction planning) and additional topics (bill of materials, life cycle assessment). Sections 3 and 4 demonstrate that suitable IT solutions are available. So, what is currently holding back the progress? The extremely heterogeneous construction and real estate industry has so far failed to clearly articulate the data needs of relevant actors on selected occasions. This is not a technical problem but a problem of content. Only if the demand for information can be clearly described approaches such as building passports can be developed further in a sustainable way. Therefore, an industry standard for structuring the exchange of information on buildings between involved actors in the life cycle of buildings is proposed. Available literature, including preparatory work by one of the present authors, provides initial approaches in this respect [28 – 32].

6. Summary and Outlook

Emerging technologies like blockchain and BIM have a great potential to support information management during the life cycle of real estate. Blockchain has a major benefit on the data security, however, one needs to carefully consider in which cases an implementation of a blockchain is beneficial. Thanks to the current development of BIM and databases/cloud computing it is also possible to secure information with its history. If there is a way to control the system-administrators it is the easier solution as of today. Still, blockchain will be a technology to keep in mind during the upcoming years and actors should have plans ready to quickly adapt to the technology if it becomes a new standard. Further business models such as making a real estate "blockchain-ready" or evaluating existing properties on the blockchain based on the stored information could be very profitable for actors who are quick to adapt.

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Context-dependent information space for construction information processes

Hilbert F[1], Schülbe R[2], Fuchs S[2]

[1]Technische Universität Dresden, Germany; [2]TragWerk Software, Germany

frank.hilbert@tu-dresden.de

Abstract. The planning and construction of buildings and structures is based on collaborative building information processes. The information supply of these processes is characterized by the exchange of heterogeneous domain-specific information. For the treatment of most problems in the construction industry, the information involved is rarely considered in isolation, but rather elements from different information models are linked with each other. The concept of the information space has established itself for the persistence of such linked information models. For sustainable building, the continuous use of existing information models or information spaces is indispensable. Various implementation approaches exist for information spaces in civil engineering. One approach that is currently in the initial phase of standardisation and will therefore spread further in the construction industry is the multimodel approach. For large construction projects or more complex buildings, multimodels become very large and often contain information that is unnecessary for the respective processing situation. This makes the handling of such multimodels cumbersome and slows down the acceptance. One approach to reducing multimodels is to adapt them to the information needs of the respective information process. Information processes are embedded in a task context that essentially determines the information requirements of the process. In order to anticipate such situational information needs, this paper presents a method to define context-adaptive multimodel templates based on a formalization of the context dependencies of the information requirements. These can be evaluated at the time of application towards situation-specific information requirements and form a basis for the creation of situational information spaces for the realization of a context-oriented information supply.

1. Introduction

1.1. Interoperability in Construction

In construction projects, various organizational and functional information must be processed together. This information describes architecture, engineering and management aspects for both, the representation of physical and functional properties of a building and for its construction and is bundled by various model-based domain-specific information models (e.g. cost models, time models or construction models) or as unstructured project information (e.g. catalogs, examples, contract bases).
For the construction industry the information formats are established and can therefore not be changed without great effort. The processes for generating and using digital information models for the planning, construction and operation of buildings during their entire life cycle are dealt with by the Building

Information Modeling (BIM)[1]. Digital information models form the basis for a common effective information logistics for all parties involved in the construction process.

1.2. Applications and Collaboration Platforms

The information models are created and processed by specific software applications (e.g. CAD, FEM or planning software). Their native exchange formats are highly heterogeneous. However, the special applications that are customary for different application areas have reached such a high degree of maturity that their use is indispensable. The collaborative processing of these information models takes place within cross-model, cross-format, cross-domain and cross-organizational building information processes. In order to achieve project-wide interoperability of the information models, adaptations or new developments would be necessary, which are too expensive for the mostly small-structured companies in the construction industry. Instead, the concept of integrating existing applications via cooperation platforms is favored for collaboration [2][3]. The collaboration platforms frequently used in construction projects offer different components and services depending on the level of integration and often contain their own information logistics components that enable data exchange between heterogeneous software tools of the project partners without the need for special coordination. The approach proposed in this paper for the context-oriented provision of information for building information processes is based on such a platform architecture. The structure of the platform and the composition and use of contextual information is only briefly presented in this paper for reasons of space. More detailed information on the proposed context-aware collaboration platform can be found under [13]. For more detailed information on the use of context, please read [16].

1.3. Information spaces

However, for most problems in the construction industry, the individual information models are rarely processed in isolation. Often elements of different information models, which are separated by the data technology, refer to same aspects and must be linked together for the treatment model and format-spreading. In particular, building-specific 4-D and 5-D software applications (e.g. iTWO, Navis-works, Synchro or Visco Office Suite) connects building structures with elements of planning and control models. The dependencies of the model elements are usually mapped into the data structures of the respective specialist application and are stored in a proprietary data format after the information process or are even discarded altogether. To avoid having to recreate this link information each time, it makes more sense to save the dependencies together with the information models concerned. The term information space has established for such a networked information model. [4]. The use of linked model elements in an information space comprising formats, models and domains leads to an increased information potential compared to originally separate information models, which is indispensable for the processing of many tasks in the construction industry. If, for example, the positions of a bill of quantities are linked with the operations of a preliminary model and elements of a building model, time, quantity, geometric or cost-oriented statements can be derived relatively simple. Two essential approaches exist for the exchange of information spaces in the building industry.

One approach is the generic multimodel [5]. This approach makes it possible to model the relationships between unchanged information models by linking their elements externally in a special link model. The links are multivalent, which means that more than two elements can be linked and these elements can come from more than two different information models. In addition to the domain-oriented models and the Link Models, a multimodel contains additional meta-information describing the general properties of the whole multimodel as well as the properties of the Link Models and the interlinked information models. For the exchange of information, multimodels are serialized as multimodel containers (MMC) with project-wide unique annotation vocabulary. Figure 1 illustrates the structure of a multimodel container on the left. Two linkmodels (left) combine the logically connected elements of different subject models for different intentions. The exchange format is published as MMC 2.0 container by BuildingSmart [6]. The multimodel approach is standardized by DINSPEC 91350 for BIM-

LV containers (IFC + GAEB). There are currently efforts to define further specialized containers (e.g. ecological construction data containers, fire protection containers, etc.).

In addition to these approaches from Germany, an interdisciplinary container for the exchange of information in construction projects was also developed in the Netherlands as part of the COINS research project [7]. The goal of the project was the standardization of a flexible information container for the connection of the entire building data set with networked data approaches.

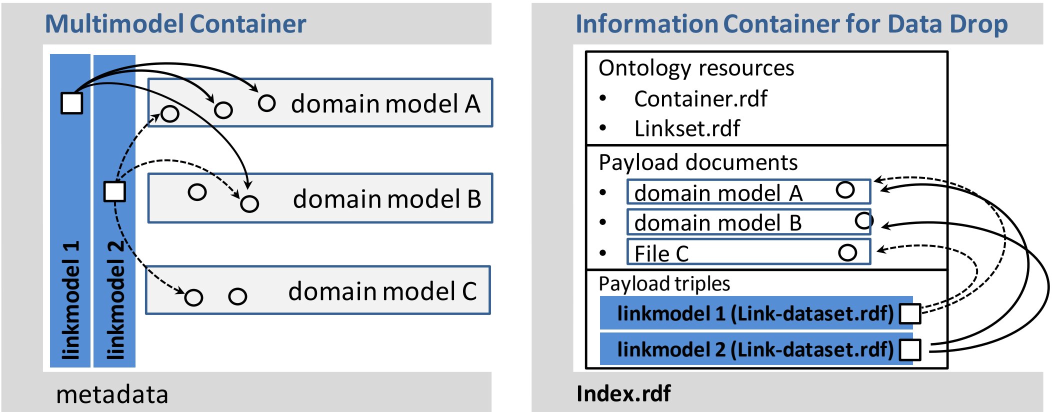

Figure 1. multimodel container structure vs. ICDD container structure

For this purpose, two versions of an information space container were published in 2010 and 2014. These versions are the predecessors of the Information Container for Data Drop (ICDD), which, similar to the multimodel, are intended to establish semantic interoperability between data or information with different data formats and domain affiliations. The main difference to the multimodel is the use of ontologies. Interdependencies between data elements are formulated as triples within the XML-based format RDF. The standardization of the ICDD takes place in two parts by the ISO, whereby ISO/CD 21597-1 describes the contents of the container format and ISO/CD 21597-2 contains the description of the semantic ontology. Both parts were accepted by ISO and CEN at the end of 2018 and ISO certification is expected in 2019 [8]. Since DINSPEC91350 is technically compatible with the ICDD-ISO on a .xml basis, multimodels can be expressed and transformed into the ICDD format. Figure 1 shows the Structure of the ICDD Container on right.

1.4. Information space enabled collaboration platforms

For the exchange of information spaces in construction projects the information logistics of the involved collaboration platforms must be upgraded accordingly. A corresponding service platform, which connects the software systems used by the construction project partners and provides the infrastructure for the collaborative use of multimodel containers, was presented in the Mefisto research project [9]. As an example, the existing GRANID specialist applications were prototypically linked with the platform services of gibGREINER GmbH (for use by the customer) and the RIB iTWO of RIB Software AG (for use by the contractor). The structure of the cooperation platform, its functionality and its use as a virtual organization of a construction project is described in [10].

1.5. Information space issues

With the increasing complexity of the building and the construction project as well as the increasing number of actors and domains involved, the quantity, scope and granularity of the information models used are increasing correspondingly. In the planning phase in particular a large number of information models are created, which, in addition to the building itself, also affect the building permit or the organization of the later realization phase. Depending on the type and size of the construction project, different types of construction plans, documents and CAD files are exchanged between the parties involved in the construction. This can range from 2000 documents (shell construction) to up to 4000 (turnkey construction for shopping center) (see Figure 2). The reason for this development, in addition to the increasing complexity of construction projects and buildings, are the increasing quality requirements placed on the used information models as a result of the extended scope of tasks. In addition to the changed legal regulations, new, more complex production processes, special work steps and a number of new requirements must be taken into account, which concentrate on specific questions such as of energy efficiency, sustainability or additional life cycle considerations and areas of responsibility.

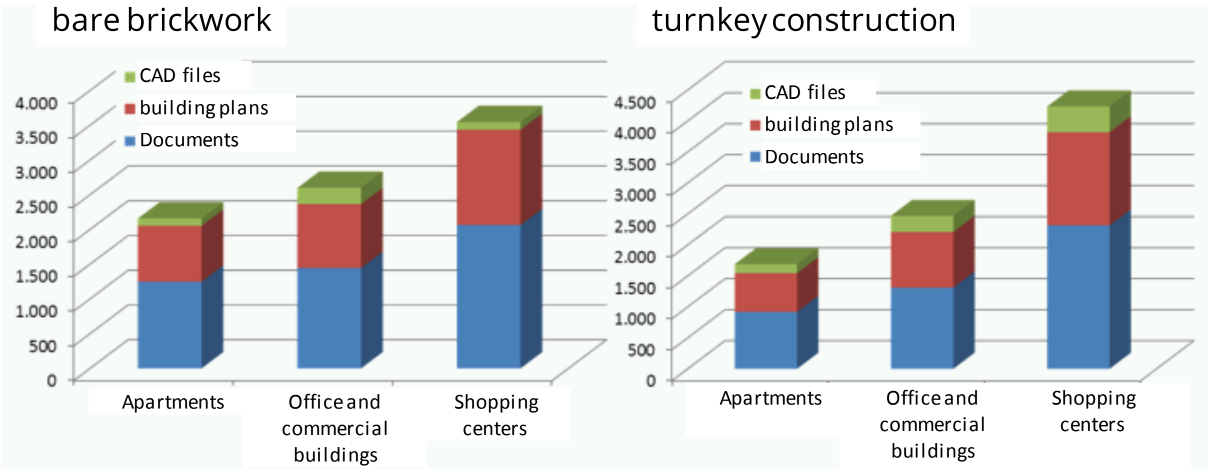

Figure 2. Average number of document types for construction projects, (source: planConnect GmbH Dresden)

With the information models, the resulting information spaces also grow and hinder the effective cooperation between the project partners. Especially in large, complex data structures the orientation effort is increased and a targeted search for required partial information as well as the tracking of model dependencies becomes more and more difficult. In addition, the semantic interpretation of the model contents is also a major hurdle for laypersons and machines. Therefore, it is difficult for those involved to estimate which parts of the information space are relevant for a current task. Against the background of this initial situation and the expected further increase in the volume of data, the targeted provision of precisely tailored information is becoming increasingly important for project success [11]. Such a provision requires intelligent information logistics that reduce the scope and complexity of the information models to be exchanged and thus ensure that the information processes are provided with information that is appropriate to the situation

2. Approach

Many tasks in the building industry require specific model sections, model qualities and model interrelationships. Often only, certain building parts, corresponding properties and allocation units or individual dates and time windows are considered. For the determination of precisely fitting information spaces for construction information processes an estimation of the information requirement is therefore necessary. Here a context dependence of the information need can be recognized. In this different aspects of the respective processing context determine the concrete extent and the quality as well as the linkage depth of the currently needed information spaces. For this reason, it is necessary to take a close look at the processing situation in order to anticipate the expected need for information. Building information processes are embedded in a processing context, which is primarily determined by three main elements: Process, actor and resource. In order to represent this processing context in a machine-readable way, a context model is required that formally represents the processing situation in a hierarchical structure [12]. Such a context model is presented under [13]. This model bundles the three main aspects and the associated sub-aspects (see Figure 3).

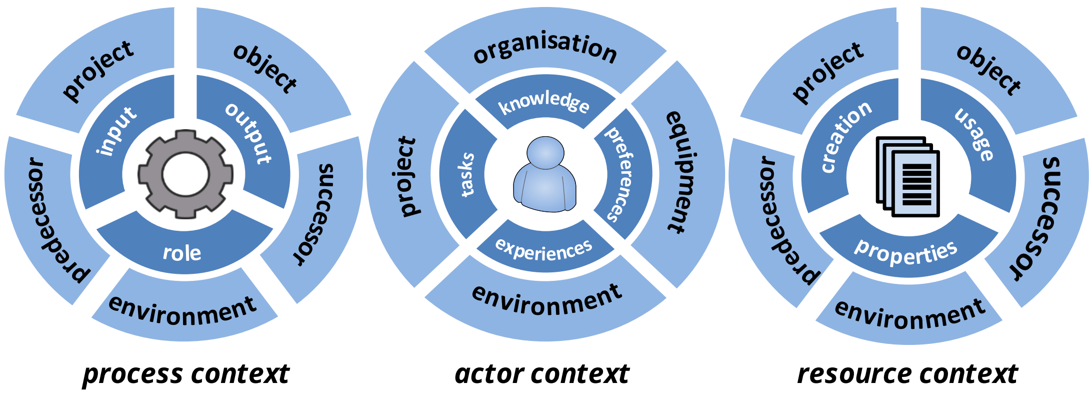

Figure 3. Context Areas [16]

There are two main points to consider when using contextual information. On the one hand, the individual context aspects have a different influence on the information requirements and on the other hand, the information logistics context information differs in relation to its update rate. Thus the relatively static actor context differs from the more dynamic resource context and from the highly dynamic interaction context. Therefore, not all context information can be determined in advance, but must be considered at the time of application. Only the selection of the context information relevant to information requirements and the type and scope of its influence on the information requirements can be estimated in advance.

In order to describe information needs in this work, the multi-model approach is preferred to the ICDD approach, since the former offers the possibility of formulating specific information space templates. Therefore, the multi-model approach is used and extended in the following to describe a situational information need.. In order to make multimodel-based information spaces accessible for automatic processing by information systems, the multimodel approach offers a comprehensive semantic description of the information models and link models involved [14]. The semantic description of the multimodel can also be used prescriptively for the specification of required information spaces. In this way, requirements for a multimodel-based information space can be formalized as so-called multimodel templates (MMT) without embedded or referenced model instances (as also defined in DINSPEC 91350). Descriptive properties of the information models involved are specified, which define their model qualities (e.g. excerpts, granularity and specialization). Figure 4 illustrates a multimodel template for the tendering of construction works and the corresponding multimodel container.

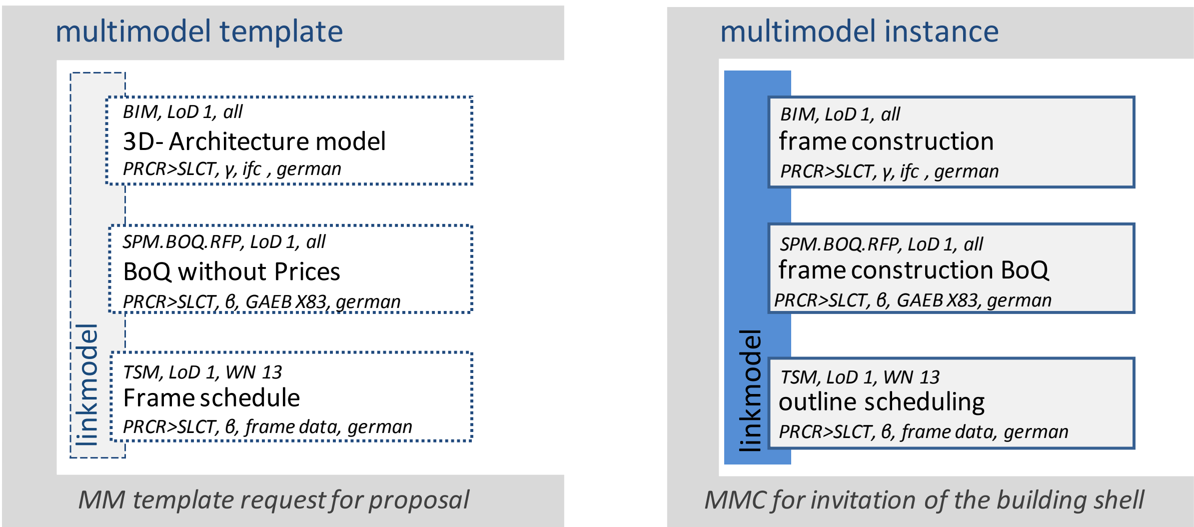

Figure 4. A multimodel template and corresponding multimodel container [16]

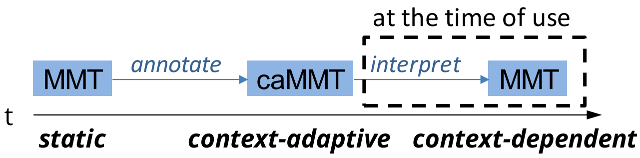

Figure 5. Creation of Context-compliant multimodel templates

The multimodel template shown here requires a multimodel that combines the logically connected elements of a 3D-Architecture model (building objects), a quantity list (BoQ items) and a general plan map (frame schedule). Static constraints describe the requirements for the quality and detail of the information models involved (e.g. model domains, project phases, levels of detail and processing status). The link depth is described using the metadata of the link models. In order to formulate the influence of context aspects on the design of situational information requirements, this static multimodel template is to be extended to a context-adaptive multimodel template. In a first step, the context-dependent components of the information requirement must be identified.

In order to formalize the influence of context attributes on the information requirement as contextual relationships, the static template attributes must be exchanged for context-adaptive attributes for the context-dependent components. Information logistics context dependencies of the context-adaptive attributes can be described by contextual relationships. In [13] the scripting language ContextScript for formalizing context relationships was introduced, which enables mapping between interacting context factors and affected information space parameters. At the time of execution, the context transformations can be evaluated with current context values in these context-adaptive multimodel templates, resulting in a context-based multimodel template. Thus, a context-dependent information need can be anticipated. Of the basis of this need a context-oriented multimodel can be created, which corresponds to the situational information requirements of the respective information process. Figure 5 illustrates the procedure: A static multimodel template (MMT) is provided with ContextScript annotations and creates a context-adaptive multimodel template (caMMT). The contextScripts of the template are evaluated at the time of execution according to the current context values and processed to a context-dependent multimodel template (MMT) (see Figure 5).

2.1. Context gathering and Integration

The prerequisite for evaluating the context dependencies is that the relevant context information is determined at the time of application. HENRICKSEN ET. Al. identified in [15] five essential phases for the integration of context information in context-related applications and distinguishes between context gathering, context reception, context management, context query and context adaptation. These five phases of operational context integration are preceded by the conceptual phase of context modeling (see Figure 6). The context gathering phase deals with the management of context sources and the insertion of recorded context information into the context model. Context information is not only collected and stored, but also further processed in order to determine high-quality context information. The context management phase organizes the administration and distribution of the available context information.

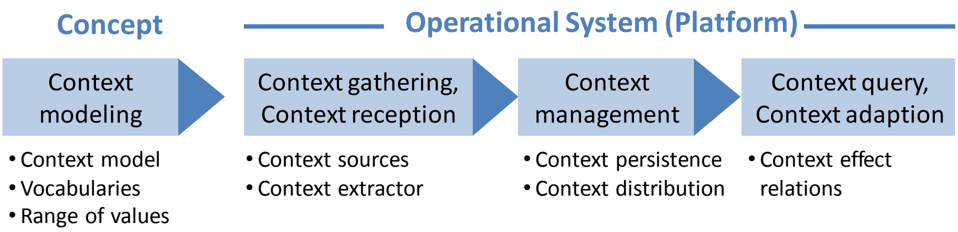

Figure 6. Phases of the operational context integration of a collaboration platform

For this purpose, the various context information obtained by the context determination must be maintained persistently and consistently. In the context usage phase (context query, context adaptation), the context model is a prerequisite for adapting the application behavior to the current context. For this purpose, the applications are provided with context information by answering context queries.

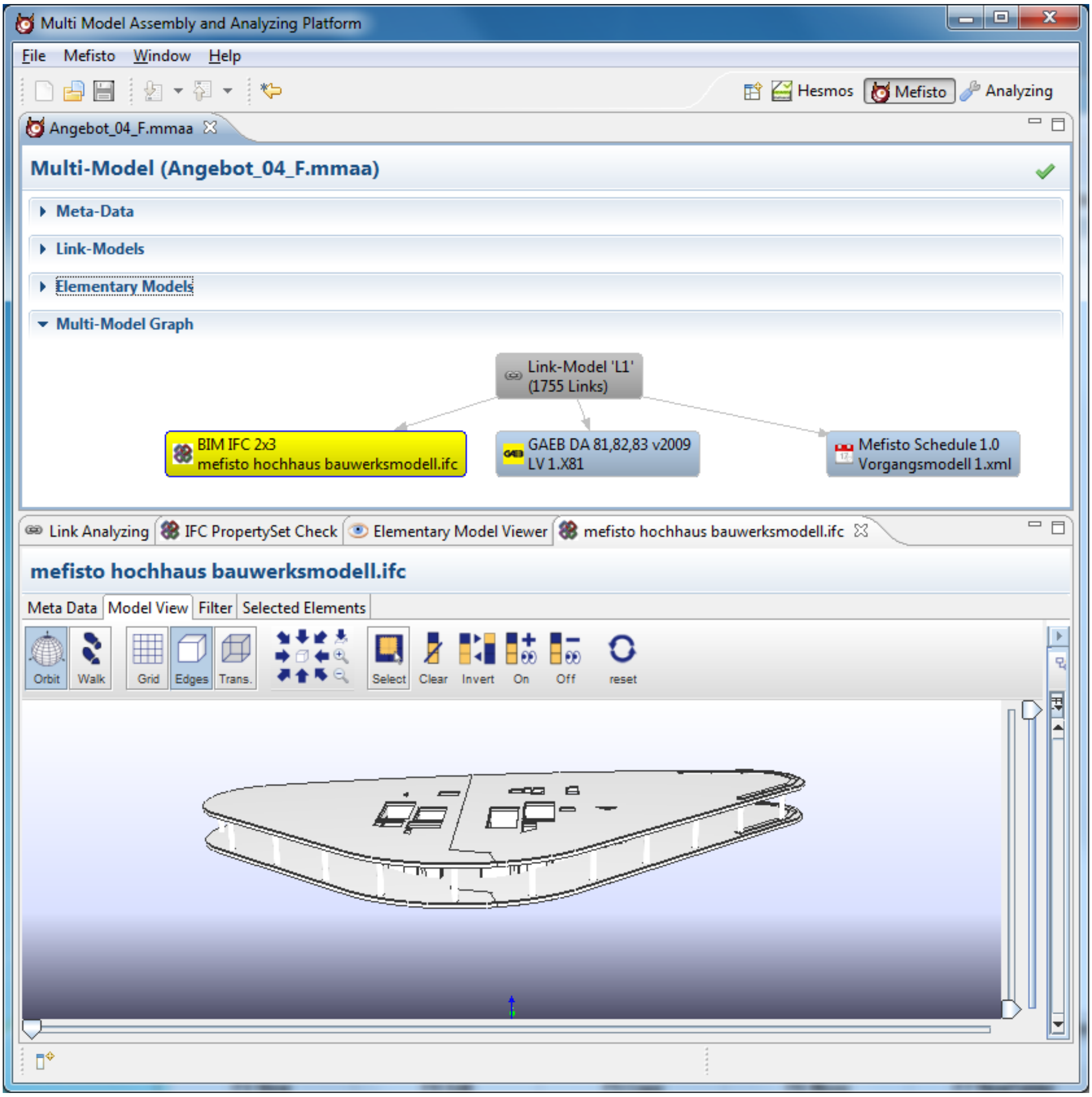

Figure 7. Evaluated multimodel container for the section of a building shell

2.2. *Context aware platforms*

For the implementation of context integration it is necessary to enable the collaboration platforms used in construction projects to become context conscious. In particular, information logistics must be expanded and the phases of operative context integration must be integrated into the elements of the platform. Depending on the level of integration, collaboration platforms already offer various components (e.g. content management system, user administration, workflow management system). These typical platform components can be used to collect context information. To do this, their functionality for integrating context information must be extended accordingly. For example, a workflow management system can determine the operational context by using the control data of the managed processes and the corresponding information resources as context sources. A document management component can be extended to determine the resource context by using the metadata of the information resources exchanged on the platform. A user management component can provide the actor context. During the usage phase of the context (context query, context adaptation), the adaptation of the application behaviour to the current context is realized. This requires additional components for contextualizing the multimodel templates. Context-dependent information spaces are generated in three stages. In the first step, the contextual relationships of the multimodel templates are evaluated on the basis of current context information. Than a context-specific information request is created as a multimodel template (see [16]). In a second step, suitable information models are determined from the project information space of the platform and adapted via adaptation services (e.g. multimodel filter services) (see [17], [18]). Finally, a multimodel generator service combines the adapted application models and generates a context-related multimodel (see [19]). In [13] a platform architecture is proposed in detail, which realizes a context-related provision of information. In Figure 7 an example of an evaluated multimodel container for the section of a building shell is shown. Table 1 shows the reduction of the information space size of the corresponding multimodel container and a coarse excerpt from the underlying context aspects.

Table 1. Example context excerpt and the Reduction of the context dependent information space

<table>
<tr><td rowspan="5">Example context excerpt
Offer carcass 12th floor
Process.project.phase: PRCR>BDDG (Bidding)
Process detail: 5th OG
Process Role: contractor
Actor.language: german
Actor.Environment.Software: ITwo
Actor.Environment.Software.File.Formats: IFC, DXF, SKP, 3DM
Actor.experience: good</td><td>information model</td><td>contextual invariant MMC</td><td>contextual MMC</td></tr>
<tr><td>BIM building model (buildingmodel.ifc)</td><td>19,18 kB</td><td>1,56 kB</td></tr>
<tr><td>SPM bill of quantities (GAEB LV1.X81)</td><td>606,00 kB</td><td>545,15 kB</td></tr>
<tr><td>TSW general schedule (processmodel1.xml)</td><td>190,32 kB</td><td>171,21 kB</td></tr>
<tr><td>linkmodel</td><td>2.964 Links</td><td>1.755 Links</td></tr>
</table>

3. Conclusion and Outlook

It is indisputable that the use of information spaces leads to an increased information potential compared to separate and unrelated information models. However, due to their growing size and complexity, comprehensive information spaces quickly become unwieldy and rarely meet the situation-related information requirements of building information processes. For the generation of precisely fitting information spaces, a multi-stage approach for the generation of contextually appropriate information spaces was developed in this article. In a first step, a method was presented to formalize the influence of context attributes on information requirements as contextual relationships in multimodel templates. In addition to the ContextScript language, a context model was introduced that covers the information-relevant aspects of the editing context. In a second step, the situation-related information requirement is anticipated on the basis of the current processing context only at the time of application. In a third step, the project-wide information pool and multimodel filter services are used to generate context-specific information spaces. For this approach, this paper outlines a context-conscious collaboration platform as a conceptual framework for the implementation of an information logistics system that implements the context-oriented information supply for information processes in the construction industry. Since this contribution focuses only on the use of context-related information for the derivation of a multimodel-based information requirement, the remaining (context-invariant) system functionality of the collaboration platform was only outlined (e.g. domain model adaptation and multimodel generation). For detailed information on the outlined context-conscious collaboration platform, please refer to [13].

In particular, the approach of an extended virtual project information space is highlighted and its application for the determination of usable and producible information models is shown. For sustainable building, a continuous use of information is indispensable. However, due to the increasing size and complexity of the information models used, this is only possible through context-specific views. The integration of context information for the situational determination of information needs and the targeted provision of context-specific multi-models presented in this paper provides a basis for this.
For the future, we must expect a steady increase in the volume of information in the construction industry. According to this trend, the importance of demand-oriented information supply will increase, because only in this way can efficient information processing be achieved by the actors. For the future, we must expect a steady increase in the volume of information in the construction industry. According to this trend, the importance of demand-oriented information supply will increase, because only in this way can efficient information processing be achieved by the actors. The approach presented in this paper is a step in this direction. However, until the methods of context processing can be established as an integral part of future application systems, some hurdles still have to be overcome and details have to be optimized. Starting points for further research include automatic model links. A manual linking of interdependent model elements is complex and error-prone. There is still a lack of methods for automatic link generation, e.g. with the help of reference link models. MAZAIRAC AND BEETZ [20] as well as FUCHS AND SCHERER [17] present first approaches for automatic link generation with multimodal query languages. On the other hand, the context-specific adaptation of domain-specific domain models was only described very abstractly. For a practicable application of the described concept, suitable model filters are required for the adaptation of the domain-specific models with regard to quality, granularity and detail. Initial work in this direction comes from [17] and [18].

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A design integrated parametric tool for real-time Life Cycle Assessment – Bombyx project

Basic S[1], Hollberg A[1], Galimshina A[1], Habert G[1]

[1] Institute of Construction and Infrastructure Management, Chair of Sustainable Construction, Swiss Federal Institute of Technology (ETH Zurich), Stefano Franscini Platz 5, 8093 Zurich, Switzerland

basic@ibi.baug.ethz.ch

Abstract. Life Cycle Assessment (LCA) has become a widely accepted method for environmental assessment of buildings, but is still not commonly applied in design practice. The biggest potential for optimization and reduction of GHG emissions lies in the early stages of the design process. Therefore, a design-integrated approach for LCA is needed. The goal of this paper is to describe the development of a parametric LCA tool for application in early design stages in the Swiss context. The envisioned users of the tool are primarily architecture and engineering students, but also practitioners. The integration of LCA throughout the design process is solved through a modular strategy. In the early stage, pre-defined components are selected to model a complete LCA. In the following design steps when more information is available, individual materials can be input with higher level of detail. The Bombyx tool is developed as a plugin for Grasshopper based on Rhinoceros3D and includes an SQL material and component database. Users are able to choose different materials and building systems and quickly modify the building's geometry while continuously receiving the calculated environmental impact in real-time. Visualization of the results, e.g. colour code indicate how the design performs in relation to a benchmark or optimization potential. The project is developed in open source to broaden the user and developer community and foster new ideas, designs and implementations in Bombyx.

1. Introduction

The built environment is responsible for more than one third of global greenhouse gas (GHG) emissions and has the largest potential for delivering long-term, significant and cost-effective GHG emission reductions [1]. Until now, the efforts to reduce GHG emissions mainly focused on the use phase of buildings. These measures have successfully reduced the operational energy demand for new and existing buildings and the limits for energy optimization in the use phase have mostly been achieved [2]. For new residential buildings, the so-called embodied GHG emissions related to material production, construction, maintenance and end of life of buildings account for half of the total emissions within an assumed life cycle of 50 years [3]. Therefore, the whole life cycle of buildings has to be evaluated. Life Cycle Assessment (LCA) has become a widely accepted method for environmental assessment of buildings in a scientific context, but is still not commonly applied in design practice. In the rare case that it is applied, LCA is used as post-design evaluation as a mandatory part of sustainability certification schemes. However, post-design evaluation through LCA is not sufficient on its own, as it does not improve the environmental performance of the design [4].

In general, decisions made in the early stages of the design process, have the greatest influence, as they set general conditions for the subsequent design process [5] (see Figure 1). As such, the early design phase has the highest influence on costs [5], operational energy demand [6] and the environmental impacts [7]. Therefore, the biggest potential for optimization and reduction of GHG emissions lies in the early stages of the design process. LCA needs to be applied in early design stages to allow for holistic environmental optimization of the building.

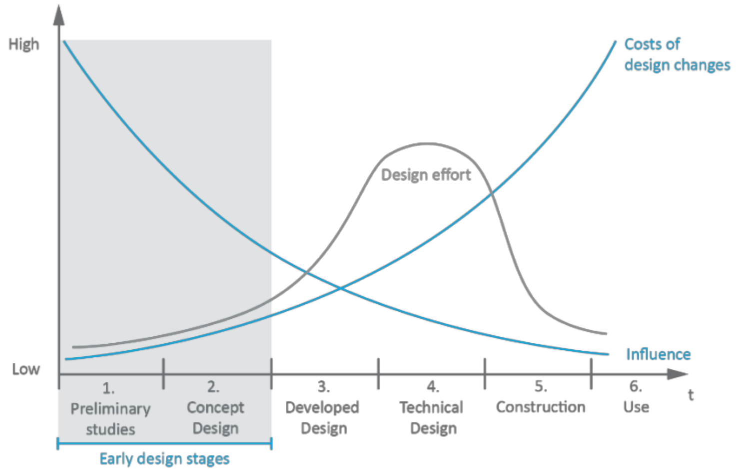

Figure 1. Influence of the early design stages (based on [5]).

Parametric design has been known for a long time [8], but gained popularity in architecture and design in the last ten to fifteen years. The main advantage of the parametric approach is the possibility to easily generate numerous different design variants. Lawson observed that many designers express a need to generate and assess alternative design ideas [9]. With the help of a parametric model, architects can fulfil this need. Once a parametric model has been developed, the generation of further design alternatives is nearly effortless. As such, the parametric approach is ideal for optimization, because design optimization is an iterative process of generating, evaluating, and comparing design variants. Parametric design allows for very quick generation of design solutions, but for time-efficient optimization, methods and tools for quick analysis are needed as well.

There is a wide range of parametric tools for building performance assessment, including energy performance, daylight availability or computational fluid dynamics. While a number of LCA tools have been developed in the last years [10], [11], only a few follow a parametric approach, e.g. Tortuga [12] or CAALA [13]. Regarding the Swiss contexts, there is a lack of adequate tools for design optimization in early design stages. Current tools are either over-simplified or too complex. Simplified tools aim to quickly estimate the embodied impact in early design stages (for example SIA 2040 Excel tool [14]), but they cannot be used to improve the building design, because of limited material options. Expert software (for example SimaPro) allow modelling the building and all materials in high detail, but inputting all necessary information is very time-consuming. Software primarily developed for engineers (for example Lesosai) is well suited for certification, but the effort to compare various design options including different geometries is high. The aim of applying LCA in early design stages should be to improve the building's environmental performance. This is not possible with the current set of tools using Swiss LCA data.

The goal of this paper is to describe the development of a parametric LCA tool for application in early design stages in the Swiss context. The envisioned users of the tool are primarily architecture and engineering students, but also practitioners. Furthermore, the tool is developed as an open source project to allow adaption to other national contexts and attract further developers in the future.

The paper first explains the method behind the tool and the implementation in form of a plug-in for Grasshopper 3D, a parametric design software based on Rhinoceros 3D. Then the intended application in a teaching project is explained and an example of using the tool in the design process is provided.

2. Concept of parametric LCA

The basic concept of the parametric LCA (PLCA) approach is combining the principles of parametric design with a simplified LCA method [15]. Here, the concept is used as described by Hollberg [16] and adapted to the Swiss context. In the following, the workflow of using the approach in the design process and the calculation procedures are described separately.

2.1 Workflow in the design process

Designer can typically influence the environmental performance of a building by three categories of parameters: 1) geometry, 2) materials, and 3) heating, ventilation, air conditioning (HVAC) systems. Each category consists of a number of parameters, such as orientation, dimensions, window area, etc. for the geometry. All parameters are input in a parametric LCA model.

The geometry is defined using a 3D model of surfaces, similar to a thermal model. The model includes, ceilings, balconies, etc. that might not be needed for calculating the energy demand but are necessary for calculating the embodied impact. The building is structured into eleven building elements (see Table 1). Each element consists of a number of components according to the Swiss structure for cost estimation e-BKP-H SN 506 511. The components are also the basis for defining the reference service life (RSL) according to SIA 2032.

The building materials are input by defining the materials for each element. This can be done in two level of details. 1) Selecting from typical pre-defined components, e.g. a timber-frame structure with mineral wool insulation (see Figure 2), or 2) by defining layers and selecting each material separately (see Figure 3). The second approach provides more flexibility and allows for a detailed assessment while the first approach reduces the effort to input the materials significantly and is therefore ideal for early design stages.

The technical equipment is always input on component level and based on the energy reference area (ERA) of the building, which equals the heated gross floor area.

Table 1. Structure of building elements and components

Building element	BKP-H Component
1. Base slab	C1 Base slab, foundation G2 Floor covering
2. Exterior wall under ground	C2.1A Exterior wall under ground E1 Exterior wall finishing under ground
3. Exterior wall above ground	C2.1B Exterior wall above ground E2 Exterior wall finishing above ground G3 Interior wall finishing
4. Window	E3 Window
5. Interior wall	C2.2 Interior wall G3 Interior wall finishing
6. Partition wall	G1 Partition wall G3 Interior wall finishing
7. Column	C3 Column
8. Ceiling	C4.1 Ceiling G2 Floor covering G4 Interior ceiling/roof finishing
9. Balcony	C4.3 Balcony
10. Roof	C4.4 Roof F1 Roof covering G4 Interior ceiling/roof finishing
11. Technical equipment	D1 Electric equipment D5.2 Heat generation D5.3 / D5.4 Heat distribution and delivery D7 Ventilation equipment D8 Water (sanitary) equipment

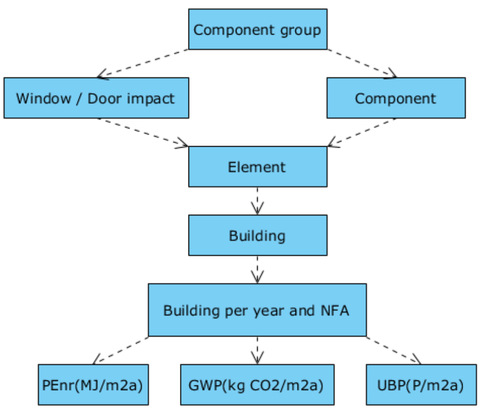

Figure 2. Component level

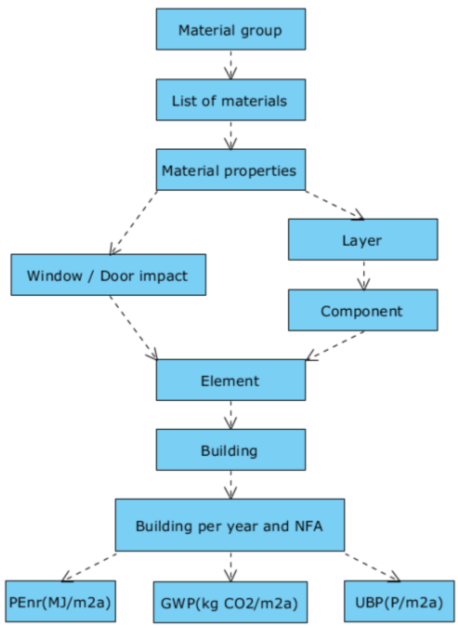

Figure 3. Material level

2.2 Calculation

The approach presented here combines the primary energy demand and environmental impact of the building in the term *impact*. It distinguishes between the *operational impact* (I_O) resulting from the operational energy use of the building (life cycle module B6 according to EN 15978 [17]) and the *embodied impact* (I_E) resulting from production and the end of life of the building (modules A1-A3, C3, and C4). The replacement of building components (module B4) is also considered as I_E. The *life cycle impact* (I_{LC}) is the sum of I_E and I_O (see Equation 1).

$$I_{LC} = I_O + I_E \quad (1)$$

2.2.1 Embodied impact

The embodied impact (I_E) is calculated by multiplying the mass of each material (M_j) by the specific *embodied impact factor* of the material ($IF_{E,j}$) (see Equation 2). To determine the mass, first of all, the areas of the different building element surfaces have to be calculated. The surface areas are then multiplied by the thickness and density of the specific material. The density is imported from the KBOB database *Ökobilanzdaten im Baubereich* [18] together with the specific IF_E. Furthermore, the number of replacements (R_j) is considered. In this way, the I_E of every component is calculated and summed up to obtain the I_E of the entire building.

$$I_E = \sum_j (M_j \times IF_{E,j} \times (1 + R_j)) \quad (2)$$

For some materials, such as windows, the KBOB database provides the IE per surface area of the element. In this case, the element area A_j can directly be multiplied with the IE.

$$I_E = \sum_j (A_j \times IF_{E,j} \times (1 + R_j)) \quad (3)$$

To calculate the number of replacements (Rj), the reference study period (RSP) is divided by the reference service life (RSL) of the building component. The RSP for residential buildings is 60 years in Switzerland. The RSL is defined in SIA 2032 [19]. R is calculated according to equation 4. For example, if a painting possesses a RSL of 20 years, it has to be renewed twice within an RSP of 60 years, so R equals 2.

$$R_j = \lceil RSP/RSL_j \rceil - 1 \quad (4)$$

2.2.2 Operational impact

The operational impact I_O consists of the sum of all different kinds of *operational energy demand* during the use phase (ED_i) multiplied by the *operational impact factor* of the energy carrier ($IF_{O,i}$) (see Equation 5). ED refers to the *final energy demand* and is calculated with reference to one year of operation. Therefore, the sum is multiplied by the number of years of the reference study period (RSP). The operational impact factor (IF_O) depends on the energy carrier employed and is taken from the KBOB database.

$$I_O = \sum_i (ED_i \times IF_{O,i}) \times RSP \quad (5)$$

The ED is calculated according to Swiss standards. The calculation approach is described in SIA 380/1 [20]. Various building categories (e.g. multi and single family houses, schools, office buildings etc.) can be calculated based on pre-defined parameters as the room temperature, floor area per person, occupancy schedule, etc. SIA provides data for 40 different climate stations in Switzerland including annual and monthly average temperatures, altitude above sea level and solar irradiation of South, East, West, North and Horizontal orientations. Here, we only include the calculation of residential buildings to simplify the process. The ED consists of space heating, hot water demand and electricity demand for appliances and lighting. The standard uses a quasi-steady state monthly energy balance to calculate the space heating demand. The monthly values are summed up to the annual value and added to the warm water demand to provide ED for heating. We use the simplified approach of SIA with fixed global values for the hot water and electricity demand.

The results of SIA 380/1 are the useful energy demand of a building. To account for different kinds of losses within a building and for the performance of the selected heating source (e.g. heat pump or gas-condensing boiler), the performance factor (PF) is used. The PF is introduced to describe different types of building services with one systematic approach. To calculate the final energy demand, the useful energy demand is divided by the PF.

The ED can also be calculated using other tools for building performance simulation, e.g. Honeybee/Energyplus or HIVE, and manually input in Bombyx. This allows for also evaluating more complex building with complex HVAC systems.

The impact factors (IFO,i, IFE,j) depend on the indicators chosen for the LCA. If more than one indicator is used, the impact factors are written as vectors of the indicators applied. In consequence, the resulting impact (IO, IE) is a vector as well. The advantage of using vectors for the impact factors is that the indicators chosen for evaluation can be easily modified depending on the available data. Equation 7 shows IFO,i and IFE,j for the indicators used by the Swiss KBOB database for building materials. UBP stand for *Umweltbelastungspunkte* or *eco points*, a single score indicator based on the Swiss *Method of Ecological Scarcity* [21]. Eco factors are used to relate between the actual emission situation in Switzerland and political targets [22]. The primary energy demand is provided as renewable part (Per) and non-renewable part (PEnr). Furthermore, Global Warming Potential 100 (GWP) expressed in CO2-equivalent as indicator for climate change is used as defined by IPCC [23].

$$IF_{O,i} = \begin{pmatrix} UBP \\ PEnr \\ PEr \\ GWP \end{pmatrix}, IF_{E,j} = \begin{pmatrix} UBP \\ PEnr \\ PEr \\ GWP \end{pmatrix} \tag{6}$$

3. Software implementation

Bombyx is designed and implemented as a plug-in for Grasshopper (GH), an add-on Rhinoceros 3D. The plug-in is free and available at Food4Rhino1. The core of the application is developed in C#. Grasshopper is based on visual programming and allows users to create scripts and components in C#, VB.NET and Python to further customise the functionality of Bombyx. The project is open source, so users can download the whole source code from GitHub2. They can also contribute with ideas and their own implementations.

The material and component data used in Bombyx is stored in a database. Further adjustments, as well as adding new materials and components can be done via specially prepared web page. Here, guest users can view all materials and components used by Bombyx and trusted users get the option to edit materials and components or add new ones. The SQL scripts to generate data tables are also provided on GitHub, but users need to setup and manage their own SQL server, where their database will reside. This could be useful to use Bombyx in other countries with other national databases in the future, for example.

[1] The latest version of Bombyx and example files can be downloaded from: https://www.food4rhino.com/app/bombyx

[2] GitHub source: https://github.com/Bombyx-ETH/Bombyx

The geometry can be directly defined within GH or drawn in Rhinoceros and automatically loaded into GH. For the second approach, a pre-defined layer structure using the eleven elements shown in Table 1 is provided (see Figure 4).

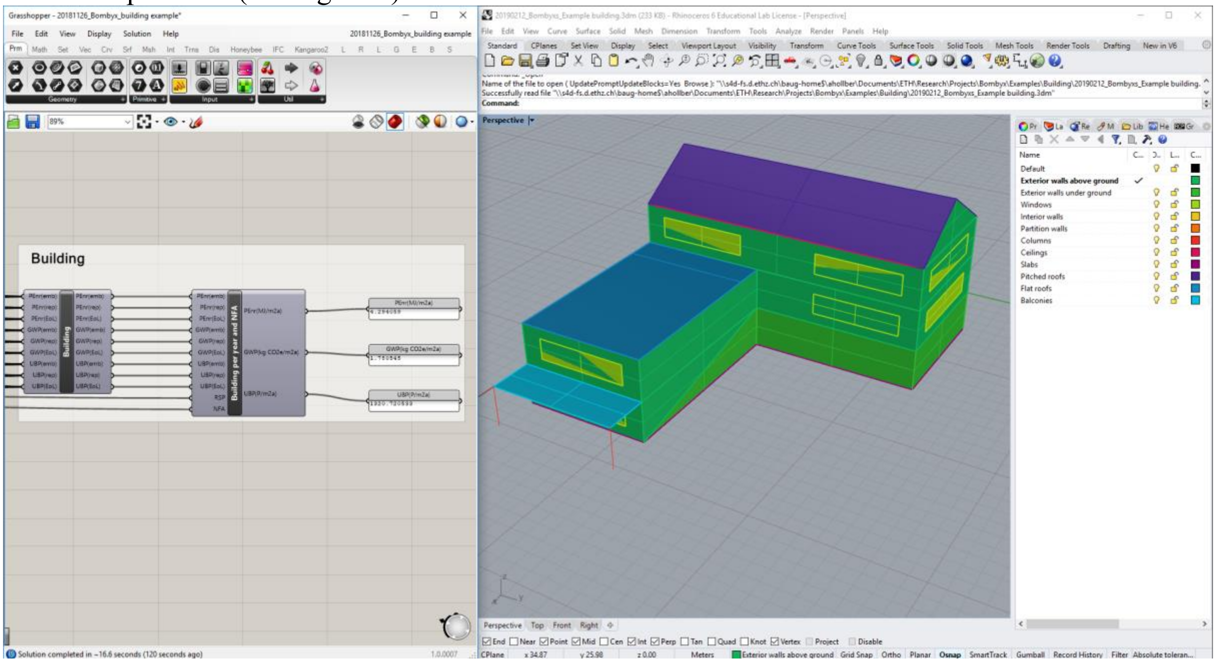

Figure 4. Bombyx plug-in in GH (left) and geometry with pre-defined layers (right).

Currently, Bombyx provides the LCA results as number in the GH viewport. They can be output on different levels of detail, for example the whole building per year, or individual components and materials separated into the life cycle stages production or end of life. A visual feedback is very import for designers [24] and will be implemented in the following versions of Bombyx (see section Future Developments).

4. Application for teaching

Bombyx will be used in the course Building Materials and Sustainability in the fall semester 2019 at ETH Zürich. It will be part of the Master course Integrated building systems and linked a design studio. A common question and concern of teachers of design studio when using performance assessment in the design process is whether this comes at the expense of the architectural design quality [25]. Clearly, the course aims at improving both environmental performance and architectural quality. We will therefore track both aspects using a graph to plot the architectural quality and the environmental quality (see Figure 5). Rating the architectural quality is not easy and can be partially subjective. Therefore, the final grades the students received in the design studio will be used as indicator for architectural quality. The environmental quality will be assessed with a simple Bombyx calculation. The comparison of students having followed the course with those who have not will be a direct evaluation of the quality of the course. If the environmental assessment has been effectively integrated during the design process, we expect that projects from our students will have a better environmental performance and a similar architecture quality, but this needs to be tested.

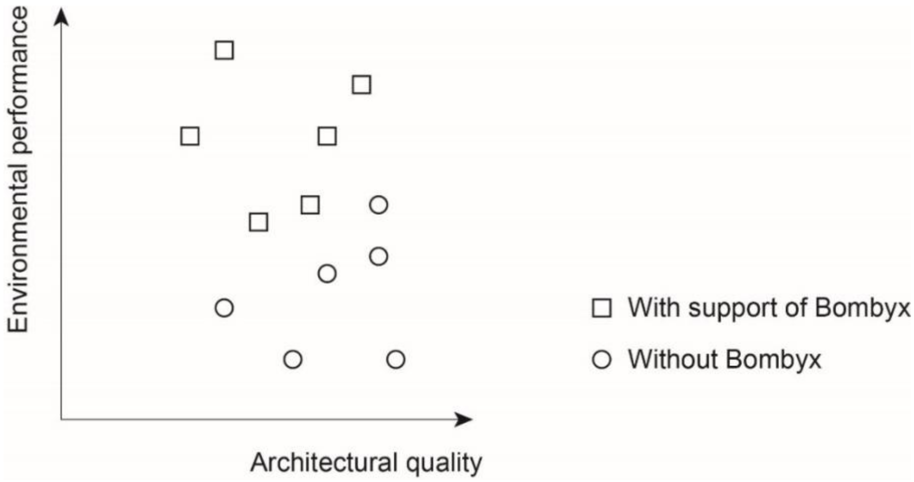

Figure 5. Expected result of the comparison between the final results of design studios of groups that used Bombyx with students that did not attend the course and apply the tool.

5. Future developments

The students' feedback will also be used to improve the Bombyx tool in the future. As mentioned above, a major task for the next version will be the integration of visualisations. We will follow two strategies. To provide insights into the relation between operational and embodied impact and the share of impact each components is responsible of, we will implement sunburst diagrams as shown by Kiss and Szalay [26] (see Figure 6). In addition, we will use the 3D model to map the results onto the model as previously shown by Röck et. al. [27] (see Figure 7). This approach allows for several types of result visualisations. The impact of each component can be directly shown on the specific component using a colour scale from green to red for example. Furthermore, to potential for improvement can be indicated by visualising the distance to a target or best-practice solution.

A future development could also integrate assumptions for buildings that have not yet been specified in early design stages. Benchmarks that can serve as reference values for Switzerland are provided by Hollberg, Lützkendorf, and Habert [28], for example. In addition, minimum and maximum values can be given out to provide a range of possible final results and show the uncertainty due to these assumptions.

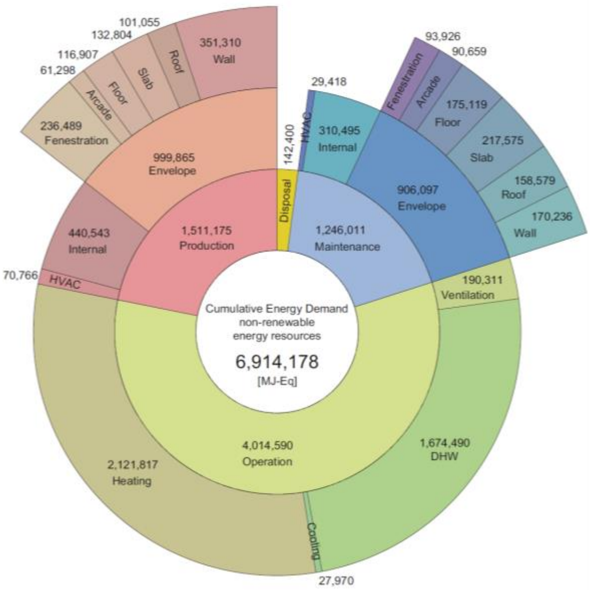

Figure 6. Sunburst diagram [26].

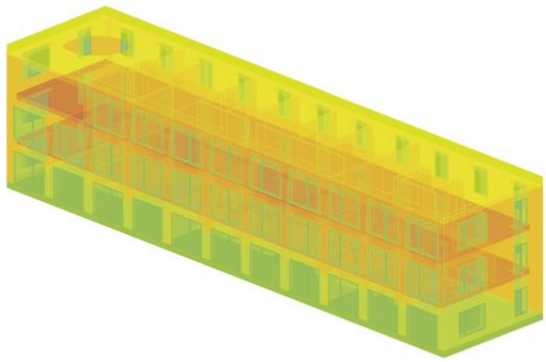

Figure 7. Mapping the results onto the 3D model to show improvement potential [27].

In the future, we will also link Bombyx to other tools for performance assessment, such as daylight analysis or structural analysis. The modular and quick calculation approach are ideal for employing optimizers, for example genetic algorithms. Furthermore, the parametric approach allows for employing machine-learning algorithms. A starting point could be to train these algorithms with saved data from student exercises to predict optimal materials and components for the geometry in either design or optimization stage. This step would significantly increase the quality and speed of the design, but would still need human verification.

Acknowledgements and remarks
We would like to thank the Innovedum fund of ETH Zürich for supporting for this project. We encourage every interested researcher, student and practitioner to collaborate on this open-source project.

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Sustainable building information modeling in the context of model-based integral planning

Ebertshäuser S[1], Graf K[1], Von Both P[1], Rexroth K[1], Di Bari R[2], Horn R[2]

[1] Department Building Lifecycle Management, Karlsruhe Institute for Technology, Karlsruhe, DE
[2] Department Ganzheitliche Bilanzierung, Fraunhofer Intitut für Bauphysik, Stuttgart, DE

sebastian.ebertshaeuser@kit.edu

Abstract. Solving complex issues of energy-efficiency – at the building as well as urban level – requires a holistic, integrated approach. The energetic behavior of a system should not only be considered in individual processes or phases, such as operation. A holistic optimization should rather consider the explicit energy flows as well as the material fluxes including the associated gray energies over the entire system life cycle. The realization of such a holistic integral planning process implies an integrated planning-accompanying evaluation and optimization of the planned object. The early use of LCA tools and sustainable building assessment systems (SBA) provides an important basis for assessing planning decisions at a conceptual level for their impact on the entire lifecycle of a building and for ensuring good sustainability performance.

In practice, however, it is currently evident that the non-standardized and inadequate connection of simulation and balancing tools (e.g. LCA) to BIM authoring tools and the resulting high time expenditure for data acquisition and LCA application counteracts with a targeted stronger penetration of the market.

For realizing a consistent integral planning process – especially in early planning phases – an IFC-based interface is being developed for the connection of LCA tools to BIM models (data input) and the preparation and configuration of the LCA result data for the designated use in different SBA. In this contribution, from the interface specifications for different levels of granularity and concretization in the different planning phases that are developed by means of norm-based processes of model standardization in an underlying research project, parts regarding the early project stages will be presented.

1. Introduction

In the field of sustainable building measurable ideas have grown up in recent years that enable a viewpoint shift by taking into account holistic lifecycle-oriented assessments of the environmental impacts of a building. Up to now the provided sustainable building assessment (SBA) systems are only used after the building is realized. Thus, great potential for optimized sustainable building design lies in the possibility to shift SBA alongside with accompanying tools as f.i. lifecycle assessment (LCA) upstream in the planning process. By showing to the decision maker and designer the consequences of their design decisions the environmental performance of the later building can be significantly enhanced.

Within the framework of a research project the question is pursued of how this can be achieved with regard to design methodology. Here, as a starting point a holistic phase model was developed for an integrated planning approach that is required for solving complex questions regarding energy efficiency and sustainability of buildings [3]. Rather than examining the energetic performance of the system in single phases only (e.g. use and operating phase), for an overall optimization all flows of explicit energy and matter together with the respective grey energy throughout the lifecycle have to be taken into consideration. In turn, a holistically integrated planning process implies a consistent accompanying evaluation and optimization of the planned object. Early application of lifecycle and sustainability assessment tools in the process constitutes an important basis in order to support decision making already during the first development of concepts for the building.

In the core of the approach stands the provision of a process-accompanying data basis for building information as needed for respective LCA. To facilitate a dynamic concretization of the building information consistently through the design process, a systematic has been developed for a gradual transformation and enrichment of an initially fuzzy and rough area-based building description towards a more and more detailed element-oriented specification (cf. fig. 1). Thus, the approach depicts multigrain information structuring for the level of development according to the project phases.

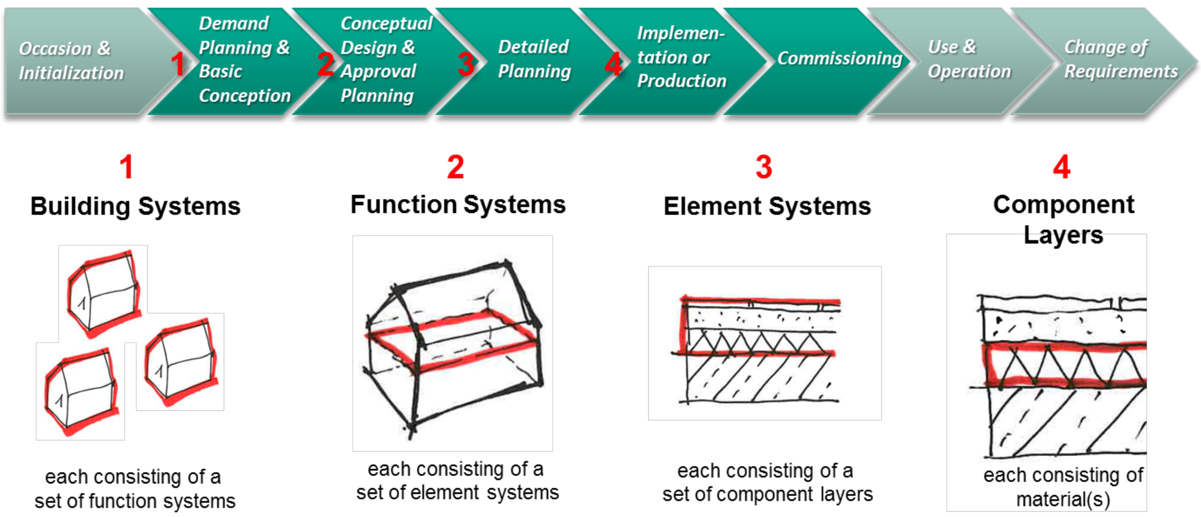

Figure 1. Multigrain information structuring approach for depicting the level of development.

At the beginning of a project, the strategic project development, a more abstract LCA-based description of targets, demands and their impacts is depicted. Successively, this building information can be enhanced to area- and shape-based descriptions, and then on to a detailed element-oriented model with references to materials and specific quantities. This granular concept will be implemented in the data model and the business logic of the IT-based tool chain from BIM to LCA and further to the SBA (c.f. [2] as well as [3]).

In this contribution we highlight norm-based methods applied in the research project in order to build a (technical) foundation regarding the data level from which shifting lifecycle and sustainability assessment tools into early planning stages can be accomplished (c.f. [1]). In order to provide model-based facility for early planning stages the information needs of two scenario-based use cases were thereby considered. As norm-based basis for specifying an appropriate data interface [4] these use cases will be presented following the short introduction to the background they are formally described in.

1.1. Foundations for norm-based generation of specific model view for sustainable building data

Within the digitalization in the field of planning and construction of the build environment a shift towards model-based methods on side of data can be observed. Thereby the established open virtual building model standard Industry Foundation Classes (IFC) plays an important role in cooperative planning as a neutral base for BIM-based software overarching data exchange. In order to specify certain agreements toward which information has to be exchanged among partners, e.g. in the framework of Employer's Information Requirements (EIR), the model standard offers the accompanying Model View Definition (MVD) Standard. Since it is important to also clearly describe the context, namely the sender resp. receiver of the information, the exchange process and (further) considered framing conditions, (technical) MVDs are specified with regard to comprehensively compiled norm-based Information Delivery Manuals (IDM).

Beside an introductory part, IDMs basically consist of two parts of definition. Process-related depictions of the exchange scenario are compiled on the basis of the Business Process Management Notation (BPMN). In this first part concerning the process diagrams the indication of where the information is to be exchanged (data transfer point) between which stakeholder is important. To each of the thereby indicated transfer points corresponding tables containing the respective one by one information demands have to be prepared in the second part of the IDM.

2. First Use Case: Assessment in Phase 1

The use case regards to sustainable building aspects as well as outlining respective coarse targets in an initial design brief prior to starting a respective project. In a first subchapter the side of process is introduced that is situated in the first phase of an underlying phase model [3] Here, actors and their specific parts in the (data) exchange are elaborated. In the following subchapter the corresponding data structures and contents regarding the data transfer points that are stated in the process are described.

2.1. Initialization phase: sustainability target corridor as part of project inspiration

A so called (initial) “design brief” document facilitates the initial information regarding sustainability in this use case. Within the document different aspects of the project to-be-initialized are compiled in a balanced way. As explicit ground work, it summarizes all initial ideas that were made in the first phase and supports the main decisions at the end of the phase – whether or not to pursue a project (and successively realize the building). If moved on from here, the initial design brief besides a documented decision support can set a first guideline on project generation and on what to (in a coarse manner) consider for this.

Fig. 2 shows a generic process of compiling the contents for the initial design brief exemplarily on behalf of the consideration of sustainability aspects. As with every thematic field that is entered into the design brief, the starting point is within the role of the initiator. This role will then finally – if all themes have been iteratively weighed carefully against each other – consume the resulting design brief alternatives as a basis of the decision making. Thus, finally one alternative with which to move on with a respective project is chosen (cf. “swim lane” at the top of fig. 2). At the beginning of each thematic field more or less information exists on side of the initiator. For the field of sustainable buildings a first set of requirements could be the basis of a first discussion with a sustainability advisor consulted by the initiator, such as coarse information on function/usage and ideas on building dimensions. Besides reiterating these initial set of requirements in terms of whether they are sufficient (or can be reduced already), the outcome of the consultation could be a task for the advisor to fix alternative inputs to the design brief. These could be based on broadly discussed alternate sustainability objectives for the project that are illustrated by the consultant on behalf of sample buildings to the initiator. Samples are thereby chosen from a benchmark database by taking into account the initially outlining requirements together with first coarse targets, e.g. a high energy standard. With these more or less structured inputs the consultant can now prepare a first set of exemplary sustainable objectives pointing to respective benchmarks or existing sample buildings that frame alternative archways of how to include sustainable aspects in the framework of the aspired project. The iterative process for generating these alternative target sustainability corridors as input to an structured BIM-based design brief is shown as interaction of the middle (executive role) and the bottom (operative role) swim lanes in figure 2. In the lane between them the data transfer points are defined where the model-based information firstly handed over to an actor in the LCA domain containing characteristics to the aspired project as well as specifier to different sustainability objectives. Secondly, after these incoming model-based information has been used to enhance the model with respective LCA-specific data in the bottom lane, it is handed back featuring the alternatives. The received models from the expert side can now be checked whether they are complete (and if not reiterated to the expert for completion) and finally, decorated with additional information characterizing them as parts of a design brief regarding sustainability, handed over to the initially requesting role of the initiator. With a decision for one of the handed in alternatives and merging its contents in the general BIM-based design brief the initiator finishes this process.

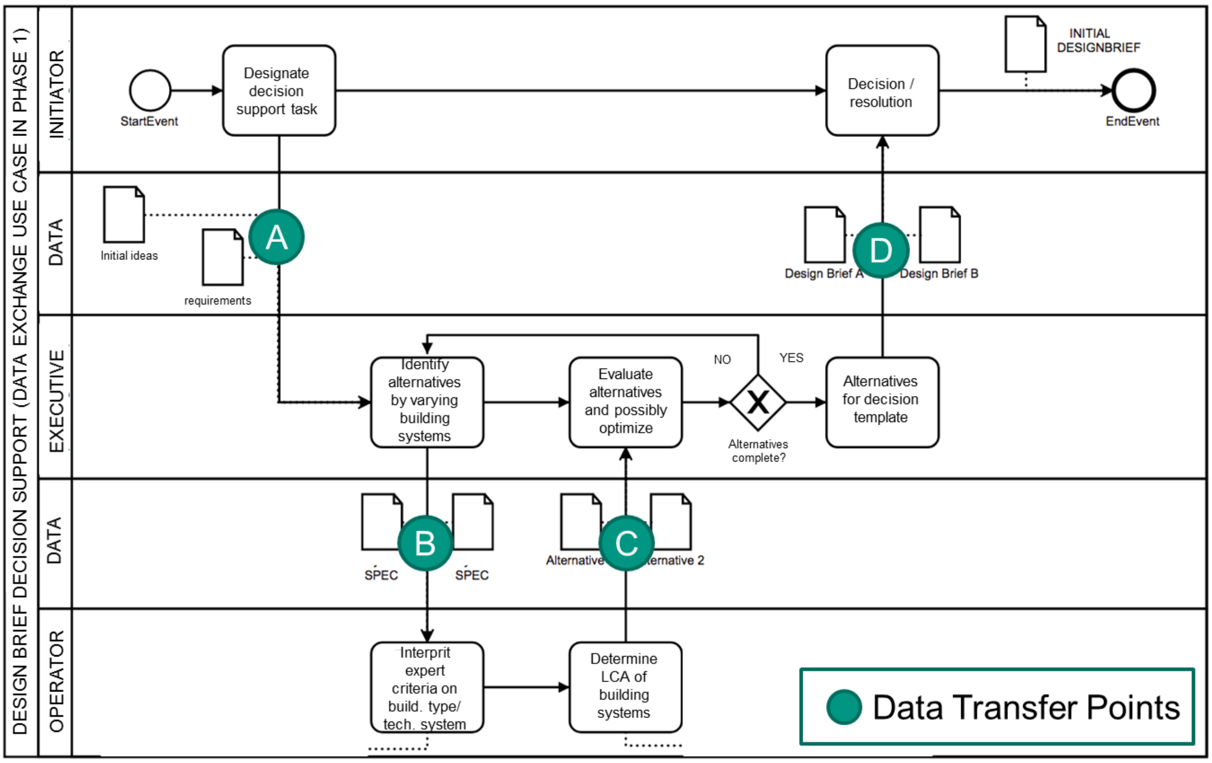

Figure 2. BPMN process map depicting a use case in the first phase.

2.2. Proposed data set of a BIM-based design brief

Different data might stand at the beginning of the above described process. The spectrum can range from a napkin with pinned down initial thoughts for a project up to (ideally) a well formed data base containing BIM-based design briefs of already realized buildings from which a template can be chosen. However, with the first (structured) data exchange between the executive role and the operative role (cf. fourth swim lane) a BIM-based model as structural base of the exchanged information is obligatory in the scenario set up. For the information systematic regarding concretization and matureness of the planned object (already published in the research project framework cf. fig. 1 and [2]), an instance of the class *IfcProject* with connected instance(s) of the class *IfcBuilding* builds the proposed base for depicting the most coarse representation stage of a „building system".

Data transfer point A – At this very early stage – prior to the manifestation of a project – especially the knowledge on sustainability on side of the initiator marks the deepness and granularity of respective involved information. For example, if the potential builder is completely new to the matter of sustainable building on the one hand side some exemplary buildings as whole (building system) where f.i. the focus is set to achieving a similar environmental performance of the hull can be feasible. Whereas on the other hand side an experienced builder might go much more into detail f.i. using benchmarked values of built samples to define concrete to be achieved boundaries while setting the outlines of his sustainability targets. Here, an example for such a systematic approach can be seen in the holistic system of Leitfaden Nachhaltiges Bauen/BNB. Although it is not obligatory yet, the early assessment of how to achieve to the most extend a sustainable building its guidelines advices the public builders to take into account can be seen as first step to respective required early goal setting.

Since the data involved in this stage is mostly generic, its central depiction concept is a linked data approach. Instead of adding information directly to these early BIM model instances, they are held as web based catalogs where the data can be referenced multiple times by respective references. In order to prepare the model instance with coarse characteristics (cf. above process description) as well as further specification of an initial target direction, e.g. by pointing out an energetic standard to be achieved, firstly the created building object is extended with a set of properties called „Sustainability benchmarks“. In this, properties can be added with a respective URL based catalogs referencing. By doing this for the added building object, all input information needed for the side of the LCA expert is already prepared. In order to precisely specify further objectives on the prepared building instance another property set “Sustainability target” can be added to the project object. Here, the specific objectives are then specified, f.i. „at least hull performance of sample building 1 and performance of technical system of building sample 2“ or „performance shall lay with in the average of building type 1 and type 2“.

Data transfer point B – By following the catalog references given in the handed-in model the expert gathers the arguments for filtering his data base. The results are then added to the corresponding building objects by extending them with a property that holds the respective value. Thereby, if the environmental performance data as CO_2 equivalent value that is filtered by the arguments given in the adjunct property set shall regard to the average of all buildings that meet the criteria instead of only one single sample building this has been indicated in the building object by setting its attribute „CompositionType“ to “COMPLEX” (as opposed to “ELEMENT” that regards to a single building).

Data transfer point C – The model-based data returned by the expert now holds the requested LCA-information, which can be checked whether it completely covers the requested sample/benchmark data. Now, by further specifying sustainability aspects through f.i. a range that is depicted by referencing the environmental impact of the hull of two returned example buildings, the advisor in the executive role can prepare the alternatives that he had earlier discussed with clients. By adding this information to different model files, explicit variants of target corridors can be specified as a decision basis.

Data transfer point D – Thus, the underlying alternative LCA-parts of a designated design brief model is finally handed back to the initiator. Here, the decision is supported by consuming the model-based information, by e.g. generating tables from its contents to visually compare the received alternatives that can also finally be used to explain in a transparent way the chosen variant. Through its standard-based depiction the chosen alternative design brief builds the (referenceable) root instance for a BIM-based data handling in the to be initialized project.

3. Second Use Case: Assessment in Phase 2

Thematically the use case regards to an implementation road map for the sustainability targets on behalf of respective project objectives. Thereby, compiling sets of strategic functional systems stands at the core of the road maps. In the first subchapter the side of process is described. The use case is situated at the end of the second phase „initialization and basic concept“ (cf. fig.1, Rexroth 2018). Here, it marks the final stage of the phase in which a respective project has been initialized by assessing and compiling the core requirements as a basis of decision whether all parts of the project are checked in terms of investment security. For this on side of data a derived set of evaluated objectives regarding sustainable building that is carefully considered in a basic concept can build a frame for the design task to be delegated to a respective planning team.

3.1. Requirements planning and basic design: support for investment security

The process shown for the previous phase involved an actor in the role of an initiator (usually a builder, or a resp. department of an institutional investment organization) that decided to move on and initialize a project on behalf of first ideas that were compiled in the frame of a model-based design brief (cf. chapt. 2). As input to the following phase, the design brief can help to set up the framework for initialization of the project e.g. by the designation of a suitable planning team to develop the design. Especially as a guideline to discussions on sustainability aspects in the requirements planning, it can thereby help to explicitly form concrete objectives derived within the initially set target corridor.

Instead of directly placing the followingly described use case at beginning of the second phase and use the design brief as direct input it was intentionally shifted to the end of the phase. By doing this the manifold and therefore difficult to generalize possible ways of how these concrete objectives are formed in different situations can be better taken into account. The end of the second phase is thereby determined by the process of the builder who wants to assure prior to kick starting the project that all contents have been carefully considered in a comprehensive investment security effort. Thus, before delegating the design to designated planners, this common decision situation is given where it should be decided upon whether all requirements of the potential builder are (explicitly) determined and respective investments are safeguarded.

Regarding the sustainability objectives within these requirements the process depicted in figure 3 shows a possible involvement of an respective sustainability advisor. After the conclusion of all requirements from the initiator the advisor is designated with the task to develop alternative setups of concrete sustainability objectives. Each of them should thereby be bound in a basic implementation concept that sets a (feasible) road map on how to achieve the expressed goals during the construction of the building. Here, it is crucial to set the right anchors for achieving the aspired sustainable building quality in order to e.g. get a specific SBA label as needed for a designated added value when placing the building in the market. Therefore, in this context the initiator delegates the task of offering alternatives on how to explicitly set project objectives regarding the building sustainability within the tender terms for respective design work to an advisor. Placed in this decision situation of the initiator, who is advised with alternative strategies that help him safeguarding his investments (cf. top process swim lane in process map), the subprocess of data exchange is furthermore embedded between the sustainability advisor and an expert LCA discipline (cf. swim lanes in the middle as well as the bottom).

Although it is not obligatory that the advisor as an input to his task of preparing the alternatives is handed over already structured (model-based) data, in an ideal case the initial design brief is at least given to build up upon in order to continually update the data in context of the project in a holistic manner. By having this single source of truth in a singleton document also all data at the basis of decisions along the lifecycle of the building can be process-accompanying captured. However, for the requirement-driven planning concerning the sustainability objectives the advisor prepares an according requirements model as a basis of the information on the environmental impact to be added. Since at this stage only coarse information is given, the modeling effort focusses on strategic building components. These are the parts of the building depicted by so called “functional systems” in the framework of the systematic on step-wise concretization of the planned object as developed in the underlying research project (cf. fig.1). In a first step based on expert knowledge regarding which of these building components are “the most relevant ones” on behalf of the advisor’s experience alternative roadmaps are considered. For these building components as in early cost planning, e.g. based on methods like the German Baukostenindex (BKI), with respective functional systems provided as items in a catalog voids of information can be filled as different kinds of construction are given based on typological data. This, together with the data that can be derived from coarse information, builds the modeling base of the requirements model. Here, for the rough information e.g. on office usage and on the coverture of the building by taking into account statistic data already default measures e.g. mean floor areas can be approximated (Rexroth Bausim 2018). In order to assess the modeled sets of (strategic) functional systems, the prepared requirement model is then in a second step enhanced with respectively characterizing information. As an example different building elements are added to the modeled alternatives each one holding a set of characteristics, e.g. medium standard equipped wood frame light weight construction, which addresses a particular item in the catalog. This model is then handed over to the expert in the role of the operator (cf. fig.3 bottom swim lane in process map) for further detailing.

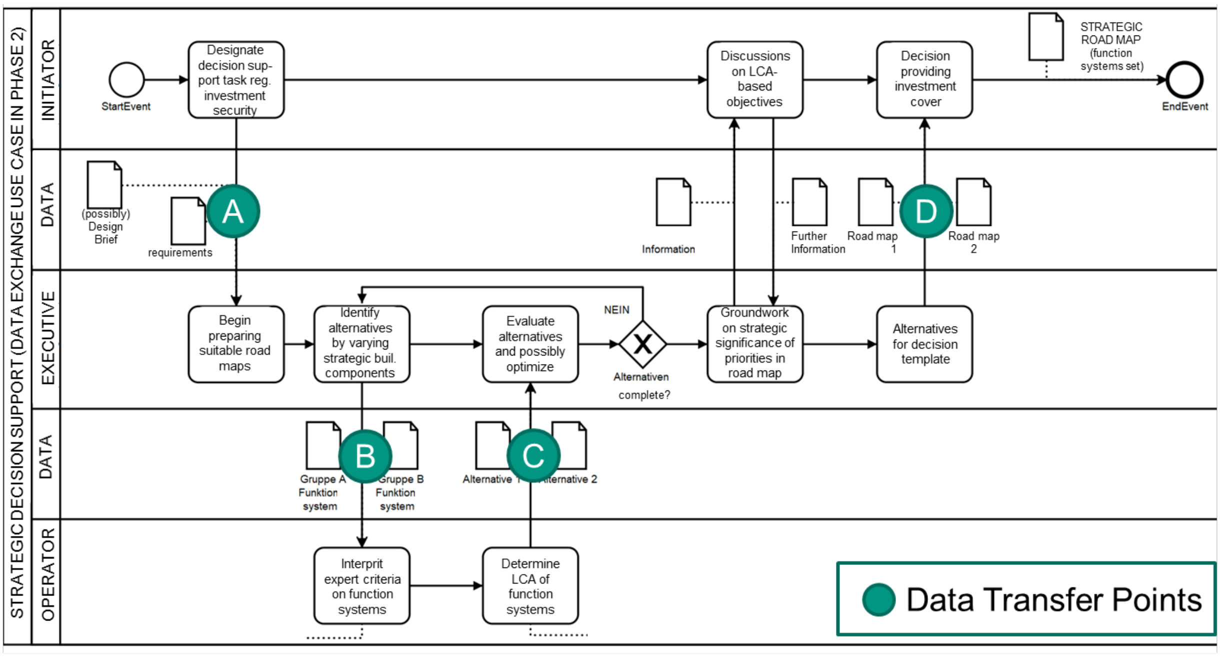

Figure 3. BPMN process map depicting a use case and data transfer points in the second phase

Once obtained the characterized model-based functional systems as well as their (approximated) measurements as an input, the environmental impacts can be added. Therefore, firstly the characteristics of each functional system of the handed in models are used to extract the according items from the catalog database. Then the required value, e.g. the environmental impact as CO_2 equivalent is calculated by taking into account other metadata like the usage that has been populated in the model. As a result, the models depicting the building requirements that have been further enhanced with the LCA-based impact information are returned to the advisor as different weighted alternatives. Here, they are checked whether they are complete and, if not, iteratively exchanged with the expert (cf. process map in fig. 3). Once the advisor approves the completeness of the prepared alternatives he can use them in further discussions with the builder about the objectives regarding sustainability to be pursued. Ultimately the alternatives are handed back to the builder that uses them as basis for his decision which strategic path to follow in the project. The chosen alternative depicting the LCA-based weighted requirements that from the view of the experienced advisor have been considered in terms of investment security can then be used downstream as basis of tender terms for respective design work.

3.2. Proposed data set for capturing the requirements planning regarding the sustainability objectives

The data exchanged in the above described process is based on IFC 4. For this a MVD is further enhanced that already contains the specification needed for the information demands regarding the first use case (cf. chapter 2.). For preparing a requirements model an instance of the class *IfcBuilding* is used. Thus, by adding a building element as complementary model for the later to be added planned object (that will reside in a separate building instance), an appropriate concept builds the base of the depiction concept for requirements information proposed in this contribution.

Data transfer point A –If an design brief was issued in the first phase (cf. chapter 2.), there has been already instantiated an enveloping project object (instance of the *IfcProject* class). This, in terms of the proposed MVD is maintained as single instance throughout the building lifecycle and can thereby help to ensure uniqueness of all the data involved. So besides the building instance(s), that represent sample (benchmark) buildings and might have already been added as design brief to the model in the first phase, another building instance is added and characterized as requirements model. In order to accomplish a consistent data exchange throughout the following described data transfer points (as indicated in the above process), different copies of this one building are the base for differently alternatives populated within it. As the first step all meta-data regarding e.g. usage or coverture that is needed in the framework of an LCA are added to this common building object.

Data transfer point B – For the different alternatives the respective copies of the base model are added with instances of derivations of the *IfcBuildingElementType* class that represents the corresponding type for a functional system. As an example, an *IfcWallType* instance is added in order to depict all building elements of the buildings' hull. This added object is then decorated with attributes and properties that characterize it in the way it corresponds to one item in the catalog of functional systems on the side of the LCA-expert.

Data transfer point C – For each object representing a respective functional system the according characteristics are extracted from the input model and used to match the environmental impact value in the catalog. This catalog value is then aggregated to the concrete value of all respective building elements, e.g. the outer walls or the roof etc., by taking into account the meta data that is stored in the building element. Finally all building element objects are enhanced with the requested information, as e.g. their environmental impacts, in the copies of the building model that represent the alternatives. Furthermore the environmental impact of the whole building can also be added before returning the resulting models to the advisor.

Data transfer point D – By adding further arbitrary information to the LCA-weighted alternatives the advisor can document certain aspects regarding the requirements as further discussed with the initiator. These could include f.i. scheduling, implementation steps or further details, e.g. regarding materials needed to be taken into account. The final prepared IFC-based information models are then returned to the initiator. As well documented basis of his decision the chosen alternative holds all relevant data concerning the involved requirements that are depicted with strategic building elements that enable for achieving the targeted sustainable building quality. Thereby the concrete objectives for that quality are also stored as the environmental impact value of each building element.

4. Summary and outlook

In this contribution we proposed a BIM-based data handling of sustainability information in the initial stages of a construction project. In the framework of two use cases a IFC-based depiction concept was thereby presented that enables for starting with BIM already with the first ideas to a project. Here, major decision that have the greatest impacts on the sustainability of the later building are made. Thus, as also emphasized by the paradigm of integral planning the transparent depiction of all data involved in decision making at these earliest stages comes along with benefits of being able to optimize the environmental performance of the building before (design) decisions are made that hinder this in a (cost) effective way. The presented use cases with their interrelated data exchange scenario are thereby contents of an general IDM for the context of BIM and SBA. A therefore proposed MVD is being further developed in the underlying research project. Thereby following the systematic in figure 1, it will be extended with contents of the data exchange use case: design tools to LCA tools and further to SBA systems.

5. Acknowledgments

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IBPSA Project 1 : BIM/GIS and Modelica framework for building and community energy system design and operation – ongoing developments, lessons learned and challenges

Wetter M[1],van Treeck C[2], Helsen L[3,4], Maccarini A[5], Saelens D[3,4], Robinson D[6] and Schweiger G[7]

[1] Lawrence Berkeley National Laboratory, Berkeley, CA
[2] RWTH Aachen University, Aachen, Germany
[3] University of Leuven (KU Leuven), Leuven, Belgium
[4] EnergyVille, Waterschei, Belgium
[5] Aalborg University, Denmark
[6] University of Sheffield, Sheffield, UK
[7] Graz University of Technology, Graz, Austria

MWetter@lbl.gov

Abstract. IBPSA Project 1 develops and demonstrates an open-source BIM/GIS and Modelica Framework for building and community energy system design and operation. The project builds further on the completed project IEA EBC Annex 60 ”New generation computational tools for building and community energy systems based on the Modelica and Functional Mockup Interface standards.” This paper describes the motivation and approach of the project, and it provides an update about recent activities. These activities include development of a core Modelica library for building and community energy systems; development of BOPTEST, a virtual test bed to test advanced controllers such as MPC; development of GIS/BIM data model translators for Modelica; development of new workflows for improved productivity and quality assurance of urban-scale energy simulation; and development of DESTEST, a validation test for district energy models.

1. Introduction

In the building energy modeling community, there is a need to standardize the approach for how component and system models are represented, both as data-model and as mathematical models that formalize the physics, dynamics and control algorithms. This is required to agree upon the physics that should be included in such components for specific use cases, and to share resources for development, validation and distribution of such component and system models; at scales ranging from individual components, through buildings to communities of buildings. There is also a need for a consolidation of models for HVAC and controls that can be used for testing [1]. Similar objectives have been shared by IEA EBC Annex 60, a project in which 41 institutes from 16 countries participated between 2012 and 2017 [2]. Annex 60 developed and demonstrated new computational technologies based on the open standards Modelica [3], used as a modeling language, Functional Mockup Interface (FMI) [4], used to exchange legacy models or simulators, and Industry Foundation Classes (IFC) [5], used to represent Building Information Models (BIM). A recent study has shown that the FMI standard is considered as the most promising standard for co-simulation [6]; furthermore, recent studies have shown that equation-based languages such as Modelica have many advantages for simulating and optimizing buildings and district energy systems over state of the art modeling languages based on causal modeling approaches [7], [8].

A subset of the Annex 60 work is now continued under the umbrella of the International Building Performance Simulation Association (IBPSA). This continuation is conducted within the IBPSA Project 1 "BIM/GIS and Modelica framework for building and community energy system design and operation." It is conducted from summer 2017 to summer 2022.

The objective of this paper is to report on the current status and future developments of this project. The paper is structured as follows: In Section 2 we summarize the challenges and in Section 3 we summarize the goals and structure of the Project 1. The challenges and goals are based on the IEA EBC Annex 60 final report, as they remain unchanged since its publication and provide the motivation for IBPSA Project 1. In Section 4 we discuss ongoing developments within the project, and in Section 5 we present concluding remarks.

2. Challenges

To meet increasingly stringent energy performance targets and challenges posed by distributed renewable energy generation in the building and district energy community, recent attention has been given to system-level integration of thermal, electrical, control and communcation systems as well as to operational optimization of buildings. The intent is to design and operate a building or a neighborhood optimally as a performance-based, robust system that can shed and shift demand, storage and production across energy carriers to provide flexible loads. This requires taking into account system-level interactions between thermal (including the building fabric) and electrical storage, electrical appliances, HVAC and renewable energy systems and the electrical and thermal grids. Such a system-level analysis requires multi-physics and multi-scale simulation and optimization using coupled thermal, electrical, behavioural and control models. Optimal operation also requires closing the gap between designed and actual performance through commissioning, energy monitoring and fault detection and diagnostics. All of these activities can benefit from using models that represent the design intent. These models can then be used to verify responses of installed equipment and control sequences, and to compute optimal control sequences in a Model Predictive Controller (MPC), the latter of which possibly requiring simplified models.

Furthermore, in the AEC domain the processes of designing, constructing and commissioning buildings and energy systems are rapidly changing toward digitalization. BIM and City Information Modeling (CIM) [9] is an enabler as collaborative method and tool to consistently gather, manage and exchange building- and infrastructure-related data on a digital basis over the entire life cycle of a facility. BIM/CIM are not a specific software, it is rather a method as part of, but not limited to, the integral design. A truly added value is expected for the near future when design and commissioning in the sense of computer aided facility management comes together. The above mentioned issues of commissioning, energy monitoring and fault detection and diagnostics can therefore highly benefit from a thorough digital planning when location and function of technical systems are together referenced in a digital model, when the as-built state is harmonized with and well documented in a model and when home and building automation becomes integrally linked with BIM. This shift in focus will require an increased use of models throughout the building delivery stages and continuing into the operational phase. It also gives rise to new requirements for building and urban simulation tools, including the following:

- Mechanical engineers should be able to design, assess the performance and verify the correctness of local and, in particular, supervisory control sequences in simulation. They should then use such a verified, non-ambiguous specification to communicate their design intent to the control provider

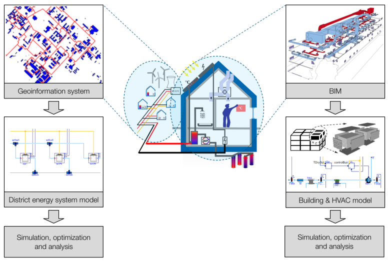

Figure 1. Overview of the scope of IBPSA Project 1.

[10]. Moreover, the specification should be used during commissioning to verify that the control contractor implemented the design intent.

- Controls engineers should be able to extract subsystem models from models used during the building design in order to use them within building control systems for commissioning, model-based controls, fault detection and diagnostics.
- Urban planners and researchers should be able to combine models of buildings, thermal and electrical grids and controls in order to improve the design and operation of such systems to ensure low greenhouse gas emissions or costs, and high quality power delivery [7].
- Mechanical engineers should be able to convert design models to a form that allows the efficient and robust solution of optimal control problems as part of MPC [11]. Such models may then be combined with state estimation techniques that adapt the model to the actual building [12].

The first item requires modeling and simulation of actual control sequences, including proper handling of hybrid systems, i.e., systems in which the state evolves in time based on continuous time semantics that arises from physics, and discrete time and discrete event semantics that arises from digital control [13]. This poses computing challenges for the deterministic synchronization of these domains [14]. The second item requires extraction of a subsystem model and exporting this model in a self-contained form that can readily be executed as part of a building automation system as shown in [15]. The third item requires models of different physical domains and models of control systems to be combined for a dynamic, multi-physics simulation that involves electrical systems, thermal systems, controls and possibly communication systems, which may evolve at vastly different time scales. The fourth item greatly benefits if model equations are accessible to perform model order reduction and to solve optimal control problems.

3. Goals and organization of the Project 1

Currently fragmented duplicative activities in modeling, simulation and optimization of building and community energy systems are coordinated through the use of the open, non-proprietary standards IFC/CityGML for BIM/CIM representation, and Modelica for model implementation. Figure 1 shows the scope of IBPSA Project 1. There are two thrusts, one for district modeling and one for building modeling. Each thrust is separated into data modeling, modeling of the physics and controls, and simulation, optimization and analysis. Data modeling include standards and transformation algorithms to link object-oriented simulation modeling with building and Geographic Information System (GIS) by adopting standards such as IFC and CityGML. Mathematical modeling include the development and validation of dynamic models that represent the physics and control logic of components and systems. Optimization includes research and benchmarking in model predictive control, and simulation includes validation of component and city quarter models. For the implementation of models for simulation and optimization, the Modelica language is used.

The anticipated outcomes are documented, validated and verified Modelica libraries, and BIM/CIM to/from Modelica translators that allow buildings and community energy systems and grids to be designed and operated as integrated, robust, performance based systems with low energy use and low peak power demand. To ensure open collaboration among the participants, all code will be released as open-source using a BSD 3-Clause License. IBPSA will be the copyright owner. The liberal nature of the license allows others to implement the code in their software and distribute it to others at no cost. Hence, IBPSA ownership of the copyright will allow others to reuse and distribute the software. All workshops, software and documentation will be open accessible to anyone. The primary target audience is the building energy research community, students in building energy related sciences, and providers of computing tools for buildings.

The project is organized into three tasks, which are further refined into work packages as follows: Task 1 further develops the open-source infrastructure of models and test suite to coordinate Modelica-based model developments for building and district energy system design and operation. Furthermore, it coordinates research in MPC and it develops a test suite for comparing the performance of advanced control sequences called BOPTEST. Task 2 is developing tool-chains that link object-oriented CAD systems, GIS, building and urban design tools at various levels of detail with one another and with Modelica models. Task 3 is focusing on validation, application, demonstration and dissemination. It includes the development of a validation test for district energy system simulation called DESTEST.

4. Ongoing developments

This section describes the goal, approach and results of the various work packages.

4.1. Task 1

Task 1 develops Modelica and FMI-based software that support the design and operation of buildings and community energy systems. It develops Modelica libraries, coordinates research in MPC, and develops a test for the performance comparison of advanced control approaches.

4.1.1. WP 1.1 Modelica library for design and operation The goal of this work package is to provide a robust, validated and well documented library of Modelica models that serve as the core of Modelica libraries for building and district energy simulation. The approach is to jointly develop the so-called *Modelica IBPSA Library*, hosted at `https://github.com/ibpsa/modelica-ibpsa` and formerly called the *Modelica Annex 60 Library*. The Modelica IBPSA Library is an open-source library that has more than 500 models, blocks and functions [16]. This library serves now as the core of the four Modelica libraries AixLib from RWTH Aachen University in Germany [17], Buildings from LBNL at Berkeley [13], BuildingSystems from UdK Berlin in Germany [18], and IDEAS from KU Leuven in Belgium [19]. These libraries integrate the IBPSA library as their core, add additional models and documentation, and distribute it to their end users. Through this method, the IBPSA library also becomes part of the redesign of EnergyPlus called ”Spawn of EnergyPlus” (`https://lbl-srg.github.io/soep/`). Recent activities and results include the addition of models for heat pumps, borefields and glycol solutions, as well as models that allow generating from a Modelica model a building emulator, packaged as a Functional Mockup Unit, for use in the BOPTEST (Building Optimization Performance Test) that is developed in Work Package 1.2 described below. Moreover, models have been further improved and are now fully compatible with the open-source, freely available JModelica simulation environment.

4.1.2. WP 1.2 Model Predictive Control The goal of this work package is to develop a framework that facilitates the formulation of MPC and that allows testing, assessing, comparing and benchmarking MPC formulations. The approach is (1) to jointly develop an open-source library of models that can be used to efficiently solve optimal control problems for building and district energy systems, and that can be combined with parameter and state estimation algorithms; (2) to develop a framework, called BOPTEST (Building Optimization Performance Test, hosted at `https://github.com/ibpsa/project1-boptest`), to virtually test and assess the performance of controllers, among them MPC. The BOPTEST concept consist of reference building emulation test cases, key performance indicators (KPIs) for quantification and assessment, and a software platform to select and manage test cases, exchange control and measurement data, calculate KPIs and generate reports. The aim of a test case is to provide a clear and unambiguously defined scenario where any controller can be tested to enable a fair comparison between different control strategies. Therefore, a test case is defined as a combination of a building emulator model and a data-set gathering boundary conditions like weather, energy prices, emission factors, occupancy schedules and comfort requirements for a one-year duration, where building location, construction type and HVAC system are consistently aligned. The ten test cases selected represent combinations of buildings and energy systems typically encountered in Europe and the US. Each test case describes the signals that are accessible at different control levels, e.g. room temperature set points at high level, damper positions, fan and pump speeds, flow rates at low level. Baseline controllers are included and operate whenever the control signal is not overwritten by the external (tested) controller. The software platform architecture for deployment and interaction with controllers has been set up. It consists of an emulator pool, a database, a simulation manager and a HTTP Rest API, which is an interface that is independent of the modelling and controller programming languages. The framework is being implemented in Docker containers, and an example test case has illustrated the capabilities of the framework [20].

4.2. Task 2

Task 2 concerns the transformation process from digital district and building information models to simulation.

4.2.1. WP 2.1 City District Information Modeling This work package addresses urban scale energy performance simulation of domestic and non-domestic buildings. Highlighting the exchange requirements and country-specific data mapping approaches, the work package also deals with archetypal definitions of buildings with respect to the generalization of country-specific age-bands, geometrical forms and building functions. Semantic data enrichment, parsimonious geometric information processing and the participation in development of the CityGML schema and EnergyADE for specific simulation tools is also emphasized. Considering different modelling techniques, generic import-export functionalities and enrichment algorithms, the team aims to demonstrate the application of the developed workflows for a range of tools, including Modelica and EnergyPlus, and for a range of geographical contexts and application use cases. The GML ToolBox [21], which extends the pre-processing of geometric prerequisites, modelling of thermal zones and openings and checks CityGML base standards and ADE conformance conditions for dynamic heating and cooling demand simulations in EnergyPlus, is one such example. Another example is an extension to the TEASER [22] tool that is currently being developed to process the five CityGML Levels of Detail and Energy ADE information as an input for annual thermal simulation using Modelica. A further example is the development of a new workflow for the preparation of large (thousands to tens of thousands of buildings) urban scenes for simulation using the CitySim+ urban enery simulation engine [23]. Open source translators and workflows for district energy simulations can be recognized as some of the outputs for this work package.

4.2.2. WP 2.2 BIM The work package starts from the core observations that CAD-integrated calculation and dimensioning requires detailed models and that such models are typically not available in the early design stages. Furthermore, common HVAC classification schemes are lacking, HVAC wiring diagrams, which are relevant for linking with control descriptions, cannot be exchanged with common software, standards are not available for digital function specification exchange and existing BIM software is typically not capable of extracting space boundary descriptions in a way to be used for energy performance simulation using zonal modeling or for CFD approaches for detailed indoor air flow analysis. The work package therefore addresses such data classification and specification, geometry and HVAC model processing. In the first phase, groundwork was set up for the collaborative development and testing of different classes of geometric algorithms for transforming building information models to building performance simulation. Various libraries were considered for reading IFC data and for processing geometric information such as IfcOpenShell, IfcPlusPlus, xBIM (IFC) as well as the geometry kernels OpenCascade, ParaSolid and ACIS.

Based on this experience, developments will be continued using the IfcOpenShell and OpenCascade libraries. Advanced space boundary algorithms for model topology analysis and model generation are currently tested [24],[25] and new algorithms are developed. Code and models are organized in the IBPSA Project 1 GIT repository. Test cases are collected with contribution from the international consortium in order to set up a robust test bed for the space boundary algorithms. A background software service analyses on an hourly basis the content of the entire repository for IFC files and automatically organizes these test cases in terms of contained entities and structures in a database with interlinked and browsable content. As of today, 54 IFC2x3 and 28 IFC4 test files containing 245 IFC entities are registered.

4.3. Task 3

The aim of Task 3 is to develop a test suite for district energy systems, referred to as the DESTEST, and to demonstrate through applications the capabilities that are enabled through Modelica. These applications will also provide feedback to the technology development in Tasks 1 and 2.

4.3.1. WP 3.1 DESTEST The aim of DESTEST is to provide a means to validate models of urban energy systems by defining specific district energy cases for testing in different simulation environments. By carefully selecting and specifying these cases, and by using different libraries for modeling these energy systems, a thorough verification, comparison and benchmarking will become possible. The description of the DESTEST cases and the simulation results of extensively verified models for urban energy systems will be available as a reference for comparing other simulation programs and model libraries. The first common exercise, a simple case in which the energy demand and the distribution subsystem of a district heating system are modelled, demonstrates how such a DESTEST could be used. The energy demand was modelled with five simulation environments, illustrating the difficulty of modelling the exact same building in different environments. Similarly, the network modelling was also used to compare the output of five network simulation models. Supplementary to this comparison, a simulation study focusing on the performance of solvers was done using one particular model.

In future work other building typologies and characteristics, climate and occupancy patterns as well as districts with different scales will be implemented. With respect to networks, cooling networks and electrical grids will also be analysed. Finally, demand and distribution subsystems will be combined to assess the performance of control actions and to check interoperability of tools that model separate subsystems.

4.3.2. WP 3.2 Application The aim of this work package is to demonstrate capabilities enabled by the use of Modelica for building and district energy systems. This task will be accomplished by gathering a number of case studies and describe them through a unified template that facilitates a systematic comparison and illustrates key findings from different applications. The template includes information such as description of the physical problem, objective of the simulation study, building/district system diagram and advantages and limitations of the use of Modelica. The expected outcome of this work package is a collection of application case studies that aim at sharing best practices and document them for dissemination to the simulation community. The systematic collection of application case studies will further lead to the identification of research needs for Tasks 1 and 2.

5. Conclusions

IBPSA Project 1 covers a wide range from data modeling to simulation of buildings and district energy systems, including detailed feedback control algorithms, performance comparison of control approaches and validation of district energy simulations. The work is based around open standards for data modeling (IFC and CityGML), for modeling of physical and control systems (Modelica) and for exchange of simulators (FMI). The tight collaboration and joint development of technologies among groups from different countries and continents, each funded by their own respective projects, would not have been possible had our work not been based on open standards, as these standards provide a common basis around which research, development and deployment activities can be organized. As such, our intent is that this project provides a strong basis for continued collaborative development of tools that lead to high performance building and district energy solutions.

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Sustainability Assessment in Architectural Competitions in Switzerland

Mobiglia M, Cellina F, Castri R

Campus Trevano, 6952 Canobbio, Switzerland

massimo.mobiglia@supsi.ch

Abstract. Architectural and urban planning decisions, that have a strong impact on all areas of sustainability, are often set during preliminary phases of project development. This work focuses on the architectural competition, that is traditionally an instrument for enhancing quality in architecture and urban planning in the preliminary phase. However, in Switzerland, only occasionally assessment criteria adopted in such competitions include principles of sustainable development (SD), as there are no specific references to SD in the specific national SIA 142 "Regulation of architecture competitions".

In the Swiss Canton of Ticino, in some architectural competitions the evaluation criteria of sustainable development have been already clearly enumerated in the tender documents. Those criteria were selected according to existing tools (Sustainable neighbourhood by SMEO, SNBS, SIA 112/1) widely used in Switzerland. In addition to the usual graphic documents each project team had to structure a sustainability report. The presented projects have been then assessed by an interdisciplinary team, after that the resultsin several representations (global index, dimension index, category index, bar graph diagram and spider web diagram) and compared them to show the strengths and weaknesses from an integrated point of view.

A change in the competition culture is needed because the sensitivity for the topic depends strongly on subjectives purposes, namely primarily on the composition of the jury.

1. Introduction

"The uncontrolled proliferation of settlements is only an indication that settlements and infrastructure development is not yet resource efficient. And this impacts not only land use, but also energy and material use, as well as social aspects. However, the high rates of land use also reflect the fact that the various practices of settlement formation and infrastructure development have not yet been brought together and integrated into an overall context. Too often, the various aspects are optimized on their own. For example, the current efforts to renovate buildings usually have no real connection to the wider building environment, and the modernization of city centers often neglects the related social aspects. Even the self-sufficient one-family house in the countryside without connection to public transport indicate that the different disciplines work independently of each other.

What is needed is a fundamental change towards an integrative approach and processing of our settlements and infrastructures in all their dimensions. [...] a change in society, only through a reduction of the growth, an economic development that leads to quality instead of quantity [...].

It is necessary to check whether it is really necessary to build a project before designing it."

Dr. Prof Eugen Brühwiler, President of the NFP 54 Steering Group

Sustainable is a development that meets the needs of the current generation without putting at risk the ability of future generations to meet their own needs and choose their lifestyle. [1][2]

Still, today the various actors (public and private clients, associations, designers, builders, etc.) involved in the design and / or transformation processes of the micro-urban environment deal with decisions that are often at the limit of the underlying concept of sustainability. Based on appropriate knowledge of the disciplines and methods that enable the prediction and assessment of the impact on SD, this approach requires a more multidisciplinary approach.

This paper focuses on the assessment of sustainability in the architectural competition phase, which sets architectural and urban planning decisions that will have a strong impact in all areas of SD. Furthermore, it generates results, that can be used more widely, for example as a general framework. The presentation of the results of four case studies aims to propose new approaches towards integrating SD criteria in architectural competitions, by setting new tasks in the process management.

2. Architectural competition procedure

In Switzerland the competition procedure is described by the specific SIA 142 "Regulation of architecture and engineering competitions" [3]. Although the procedure is dedicated to find the best quality projects, there are no specific references to SD in its recommendations. This is delegated to the involved actors, above all to the jury, the client or the experts. The regulation, for example, defines the composition of the jury, only by differentiating jury members between professional and non-professional subjects and fixing that the majority has to be represented by professionals.

In this procedure, the few instruments available to stakeholders to guarantee the inclusion of SD criteria are the selection of the jury, who is in charge of choosing the winner project, the project assessment by a team of experts in SD, the requirements defined in the competition program or the sensibility of the competition coordinator.

To encourage the introduction of sustainability criteria in the construction sector, the trend of recent years has been to move from simple environmental requirements to a complete analysis, pursued by representative interdisciplinary teams.

3. Assessment tools

In addition to the competition procedure, the SIA proposes a documentation with a methodology to assess sustainability, namely the SNARC (System to assess environmental sustainability in architectural projects) [4]. Moreover, contracting authorities may use the Albatros tool, a methodology that incorporates the criteria of SD in the strategic planning of public buildings [5]. In recent years, the SméO / Sustainable Neighbourhood by SméO, a project promoted by the two Swiss Federal Offices of Energy and Territorial Development [6], has partly replaced SNARC and Albatros.

To evaluate a topic as complex as sustainability, a multi-criteria analysis has to be used, as they allow the solution of complex problems by assessing each variable and assigning each one its relative importance.

However, the tools to evaluate a complex concept such as sustainability, which aggregate the results into a single index, are very problematic. The Dashboard of sustainability, model created within the UN Commission on Sustainable Development (UNCSD) and later enhanced by a small group of researchers led by the International Institute for Sustainable Development (Canada) and presented in 2002 at the World Summit in Johannesburg, aims to integrate everything into a single index of economic, social and environmental aspects. The objective pursued is therefore to provide an instrument that can be used to briefly illustrate the level of sustainability of a given territorial reality based on a set of selected indicators.

For this reason, the interpretation and understanding of the obtained results is very difficult. Consequently, the "dashboard" has also been defined as a "black box": an instrument that shows an output after entering data, but without knowing what exactly is happening in there.

Aggregating different criteria into a single sustainability index, even if it is obtained as a result of a multi-criteria evaluation process, is very close to the concept of weak sustainability due to the compensatory effect that appears between socio-economic and environmental aspects.

The approach that currently obtains the greatest favours and attentions is the one of an instrument close to strong sustainability, which, according to many, should be considered true sustainability. This aggregative logic leads to the integration of social, economic and environmental aspects, while maintaining their own autonomy, so that no aspect is penalised. This approach of multi-criteria analysis is at the basis of evaluation tools as decisional support. [7]

4. Competition tender

The involved stakeholder has the chance to influence, positively or negatively, the process of sustainability in the architectural competition. Among them the clients/promoters have the main and most important role. In fact, it is up to them to define the composition of the jury and the experts. As assistance they have a coordinator which has the role to follow the SIA 142 Regulation. Afterwards, promoter and jury define the criteria of judgment in the competition announcement and define the experts. This means that in the initial phase of the architectural competition, key decisions are taken by the promoter. Those decisions significantly influence the sustainability of the project.

The preparatory phase of the competition is the right moment to integrate the principles of SD in the tender, that will be held throughout the process. Namely it is necessary to clearly set the evaluation criteria. The selection of indicators is mainly based on the SméO instrument.

5. Case studies

In 2018, the Institute for Applied Sustainability to the Built Environment (ISAAC) of the University of Applied Sciences of southern Switzerland (SUPSI) had the opportunity to assess the sustainability of four different architectural competitions in Canton Ticino:

- New Campus SUPSI in Mendrisio [8], 22 projects in the 2nd competition phase
- New Campus USI-SUPSI in Viganello, 12 projects in the 2nd competition phase
- New Retirement home in Coldrerio, 5 projects in the 2nd competition phase
- New Kindergarden in Gerra Cugnasco, 6 projects in the 2nd competition phase

In the specific case of the Campus in Mendrisio, thanks to the involvement of a team of sustainability experts before publishing the tenders, it was possible to introduce some SD principles already in the preface: "The new campus will serve as a showcase and model of sustainability for its users and territory, in order to guarantee the principles of sustainable development a diffusion in today's society".

The experience of this first competition served as solid base for the other ones.

In each competition, the evaluation of the projects reaching the second selection phase was carried out by an interdisciplinary team. Each project team produced a specific sustainability report that explicitly described the decisions taken. These should also be visible in the provided plans.

The multi-criteria analyses carried out are based on an aggregation principle. A colour is assigned to each answer (from green - good to red - bad).

6. Results

6.1. Sustainability assessment

At the end of each evaluation process, it is necessary to explore how to deliver results in ways that are easy to understand to all the possible actors, even non-experts.

The evaluation results of the various architectural competitions have been presented in several variants.

The first option is to present the results of aggregate logic with the global index, but this does not express the full complexity of a score. In Figure 1 in the next page an example from the architectural competition of the Campus SUPSI in Mendrisio is shown with single or global index, for all the projects accepted in the second phase of the competition: weaknesses and strengths of each project are not visible here, but only the general ranking.

Dividing the global index into the domains of sustainability, and dividing each domain into categories can facilitate the comparison. The Figure 3 and Figure 4 in the following page have the advantage that a compensation logic between the different domains is not possible. In this way, the weaknesses and strengths of each project are better visible. Hence the expert can express clear and understandable recommendations.

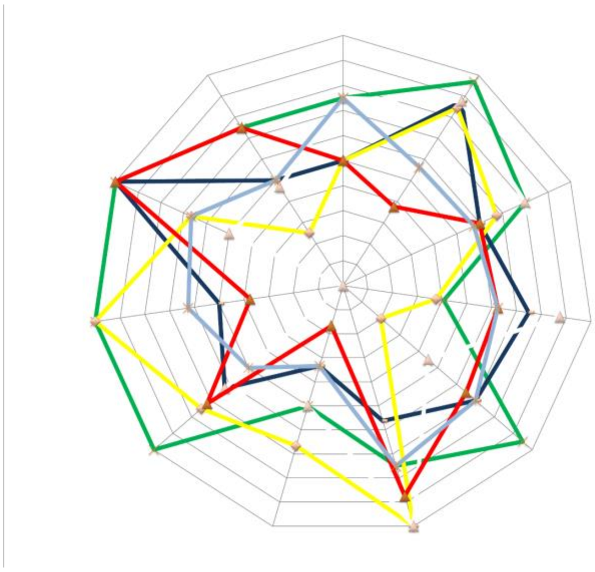

Figure 1: Competition Campus SUPSI in Mendrisio: spider web

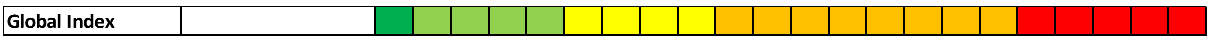

Figure 2: Competition Campus SUPSI in Mendrisio: global index

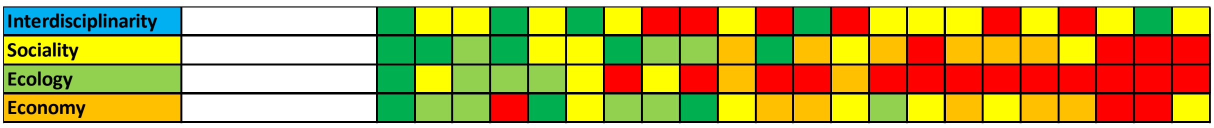

Figure 3: Competition Campus SUPSI in Mendrisio: dimension index

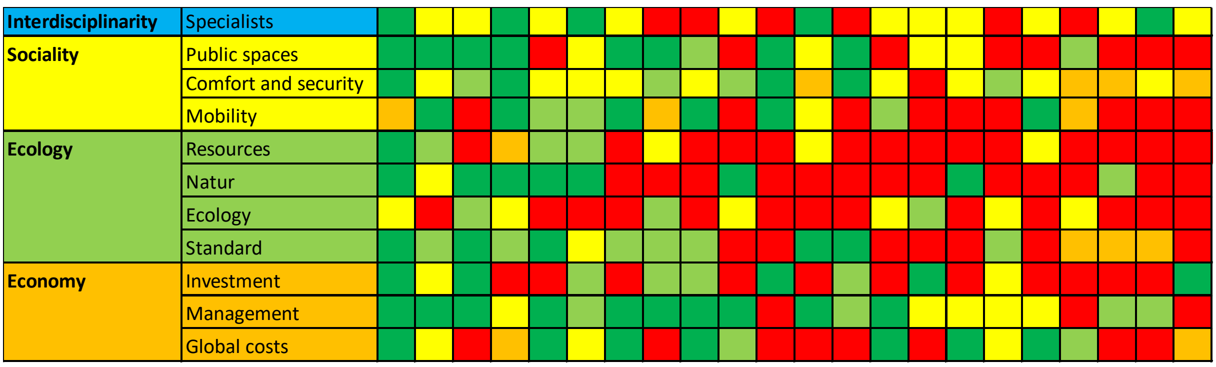

Figure 4: Competition Campus SUPSI in Mendrisio: category index

Another possibility of representation is the bar chart. The Figure 5 shows again the comparison between the 22 projects of the SUPSI campus in Mendrisio.

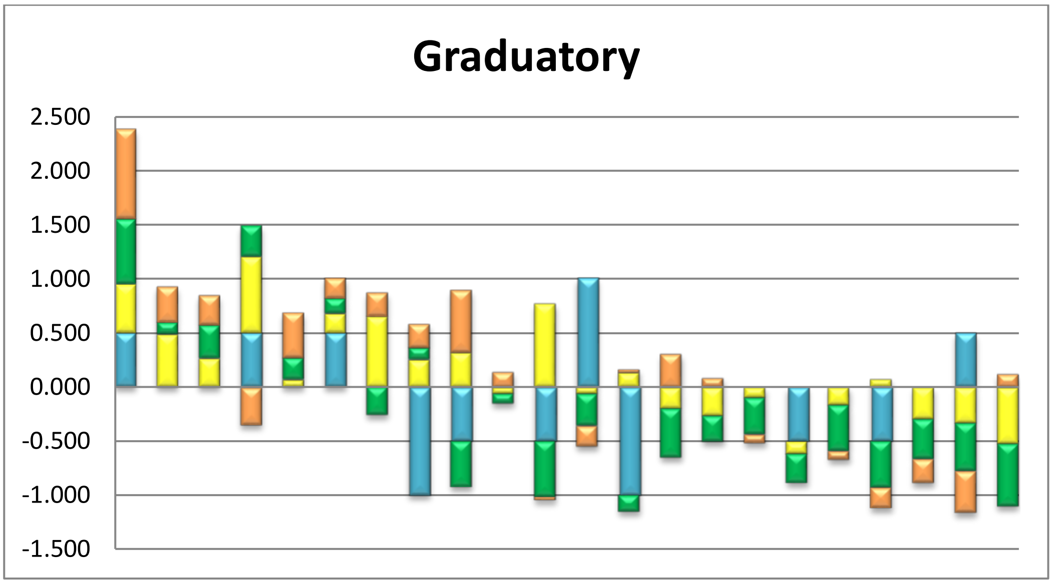

Figure 5: Competition Campus SUPSI in Mendrisio: bar chart

At first glance, Figure 5 easily allows everybody to see the peculiarities of every project: on one hand, the height above 0 of the cumulative bars identify the strength of each project, on the other hand, the bars below 0 identify the weaknesses.

A further representation is the spider web diagram. This type of illustration is easy to understand, as long as it displays a rather limited number of projects.

The following figures show two different ways to use spider web diagrams:

- Figure 6: the six projects of the SUPSI campus in Mendrisio, which have received the best sustainability indices. Reading is difficult in this representation.
- Figure 7: three projects of the architectural competition of the new campus USI-SUPSI in Viganello. Here the comparison of the projects is easier.

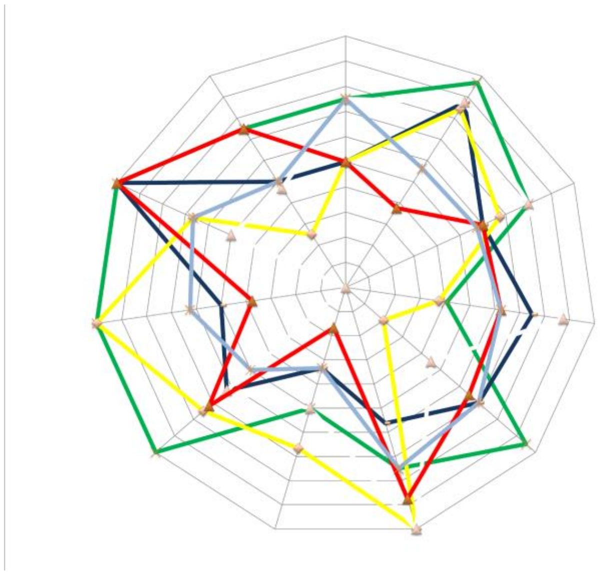

Figure 6: Competition Campus SUPSI in Mendrisio: spider web with the best 6 projects

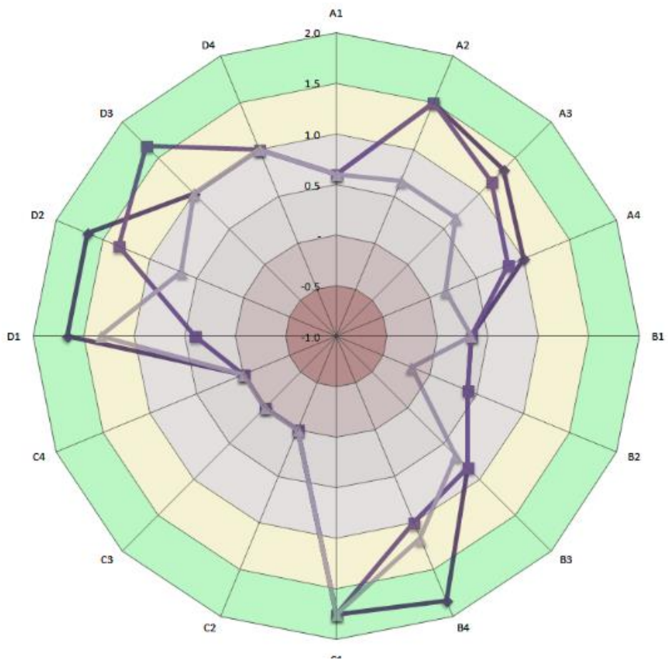

Figure 7: Competition Campus SUPSI in Viganello: spider web with the 3 best projects

6.2. Winners of the competitions

Only in the competition related to the SUPSI Campus of Mendrisio the decision of the jury coincides with the ranking of the sustainability assessment. In this case, more jury members were really interested in the SD assessment and did clearly understand the potential.

In the Coldrerio case study, the winner was placed second in the sustainability assessment, among the 5 competitors passing the second selection phase.

In Cugnasco Gerra, the winner reached the fifth place in the sustainability assessment, among the 6 selected competitors of the second phase.

In Viganello, the winner attained the eleventh place in the sustainability assessment, among the 12 selected competitors of the second phase.

This shows that the criteria of the jury differ from the ones of the sustainability team. In our experience the composition of the jury plays an essential role.

7. Conclusions

7.1. Choice of the best representation of the results

Thanks to the experience accumulated in the four architectural competitions, it was possible to identify the representation of the results that better visualize the facets of the assessment of SD:

1. The representation that allows in a quick way to highlight the strengths and weaknesses of a project is the bar chart. We therefore believe that this is the right way to represent the results of a sustainability assessment with more projects;
2. The spider web diagram is useful to present a single project rather than comparing many projects. But it has the advantage to better follow the development of a single project in its realisation;
3. The global index is of great interest to the client because it explicitly expresses a ranking, but it does not allow for any comparison.

7.2. New approaches towards more sustainability in architectural competitions

The architectural competition is traditionally an instrument for quality research in architecture and urban planning. Often, however, the assessment criteria do not include the principles of SD or, if they do so, they are very weak.

In order to emphasize the qualitative requirements of projects, including architectural aspects or urban planning, it is necessary to change the culture, as the sensitivity to the topic depends heavily on the composition of the jury.

Therefore, we propose a new approach toward more sustainability in architectural competitions. The new tasks in the process management are:

- Adaptation of legislation
  an adaptation of the SIA Recommendation 142 would be desirable by introducing explicit paragraphs on SD. First of all, in the initial preface, then in the definition of the type of architectural competition, but especially in the definition of the different actors involved in the competition procedure and in the definition of the documentation.
- Coordinators' training - drafting of the tender
  in order to implement the proposed change in the SIA Recommendation it is necessary that the involved personnel are prepared. From this point of view, the person who has the most influence is the coordinator of the competition, namely the person to whom the public bodies normally refer to, to prepare the competition procedure. If the coordinator has a solid foundation in SD, he can make sure that the tenders include the underlying concepts of sustainability as one of the main criteria of choice.
  The training of coordinators could be implemented by the order of architects.
- Composition of the jury
  To include sustainability in those processes, it would be desirable a composition of the jury 1/3 professional (Architect, urbanist), 1/3 SD-professionals, 1/3 non-professional.
- Role of the experts of SD
  Actually, the experts of SD only have advisory function without voting rights. In this way the proposal is to include them in the jury (1/3 of the jurors).

7.3. Next steps

In the near future, the method will be applied to other architectural competitions in the Canton of Ticino, Switzerland, and namely for a new retirement home in Vacallo and for the refurbishment and extension of the retirement home in Morbio Inferiore.

It would be desirable to propose the following proposal to the SIA.

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Multi-objective optimization of building's life cycle performance in early design stages

Yu H, Yang W, Li Q

School of Architecture, Tianjin University, 300072, Tianjin, China

hanzeyu@tju.edu.cn

Abstract. The early design stages of buildings have the highest potential for optimizing energy efficiency. From the aspect of architectural design, the architects can hardly make the best decisions of the complexed variables of geometries and materials. The choice and weighting of different optimization objectives also have no reference while considering the impacts from the whole view of the life cycle. In this paper, a simulation-based parametric approach through the use of multi-objective optimization method is framed. The extraction of geometry variables from the original design and the principles of explaining optimization results obtained from different objective combinations are discussed.

This process is carried out in Rhino and Grasshopper. To fully consider the aesthetic and building performance step by step in early design stages, the geometry and material parameters are tested simultaneously. The life cycle inventory data of materials and energy resources are imported by programming, and local data is partly used. Life cycle environmental impacts (PED and GWP), life cycle cost, and operating energy consumption are used as optimization objectives. A case study is verified on a project of a small campus museum building in northern China. The results indicate that the combination of geometry and material values in the optimal solution set is various and needs to be artificially selected according to actual needs. The optimization objectives should be considered comprehensively; an incomplete set may result in poorly behavior of the unselected objectives.

1. Introduction

The construction, operation, and demolition of buildings are the essential reasons for the consumption of resources and energies worldwide, which also lead to vast amounts of pollutions. In 2016, China's total building energy consumption was 899 million tons of standard coal, accounting for about 20.6% of the country's total energy consumption[1]. The resource conversion rate of construction waste is lower than the average level of developed countries. Less than 5% of the construction waste is recycled[2]. It is necessary to consider the environmental impacts of buildings from the early design stages. The International Standards Organization identifies the Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) methods as an essential method for building sustainability assessment (ISO TS 21929-1). The optimization which aimed at life cycle environmental impacts and costs plays a vital role in improving the overall performance of the building[3].

In the process of building design, due to the variety of parameters, the influence of these parameters (such as orientation, layout, geometry, structure, equipment, etc.) on the performance of the building is not intuitive[4]. The concept generation will become too complicated for designers while considering environmental impact, economic performance and aesthetics requirement at the same time. Questionnaire research also points out that time-consuming and none available workflow are the two main factors that the design companies do not run simulation and optimization in the concept generation[5].

Most of the decisions related to building performance occurred in the early stages of design[6]. At these stages, the variable range of the building geometry parameters is broad, and the material selection often comes from conventional construction practice. The parametric modelling platform can take care of these two demands. It can effectively complete the modelling of simple mass and combine the geometry with life cycle inventory (LCI) data to achieve multi-objective optimization of building's life cycle performance.

2. Framework

This paper proposes a framework for performing multi-objective optimization of building design using parametric modelling platform. Figure 1 shows an overview of the frame.

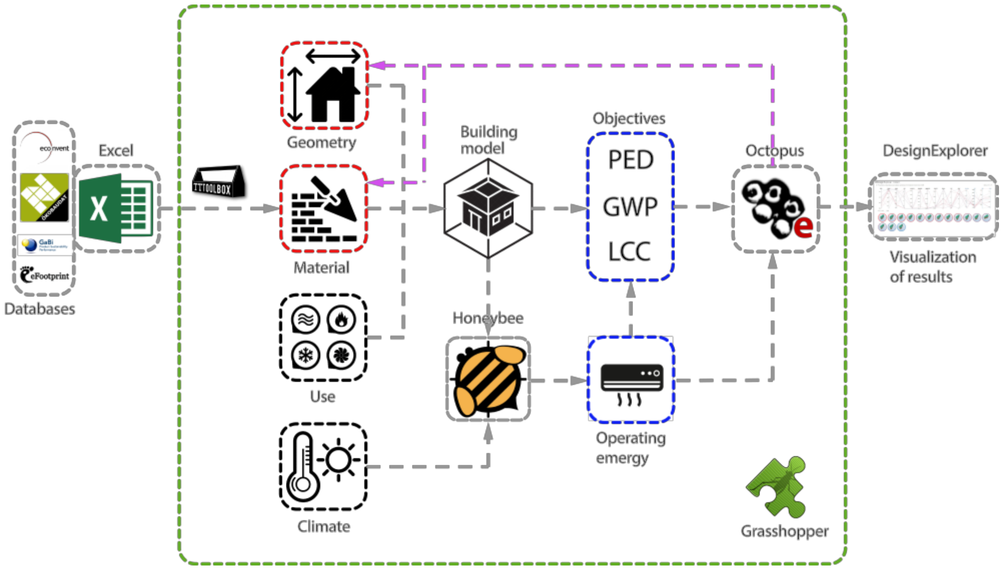

Figure 1. Framework for performing multi-objective optimization.

The framework is based on Rhino's plugin Grasshopper[7] and its components. Firstly, the physical and LCI information of materials are collected from the database and imported into GH as an Excel file. Then the data is compared with a geometric model to generate the building model containing the complete information. Secondly, the Honeybee[8] component is used after completing the geographical location, equipment, running time and other information of the model to calculate the energy consumption of the building. Then the environmental impact and LCC of the project is estimated by comparing the material quantity and energy consumption with the LCI information. Finally, the objectives are optimized by the genetic algorithm through the Octopus[9] component to obtain the optimal parameter combination. The combinations of parameters and results can be exported to Design Explorer[10] for visual visualization of further guidance on architectural design.

3. Case study

This study selects a public building with a strong diversity of geometric variables. The small museum is located in Tianjin (39°N), a northern city in China. The air conditioning in summer is run by electricity and the central heating in winter is powered by burning natural gas. It is used to display the dinosaur skeleton donated by alumni of a university, four floors above ground and a total area of 5,200 square meters. The building is located on an east-west narrow site on campus. The main exhibition hall is designed on the north side. The curtain wall of the exhibition hall has a wrinkled shape to simulate the geological effect of the rock formation（Figure 2）. Designed for a service life of 50 years, the price index and discount rate of the material are 2.0%/2.3%, of the energy are 3.0%/2.3%[11]. Table 1 shows the variables.

Table 1. Input variables and their ranges for optimization.

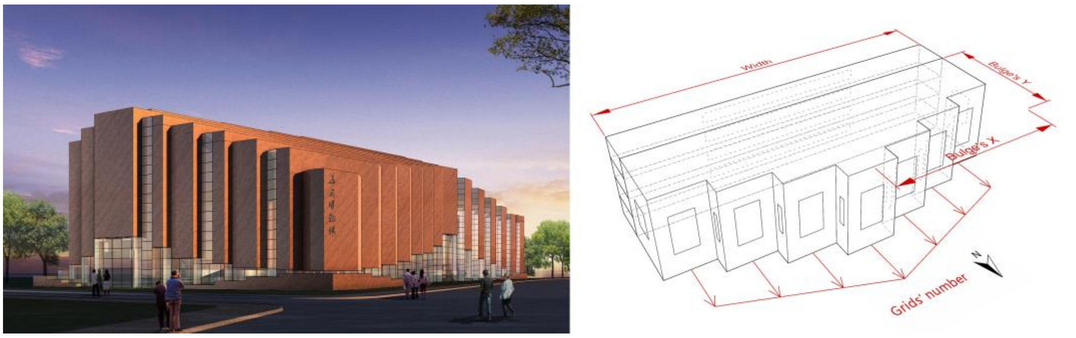

Figure 2. The rendering(left) and energy analyse model(right).

Categories	Description of variables	Unit	Distribution	Sampling ranges
Building geometry	Width	m	Uniform	(70.0,80.0)
	Bulge's X	%	Uniform	(0,100)
	Bulge's Y	m	Uniform	(40.0,60.0)
	Grid's number	-	Discrete	(3,5,7,9,11,13,15)
Window to wall ratio	North WWR	%	Uniform	(20,40)
(WWR)	West WWR	%	Uniform	(10,30)
	South WWR	%	Uniform	(20,30)
	East WWR	%	Uniform	(10,30)
Building element	Window	-	Discrete	(1-5)
	Exterior wall	-	Discrete	(1-21)
	Roof	-	Discrete	(1-19)

Table 2 shows the physical properties of the building elements.

Table 2. Building elements in this case study.

Index number (Window)	Glass type	Frame type	U-value [W/m^2·K]	SHGC	Visible transmittance
1	Double Low-E	Aluminum alloy	2.16	0.4767	0.76
2	Triple Low-E	Aluminum alloy	1.78	0.4759	0.72
3	Triple Low-E (Argon filled)	Aluminum alloy	1.51	0.4721	0.68
4	Double Low-E	Wood-aluminum	1.30	0.4767	0.76
5	Triple Low-E	Wood-aluminum	0.80	0.4759	0.72
Index number (Exterior wall)	**Layers (from outside to inside)**	**Thickness [m]**	**Thermal conductivity [W/m·K]**	**Density [kg/m^3]**	**Specific heat capacity [J/kg·K]**
	Curtain (Stone panel)	0.005	3.5	3300	920
	Curtain (Aluminum frame)	0.02	203	2700	900
	Cement mortar	0.01	0.93	1800	1050
1-11	Rock wool panel	0.05-0.15 [a]	0.048	140	1220
12-21	XPS panel	0.04-0.13 [a]	0.0384	30	1380

Index number	Layers (from outside to inside)	Thickness [m]	Thermal conductivity [W/m·K]	Density [kg/m³]	Specific heat capacity [J/kg·K]
	Autoclaved aerated con crete block	0.2	0.175	500	1050
	Cement mortar	0.01	0.93	1800	1050
Index number (Roof)	**Layers (from outside to inside)**	**Thickness [m]**	**Thermal conductivity [W/m·K]**	**Density [kg/m³]**	**Specific heat capacity [J/kg·K]**
	Polymer waterproofing membrane	0.002	0.15	580	1680
	Thermal insulation mortar	0.065	0.08	400	1050
	Perlite insulating concrete	0.002	0.435	800	1320
1-11	Rock wool panel	0.1-0.2 [a]	0.048	140	1220
12-19	XPS panel	0.08-0.15 [a]	0.0384	30	1380
	Reinforced concrete	0.1	1.74	2500	920

[a] Due to the consideration of the actual product specifications, the thickness of the insulation material is not set as uniform but discrete with a span of 0.01 m. Study has also pointed out that too many uniform variables will produce a near-infinite combination, reducing the efficiency of the optimization process[12].

Table 3 shows the environmental data of the building materials.

Table 3. Environmental data of materials used.

Categories	Components	Unit	PED [MJ]	GWP [kg CO2 eq]	Database	Initial cost [Yuan]	Initial cost's unit	RSL [a]
Insulation material	Rock wool panel	kg	14.96	1.13	Ecoinvent	474.61	m³	30
	XPS panel	m³	3020.1	96.37	ÖKOBAUDAT	747.2	m³	30
Structure	Autoclaved aerated concrete block	kg	4.00	0.47	Ecoinvent	463.93	m³	＞50
	Reinforced concrete	kg	0.50	0.13	ÖKOBAUDAT	743.66	m³	＞50
Cladding	Curtain (Stone panel)	m²	535.76	35.92	ÖKOBAUDAT	805.56	m²	30
	Curtain (Aluminum frame)	kg	48.22	11.12	ÖKOBAUDAT	340.44	m²	30
	Cement mortar	kg	1.47	0.18	ÖKOBAUDAT	49.23	m²(10mm thickness)	20
	Polymer waterproofing membrane	kg	4.18	0.08	ÖKOBAUDAT	5.69	m²	30
	Thermal insulation mortar	kg	2.05	0.29	ÖKOBAUDAT	33.72	m²	30
	Perlite insulating concrete	kg	14.58	1.23	Ecoinvent	366.26	m³	30
Window	Double Low-E(A)	m²	1792.07	131.54	Gabi	756.78	m²	30
	Triple Low-E(A)	m²	2362.21	172.58	Gabi	963.61	m²	30
	Triple Low-E(A) (Argon filled)	m²	2387.27	174.53	Gabi	1313.61	m²	30
	Double Low-E(WA)	m²	3301	180	Gabi	3104	m²	30
	Triple Low-E(WA)	m²	3520.52	193.91	Gabi	3311	m²	30
Energy	Electricity	kW·h	14.98	1.18	CLCD[13]	0.9	kW·h	-
	Natural gas	m³	15.49	0.28	CLCD	- [a]	-	-

[a] There is a starting fare 12Yuan/m² on the whole building and 0.25Yuan/kWh fee for the actual cost.

3.1. Variables' preparation
Based on the original design, geometry parameters that can make a significant change in the shape are selected. All the extreme combinations of geometric variables have been tested to prevent modelling errors during the optimization process and to meets the requirements from the site and function.
A pre-optimization artificial selection of the material variables has been made to make sure the material be chosen is not performing poorly at either thermal property or embodied energy than the others, as shown in Table 4. If insulation material A is poorly at all three factors (λ·PED, λ·GWP, λ·LCC) than material B, it means A has a more significant environmental impact and cost than B while providing the same thermal resistance. Only material that has its own strength in at least one factor can be chosen.

Table 4. Insulation variables pre-optimization compare.

Compared variables	Thermal conductivity λ [W/m·K]	λ·PED	λ·GWP	λ·LCC
Rock wool panel	0.0480	100.50	7.60	22.78
XPS panel	0.0384	115.97	3.70	28.69

3.2. Genetic algorithm parameters and computational efficiency
The optimization process uses the HypE[14] algorithm within Octopus. The following parameters are used: population size = 50, crossover rate = 0.8, mutation rate = 0.5, and elitism = 0.5. Five optimization scenarios are performed with the objectives of Operating energy(OE, kWh/m^2/a), Life cycle cost(LCC, Yuan/m^2), Primary energy demand(PED, GJ/m^2), Global warming potential(GWP, t CO_2 eq/m^2) and any of the three among the four. The convergences of the objective functions in all these five scenarios complete within 50 generations. It takes a desktop computer with a 3.6 GHz Intel® I9-9900K CPU 20-22 hours for one single scenario.

3.3. Results
In the five optimization scenarios, the objective functions converge to the Pareto optimal solution set in four out of the results. Only in the case of OE, PED, and GWP, the only optimal solution is approached in the 30th generation, as shown in Figure 3.

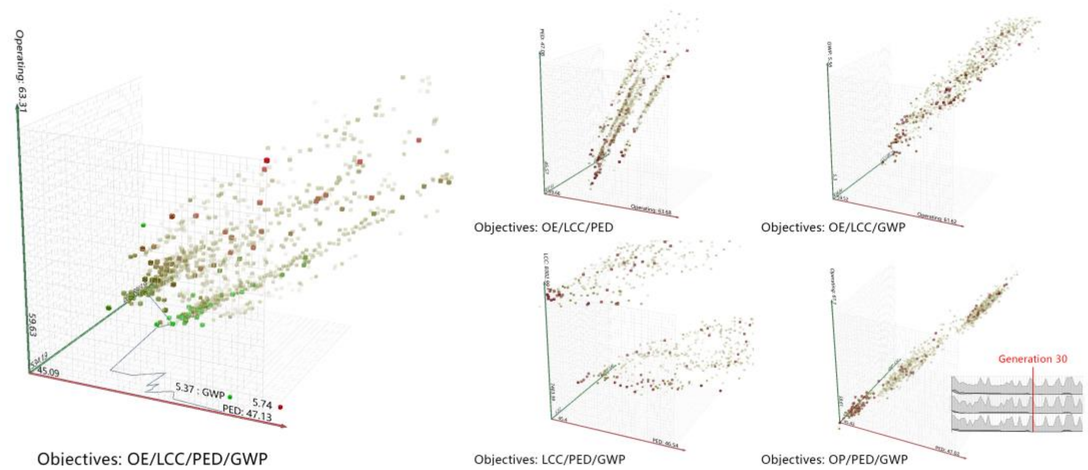

Figure 3. The scatter charts of all scenarios.

Due to the different dimensions and units of optimization objectives, the 50th generation Pareto optimal solution sets is standardized by SPSS[15] to make a comparison. It can be seen from Figure 4 that the objectives' value of OE, PED, and GWP is inversely related to LCC and there is not a clear trade-off relationship between the operating energy and embodied energy (PED, GWP) as some previous studies[16, 17].

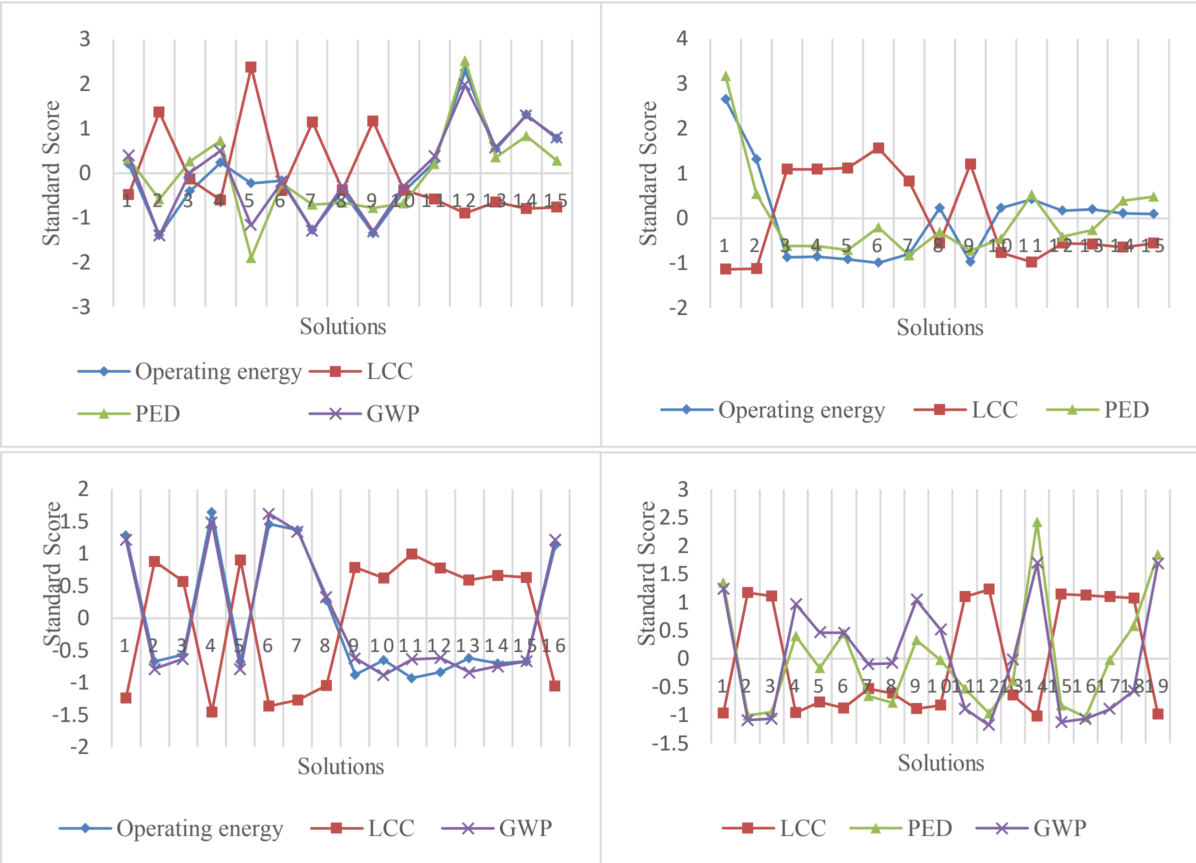

Figure 4. The standardized Pareto optimal solution sets.

By using Design Explorer[10] to visualize the optimal solution set and the related 3D models, it can be seen from Figure 5 that the solution space of geometric and material parameters are scattered. Architects need to make a subjective choice.

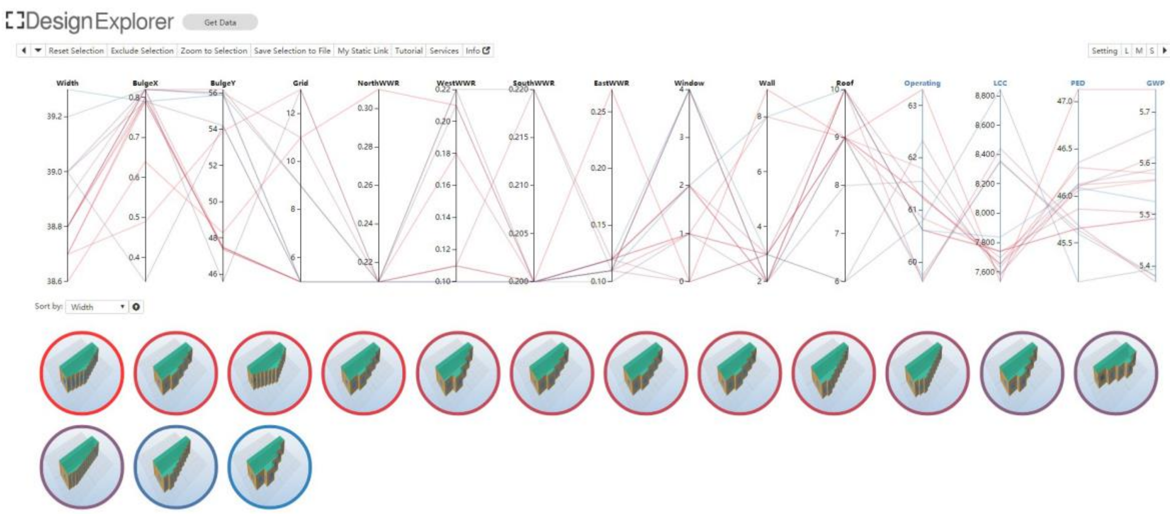

Figure 5. Pareto optimal solution set of OE/LCC/PED/GWP scenario.

4. Discussion

For each scenario, the optimal solution set obtained by this experimental framework is only more than ten, which can be used for manual comparison. The selection process by the architect can be based on specific values. For example, each objective is normalized in the set and summed to obtain a total score (the lower the better) for comparison, or only the LCC (or initial cost) which below the average cost is selected (Figure 6). Also, it can be considered from the architectural form: whether the optimal solution geometry meets the size of the exhibits or the site and surroundings.

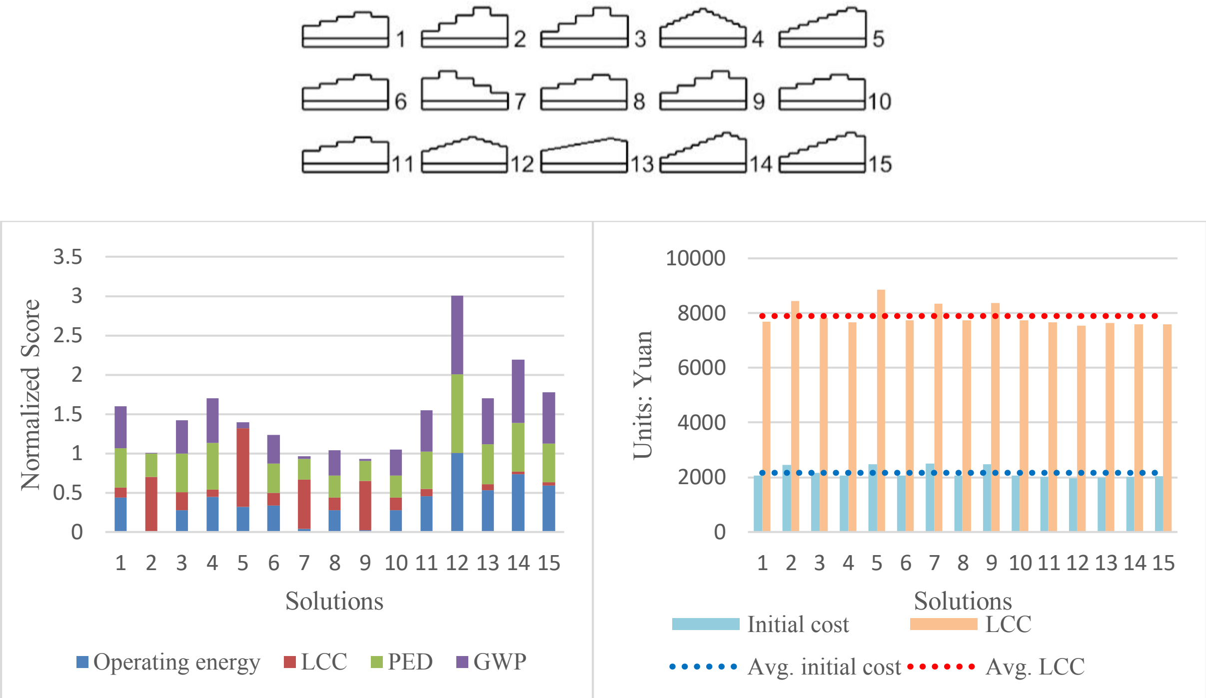

Figure 6. The OE/LCC/PED/GWP scenario's optimal solution set. Solution No.9 has the lowest sum normalized score (left) and solution No. 1/3/4/6/8/10/11/12/13/14/15's initial cost and LCC are both under the average (right).

The interpretation of the same optimization objective in different optimization scenarios is also different. When there is no explicit requirement, including as many optimization objectives as possible can ensure the generation of the optimal solution set after the multi-objective optimization process. Otherwise it can lead to poor performance of the unconsidered objective. In this study, the LCC value of the optimal solution from the OE/PED/GEP scenario is 8652.74 Yuan/m^2. The average LCC of the optimal solution set from the OE/LCC/PED/GEP scenario is 7893.48 Yuan/m^2, and the minimum value is 7534.19 Yuan/m^2. When comparing the values of the parameters between the optimal solution sets in different scenarios, it is found that there is no set of solutions with all eleven variables close to each other. This also proves that there is no clear linear relationship between the optimization objectives.

5. Conclusions and future work

This study attempts to optimize the parameters of building performance, environmental impact and LCC from the process of the initial stages of the architectural design. It is more detailed than the previous research in the geometry of the shape, but it also leads to a problem that the model is only for this project and cannot be reused. The relationship between the objective functions and the consistent and inconsistent among the optimizations with different objectives also requires more case studies to prove its universality.

Future work should be broken down into the early stages of design and deepened into the late stages, combined with BIM models and databases for detailed calculations. Another issue is that the original plan is to use local LCA data, but the Chinese database currently only has a small number of basic building materials, the EPD data from the manufacturers is also lacking, which is necessary for improvement in the future.

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Early Design Stage Building LCA using The LCAbyg Tool: New Strategies For Bridging The Data Gap

Kanafani K[1], Kjær Zimmermann R[1], Nygaard Rasmussen F[1], Birgisdóttir H[1]

[1] Danish Building Research Institute, Aalborg University, A.C. Meyers Vænge 15, 2450 Copenhagen, Denmark

kak@sbi.aau.dk

Abstract. There is an increasing demand for Life Cycle Assessment (LCA) as a method for environmental impact and resource assessments of buildings. At early design stages, where major design decisions are made, the potential for improving the environmental performance using LCA is greatest. However, detailed building information is usually not available at this time. This paper presents the recent extension of LCAbyg, the official Danish building LCA-tool, integrating an LCA approach for situations, where building design and material choices are not yet fully determined. The tool assists the user in establishing a complete building inventory by providing a default component library including building services and a guide for estimating quantities. Default components in the library are based on the integrated product database Ökobaudat. A convenient generation and comparison of variants improves usability, while a new LCA design guide shall increase the uptake of LCA in larger parts of the building industry. The methodological choices of the approach are laid out and discussed. The presented approach is not limited for use in early stages, but may improve feasibility in building LCA in general as default and estimated values may be refined towards more detail in later stages of the project.

1. Introduction

Life cycle assessment (LCA) has become a widely accepted approach for assessing the environmental performance of buildings. Comprehensive LCA, however, require expert competencies, a considerable data processing and advanced calculation tools and databases. In order to increase feasibility and making it a routine building parameter, LCA is often conducted based on simplifications, such as in green building certification schemes, which have been a driver for the uptake of LCA in the built environment [1][2][3][4].

In Denmark, LCA requirements for integration into the Building Code are currently under development. As a precondition, the requirements shall be voluntary to follow and feasible for broader parts of the building sector. This paper proposes a simplified approach to LCA, allowing a feasible and low-cost adoption at the current state of the industry. Based on LCAbyg, a free building LCA tool recognized by DGNB in Denmark [5], the approach is implemented in the new version LCAbyg 4.0 beta [6].

Existing LCA simplification often includes reducing the number of parameters in the building life cycle or the functional unit, which may be called a horizontal approach. Simplification by reducing data quality and allowing generic data address information depth and may belong to a vertical approach.

Integrating LCA feedback in early design stages, where major decisions can be made, is essential for meeting a given benchmark at a later stage of the project [7]. Here, feasibility is dependent on the level of integration into existing workflows, since clients cannot be expected to accept the cost for advancing detailed design e.g. regarding building services or structural analysis solely for achieving a complete LCA inventory. However, there are different strategies for filling data gaps.

Some research contributions attempt at identifying critical parameters with greatest relevance or sensitivity to variation regarding the overall result in order to omit other parameters for workload [2][8][9][7]. Selective approaches are dependent on knowledge on the relevance and sensitivity of included building parts for all the cases to which an LCA is applied, however studies are limited to a narrow range of building types and properties [9][8]. The same problem of generalization applies to the level of detail in a given building element, where often neglected products show varying relative influence depending on the construction principle, building type or other variables[10]. Common to a selective approach is an uncertainty related to the omitted parameters.

Another approach is pursuing a complete and detailed inventory from the start. As a full building model is usually not available, this approach is dependent on a reliable methods for bridging missing input data related to building design, material choice and environmental impact.

A possible, emerging solution is linking LCA with existing BIM/CAD models [11][12]. Here, feasibility is dependent on the question, if digital models with suited data structure are already used in early design stages and if eventually more parameters such as energy and indoor environment are assigned to a shared model.

Yet, complete and detailed inventories may be achieved by manual input as well. Similar to the BIM approach, this solution shares the dependency on data bridging methods. Manual inputs are independent from the adoption of certain design tools and potential data compatibility issues in early design. Crucial for feasibility is the availability of default values and an easy transfer of quantities, which are based on already available information in concept design.

The manual input approach is chosen, because it is expected to meet the requirements of an LCA tool adoptable for most of the building practitioners and different projects type and scale. The new functions are implemented in the existing LCAbyg tool enabling building generalists to integrate LCA into early stages of design, eventually pursuing a DGNB screening, however, and providing a seamless adaptability for further refinement e.g. later full DGNB reportings. LCAbyg already uses a simplified system boundary including the product stage, replacements, operational energy and End-of-Life stages [13], see the feature list in the appendix.

2. Method

The three main features presented are a component library, guided quantification and comparison of variants (figure 1). A case study-based test of deviation compared to LCA with specific inventory is presented in a separate paper [14]. The project was carried out in collaboration with architects, civil engineers, surveyors and other representatives from the Danish building sector in series of open workshops in 2017/18.

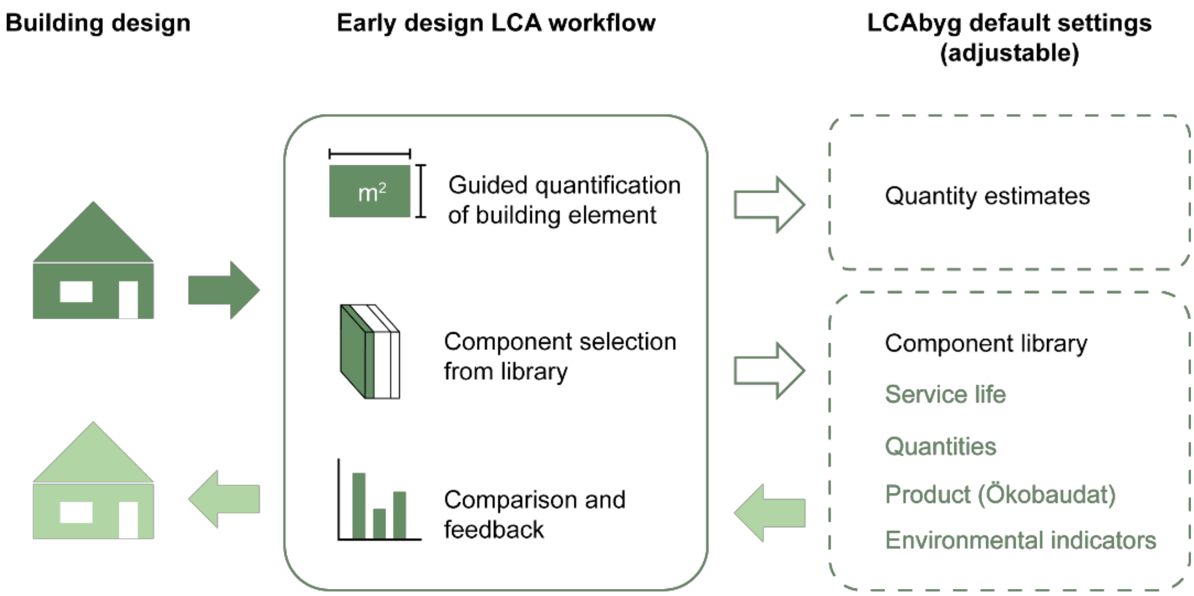

Figure 1. Early design LCA approach: Key elements include guided quantification, component library and comparison & feedback

3. Proposed early design approach

3.1. Default component library

A default library is proposed for bridging incomplete information on the detailing of the building model – or just for quicker and more convenient data input in general. Components are based on the data structure level between building elements and building products (table 1).

Table 1. Building model structure

Level	Function	Example
Element category	Main building parts	*External wall*
Element subcategory	Quantity estimation rules for specific kinds of building elements	*External basement wall*
Element	A member of the actual building design	*Specific wall in project*
Component	Functional layer of an element	*Brick wall with EPS insulation*
Product (Ökobaudat)	Includes quantities and service life	*Brick*
Stage	Environmental life cycle data	*Brick production (A1-3)*

Components consist of aggregated products and are functionally independent layers (figure 2). Making use of the already integrated database Ökobaudat, products are further aggregated to components (table 1). The layering method has been innovated by the previous LCA-profiles approach[15], however with different rules for layer division. The present approach is based on a load-bearing and insulating core layer (figure 2). Including both functions in one layer allows for specifying their mutual quantities, as in framed constructions and for better compatibility among all layers in general. This approach, though, requires a larger number of core samples in each element category in order to provide a palette of different dimensions and insulation types.

The two remaining layers cover the core from each side. These layers do not need to be scaled within each solution as much as the core allowing for a greater variety of solutions for covering layers. Scaling may include fire protection or acoustic insulation functions.

A given exterior wall might for instance include plaster rendering as interior layer (1), a brick wall with EPS-insulation as the core layer (2) and a facing brick façade layer (3).

Non-planar building elements use the layer structure conceptually for functionally independent system parts such as production (layer 1), distribution (2) and terminal units (3) in building services (table 2).

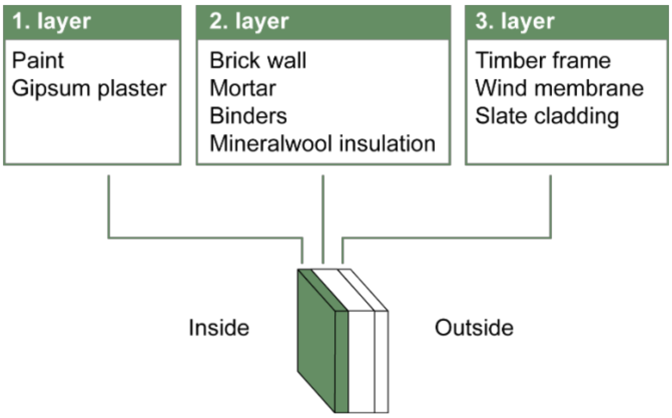

Figure 2. Layering of building elements. Example of an exterior wall divided into three functional layers. The individual layers can be replaced by compatible items from the component library.

The library offers sufficient components for modelling inventories of all supported building types. A complete level of detail including membranes and fastening is pursued, however joints between elements, corners or overlaps are not considered in most of components.

Both detailing and assignment of environmental product data follow conservative assumptions, such as low-energy insulation, ample dimensioning and tight grids. The approach tries to avoid rewarding the use of default values by accepting slightly higher mass and environmental impact compared with LCA based on complete specific inventory data.

Table 2. The function of levels and number of variants

Element category	#	Layer 1	#	Layer 2	#	Layer 3	# 1-3
Foundations	13	Foundations		-		-	13
Ground floor slabs	15	Flooring	3	Load-bearing system	2	Insulation and underlay	15
External walls	17	Inside finishing	31	Load-bearing and insulating system	19	Façade system	67
Internal walls	15	Finishing	25	Load-bearing and insulating system	16	Finishing	56
Floor decks	15	Flooring	11	Load-bearing and insulating system	12	Ceiling	38

Element category	#	Layer 1	#	Layer 2	#	Layer 3	# 1-3
Stairs and ramps[2]	0	Structure	0	Flooring	0	Balustrades and handrails	0
Columns and beams	84	Columns and beams		-		-	84
Balconies	5	Platform	8	-	3	-	16
Roofs	7	Roof cladding	20	Load-bearing and insulating system	12	Ceiling	39
Windows, doors, glazing systems	18	Profiles[1]	2	Panes	0	Solar shading[2]	20
Building services[3]	18	Production unit	6	Distribution	3	Terminal unit	27

3.2. Guided quantification

LCAbyg provides help for estimating quantities within a couple of element subcategories requiring no more than the information given in concept design (table 4). Some guidelines are mere intermediate calculations integrated in the tool, while others are based on actual default values based on estimates. The latter includes building services, balconies and foundations.

Guided quantification is presented as a proposal in a permanent wizard section of the programme window. As a principle, the user has to actively select the transfer from the wizard to the model every time, an adjustment is performed in order to prevent unintended change of quantities. User help text explains the assumptions and procedures related to every estimate. The calculation of relevant quantity suggestions requires the placement of building elements under correct subcategories and a minimum building information (table 3).

Table 3. Required basic building information input

Building type
Gross area
Gross area, heated
Gross area over terrain
Floor-to-floor height
Number of basement floors

Table 4. Required input for element quantification

Element category	Element subcategory	Required quantity input[4]
Foundations	Strip footings, deep	Length
	Pad foundations, shallow	Number
	Pad foundations	Number
	Pile foundations	-

[1] Including full product datasets, which are not divided into components, e.g. doors
[2] Not implemented yet
[3] Includes the categories drainage, electrical systems, water systems, ventilation/cooling and heating
[4] Minimum input refers to assigning area-based quantities to the components. Not included is the specification og layer thickness and basis building data (table 3)

Element category	Element subcategory	Required quantity input[4]
Ground floor deck	Ground floor deck	-
External walls	Basement external walls	Length
	External walls	Length
Partition walls	Non-load-bearing basement walls	Length
	Load-bearing basement walls	Length
	Non-load-bearing walls	Length
	Load-bearing walls	Length
Floor deck	Ground floor deck	-
	Floor deck	-
Stairs and ramps	Stairs and ramps	Number
Columns and beams	Columns	Number
	Beams	Length
	Fire protection	-
Balconies	Platform	Length, width
	Balustrades and handrails	Length, width
	Mounting	Number of balconies
Roofs	Roofs	Inclination
Windows, doors, glazing systems	Windows	Window number and area or Window-facade ratio and facade area
	Doors	Number, area
	Glazing systems	Area
Drainage	Plumbing	-
	Down comer	-
Drinking water	Production unit	Number of shafts
	Plumbing	Number of shafts
Space heating	Production unit	-
	Plumbing	Number of shafts
	Radiators	-
	Underfloor heating	-
Ventilation and cooling	Production unit	-
	Ductwork	Number of shafts

3.3. Comparison & feedback

The tool offers data comparison in different ways. First, Items on any level may be compared by checking a box. Up to five items can be displayed in a graph showing results within three indicators. Alternatively, comparison may be performed already in the dialogue window for selecting new items from the library. Finally, the currently opened project can be compared with a number of other projects, results are aggregated on building level.

Separate projects files can be opened in multiple windows, eventually for generating variants or for review reasons. Input changes are immediately shown in the results, although these changes are not traced or marked for immediate review.

4. Conclusions and discussion

An early design approach has been developed and implemented based on existing simplifications and integrated product database in LCAbyg. New functions include a default component library and a guide for estimating material quantities in order to fill incomplete data with default values. Focus has been on guiding practitioners to achieve a complete and detailed inventory and allowing for variant-based design.

Since the system boundary given in LCAbyg 3.2 is already simplified and all stages for embodied impacts are being calculated by default, a further simplification by reducing stages would not increase feasibility.

The functional unit is based on a whole building approach and a detailed and complete inventory already in early design. The effort and robustness of achieving a full detail and complete model has been evaluated more manageable than managing uncertainty in a reduced inventory approach. Here, simplification refers to making full detail inventories as simple to generate and manage as possible.

Functional layers make the detailing of building elements manageable, since the user selects solution packages without having to specify every single product, its dimension and quantity.

Further, the user is guided through specifying a number of element quantities including those, which often remain undefined in concept design such as foundations and building services. Inventory input is based on information on quantities, which usually will be available during concept design such as wall length, storey height and number of cores. Insulation thickness is given by default, however dimensions of load-bearing walls, columns or beams have to be selected from a handful of choices, since this information is evaluated difficult to generalize.

The full and complete inventory approach is expected to reduce the risk of incomplete Bill of Masses, however, the risk is being transferred to the reliability of default quantities and components. This uncertainty is sought to be addressed by making conservative assumptions and choices in specifying dimensions, included products, membranes, densities, lambda-values or selection of environmental dataset. Ideally, this in-built uncertainty margin shall lead to slightly higher mass and impact results in the early stages. However, guided input and default values are optional to use and may be edited or replaced as the project evolves and specific data becomes available.

Since the project result may serve as a prototype for potential LCA regulation in the building code, the solution had to be accessible to a large variety of actors and projects under the given digitalization level in the Danish building sector. A stand-alone LCA tool is proposed in order to achieve robustness in light of a diversity of workflows.

5. Perspective

Component library and quantity estimates will need further testing and feedback from practical use in order to better meet real life building inventories. Future improvements in usability may be achieved by integrating a visual representation of components or results, a sensitivity analysis module and the integration with building design tools.

Acknowledgements

The authors wish to thank the numerous building practitioners, which have participated in workshops on the development of the tool and component library and for testing the approach on their projects. Thanks also to Karoline Geneser and Steen Haugaard from Moe consulting engineers for estimating quantities of building services as well as Thomas Cornelius from the Danish Building Research Institute for estimating dimensions of load bearing elements. The project was supported by ELFORSK, the Danish Energy's research and development programme.

Appendix: LCAbyg 3.2 and new features in LCAbyg 4.0 beta[5]

Topic	Feature	Definition	New
Input	Building model structure	Default building model structure (table 1)	x
	Data exchange	Import/export on all levels of detail, manual EPD input, project export to Microsoft Excel format	
	Default database (product)	Building product library, adopted from Ökobaudat 2016	
	Default database (component)	Component library covering solutions for all supported building types, 3-layer structure, conservative assumptions	x
	Reference study period	Guidance in national report [16]	
	Service life	Guidance in national report [16]	
	Environmental indicators	GWP, ODP, POCP, AP, EP, ADPe, ADPf, PEtot, Sek	
	System boundary	A1-3, B4, B6, C3-4	
Output	Quantification	Bill of Quantities including assigned service life	
	Score	Aggregated score on all levels between building and product life cycle module (all supported environmental indicators)	
	Functional unit	Buildings in total, gross area or gross area / year	
Usability	User support	Built-in user guide (revised version), no user forum	
	Learning resources	Publication[6] introducing early design LCA	x
	Flexibility & adaptability	Default building model structure and component library are optional	
	Incomplete inventory support	Guided quantity estimation, building model structure as a checklist for completeness	x
	Building types	Residential (detached / terraced, multi-storey), school / day-care, office	
	Data review/change	Component dimensioning indirectly available by a variation in the library. Responsive quantity estimation based on a few available variables (table 3)	x
	Loss of data	No auto save or undo/redo functions	
	Variant-based design	Create, replace and duplicate functions on all instances. Variants are stored in the project file. Persistent user data can alternatively be stored by using export/import (external user database)	x
	Comparison & feedback loops	Variant comparison on the level of elements, components, products and stages both in the model or dialogue for selecting new items. Project comparison on building level. Multi-window work possible	x
	Visual editor	No visual representation of the building	
	Proposal generator	No automatic solution generation	
	Integration with other tools	No direct link. Developer solution for indirect BIM-integration	
	Results informing design decisions	Exportable results in table and graph format, mass and indicators aggregated on all instances and indicators. They include operational/embodied impacts comparison, accumulated life cycle impact, hot-spot analysis, and DGNB reference values. Export to Microsoft Excel format for further data analysis.	
	Normalization	CML 2001	
	Documentation	Report generator including a selection of results.	
	Uncertainty	No integrated sensitivity analysis	
	Calculation time	Real-time calculation and results	

[5] The feature list is based on the requirements for early design LCA tools by [17]
[6] Publication with guidance on early design LCA [18]

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Early Design Stage Building LCA using the LCAbyg tool: Comparing Cases for Early Stage and Detailed LCA Approaches

Kjær Zimmermann R[1], Kanafani K[1], Nygaard Rasmussen F[1], Birgisdóttir H[1]

[1] Danish Building Research Institute, Aalborg University, A.C. Meyers Vænge 15, 2450 Copenhagen, Denmark

rkz@sbi.aau.dk

Abstract. Life Cycle Assessment (LCA) is used and accepted as a method to assess environmental impacts and resource use of buildings. In practice, LCA is typically used in stages where the design of the building is already finalized. However, LCA-calculations from early design stages can be used actively in design and optimization of the building. One of the obstacles to early stage LCA is that extensive data input on precise material types and amounts is needed, which is limited in early design stages. The simplifications needed for a designer in an early design LCA is addressed in a research project, where an extensive library of predefined building components and installations were developed and integrated into the existing Danish LCAbyg tool. The library assists the user in establishing a full building inventory by simple inputs of geometry of the building and a selection from the library of building element layers. However, the simplified approach to LCA of a building at early design stages inevitably affects results compared with results of a calculation made at later design stages where more, specific data is available. This paper presents an evaluation of building cases, modelled with the same background database and life cycle stages, using the simplified early design LCA approach and a detailed LCA approach. The evaluation includes testing of how well the predefined components in the early design approach fit with the case buildings and comparisons of the total material input and precision of the final LCA results.

1. Introduction

1.1. Early design LCA for buildings

Life Cycle Assessment (LCA) is an established and widely used method for assessing and documenting the environmental impact and resource use for products and services.

Conducting a full scope and detailed building model LCA requires both qualifications and large amounts of documentation. Full scope LCA's on buildings are thus rarely made [1,2]. The LCA scope is typically adjusted to a more simplified LCA approach that includes less processes, for instance by reducing the number of life cycle stages, which is also the recommended approach in the sustainability initiatives from the European Commission's Joint Research Centre Level(s) and EeBGuide [3][4]]. But even with these simplifications, the work going into a building LCA is still very large: For instance, it requires inputs of quantity and product type for all the materials used.

In the early design phases of the building project it is an even larger challenge to quantify and specify building products because final dimensions are not known and several design options may need to be compared. However, the early design phases are the phases when informed decisions can be made. The LCA-task should therefore be easy and fast in early design phases.

Approaches for early design tools for LCA include simplifying the method even further with a selective approach; by only including elements that have the greatest relevance to the results [5]. Another approach is to use predefined elements from a library which is also a recommended approach for early design environmental assessment tools [6]. This is the approach used in the new LCAbyg tool

1.2. LCAbyg tool – Early design functions in version 4.0 Beta

In the new version of LCAbyg (version 4.0 beta), a library-based simplification approach has been used [7]. LCAbyg is a free tool from Denmark for performing LCA on buildings [8,9]. The predefined component library in version 4.0 beta contains building products that are bundled together in typical or conservative dimensions. For estimating quantities, the tool introduces a "guided inventory input". The tool is designed to be used in all stages of the building project, and it is therefore possible to adjust dimension in the component library, as more knowledge becomes available in the project.

LCAbyg 4.0 Beta differs from the existing LCAbyg version 3.2 only by introducing the above mentioned functions. The calculations are based on the same selected life cycle stages and LCIA data.

1.3. Evaluating early design approach

When using an early design approach with a library of building components, the results will naturally vary from the detailed LCA approach. Testing the performance of the early design tool compared to a more detailed LCA is therefore relevant for estimating if the tool gives a true representation of the building's environmental performance. This can be evaluated by testing the early design approach against a more detailed approach.

A similar evaluation has previously been done in the library based (and simplified geometry) early design tool, LCAP [10], where the performance of the early design tool is tested against a more detailed LCA approach [11]. The result is 4-19% lower in global warming potential (GWP) for the buildings where the early design tool was used. The reduced impact is mainly due to the exclusion of some building elements in the early design tool, including building services and internal doors.

In LCAbyg 4.0 Beta, the early design approach has a comprehensive component library, that also includes several building services and the completeness of the inventory is high. The component library uses conservative estimates in terms of material use and LCIA data. Contrary to the LCAP-tool, the impact from the materials in the early design approach should therefore give higher impacts than a detailed approach because the catalogue is conservative and completeness is higher than a typical LCA on building.

This paper evaluates building cases where a detailed LCA has been performed with an early design component library-based LCA approach using two generations of the tool, LCAbyg (version 3.2 and 4.0 beta). The evaluation will consider the inventory of cases with a detailed LCA approach compared with component library in early stage approach, and the mass and impact in GWP of the two approaches. Lastly the precision of the early design approach will be estimated.

2. Method

2.1. Study samples

The case samples presented in table 1 consists of three residential buildings that have been certified with the Danish version of DGNB certification system for sustainable buildings [12]. The buildings are completed between 2016 and 2018. The cases are selected because they represent different material compositions: One with wooden-frames, one in Cross Laminated Timber (CLT), and the final with concrete walls and wooden roof.

Table 1. Case buildings

	Building type	Description
Case A	Residential, Terraced house	*Foundation and ground floor slab*: concrete, EPS insulation *Walls and slabs/roof:* prefab wood elements, mineral wool insulation *Surfaces:* paint on internal surfaces, externally plaster on ventilated facade and roofing felt on roof.
Case B	Residential, Multi-family building	*Foundation and ground floor slab*: concrete, EPS insulation *Walls and slabs/roof:* CLT wall elements with columns and beams in steel and wood, slabs in concrete/CLT-hybrid, truss roof, mineral wool and cellulose insulation *Surfaces* in wood and roofing felt on roof.
Case C	Residential, Terraced house	*Foundation and ground floor slab*: concrete, EPS insulation *Walls and slabs/roof:* concrete walls with roof in wood and CLT. Mineral wool insulation. Structure with steel and wood beams and columns. *Surfaces:* paint on internal surfaces, externally brick and roofing felt on roof.

2.2. Scenarios

The early design approach for LCA is evaluated through three modeling scenarios listed in table 2. BL scenario has been calculated using LCAbyg 3.2, while LCAbyg 4.0 is used for scenarios ED1 and 2 in order to make use of the new component library.

Table 2. Scenarios

Abbr.	Scenario	Inventory
BL	Baseline (detailed approach)	**Specific inventory** taken from DGNB-certified cases. Example (wall): Actual wall area with material type and dimension according to inventory from DGNB.
ED1	Early design 1	**Component library.** A combination of predefined components from library and specific element areas from DGNB-certified cases. Example (wall): Actual wall area, but material type and dimension according to the closest match available in the component library.
ED2	Early design 2	**Adjusted component library.** Same as ED1, but with adjustments of materials type and dimensions. Example (wall): Actual wall area with material type and dimension according to inventory from DGNB, however, without removing extra library elements such as paint, connecters etc. (which may not be included in BL).

BL is the life cycle inventory taken from cases, which have been DGNB certified. The inventory elements from the three cases can be seen in table 3.

ED1 uses the component library to match material type and dimensions of the building elements in the cases as good as possible.

ED2 follows ED1, however, dimensions and material type for major elements in the building structure and insulation have been adjusted where needed according to the original case inventory. Table 3 shows all adjustments and their nature, may it be changes in material property or quantity.

Scenarios ED1 and ED2 include all the element layers listed in table 3 (if applicable), thus making the building inventory more complete than the detailed approach (BL). For estimating quantities in the element layers that are not included in the DGNB cases (and therefore no data is available); the "guided inventory input" from LCAbyg 4.0 Beta is used. The guided inventory input uses basic building information including gross and heated floor area, floor height, no. of floors etc. for estimating quantities. In this study only the technical installations have been estimated, if they are not already given in the DGNB cases.

Table 3. Inventory scheme. Level of completeness and adjustments are given for all cases and scenarios. Columns BL show the as-is state of completeness in the DGNB cases. Columns ED2 show the adjustments made. Scenario ED1 uses library material choice and detailing for all element layers and is not shown.

Building element	Element layers	Case A		Case B		Case C	
		BL	ED2	BL	ED2	BL	ED2
Foundations	Foundations	x		x		(x)	
Ground floor slab	Flooring	x		x		x	
	Load-bearing system	x	m	x	q	x	q
	Insulation and underlay	(x)	q	(x)		x	q
External walls	Inside finishing	(x)		n/a		x	
	Load-bearing and insulating system	x	q, m	x	q, m	x	q
	Façade system	x		x	m	x	
Internal walls	Finishing	x		x		x	
	Load-bearing	x	q, m	x	q, m	x	q
	Finishing	x		n/a		x	
Floor deck	Flooring	x		x		x	
	Load-bearing and insulating system	x	q	x	q	x	q, m
	Ceiling	(x)		x		x	
Columns and beams	Columns and beams	n/a		x		n/a	
	Finishing	n/a		-		n/a	
Balconies	Platform	x	q	n/a		n/a	
	Mounting	-		n/a		n/a	
	Balustrates and handrails	x		n/a		n/a	
Roof	Roof cladding	x		x		x	
	Load-bearing and insulating system	x	q, m	x	q, m	x	q, m
	Ceiling	x		x		x	
Windows, doors, glazing systems	Profiles	x		x		x	q
	Panes	x		x		x	
	Doors	x		-		x	
Drainage	Soil pipe	-		-		-	
	Down comer	x		-		-	
Drinking water	Hot water tank	-		-		x	
	Piping	x		-		-	
Space heating	Supply	x		-		-	
	Piping	n/a		-		-	
	Radiator / floor heating	x		x		-	
Ventilation and cooling	Supply	-		x		-	
	Ductwork	x		-		-	
Electrical units	PV-panels	x		n/a		x	

BL: [x] complete or including main elements. [(x)] poor completeness within the element layer. [-] not included. [n/a]: not relevant to case.
ED2: [q] quantity adjustments. [m] material adjustments.

2.3. *Life cycle assessment*

The LCA is conducted in compliance with the standards ISO 14040-44 and [13,14] EN 15978 standard [15] for LCA on buildings. The functional equivalent is set to 1 m^2 residential gross floor area. The LCA includes the following life cycle stages: A1-A3 production of building products, B4 replacement of building products in use stage, C3-C4 waste treatment and disposal of building products at End of Life (EoL). Operational energy consumption (stage B6) is not included in the LCA, due to the study's focus on impacts related to embodied materials. The LCA uses a reference study period of 100 years following the Danish guidelines on building's service life [16]. This report also provide service lives for building products, which are used for estimating the number of replacements of building products in the use stage (B4).

The modelling is carried out in two generations of the Danish LCAbyg tool. Both tools use the same LCIA database, which consists of mainly extracts of Ökobau generic database from version 2016. In the Ökobau database the life cycle impact assessment is done with characterisation method

CML-IA baseline version 4.1. The study only reports on the impact category Global Warming Potential (GWP), for simplicity reasons.

3. Results

3.1. Impacts from early design scenarios

Impacts for GWP can be seen in figure 1 for the three scenarios. Using the early design tool (scenario ED1) gives a higher impact of 18-42% for the whole building compared to the detailed LCA approach. This is due to the additional building elements, the conservative materials estimation and the completeness of inventory from the early design approach.

The library material estimates are adjusted to the specific case in scenario ED2; here the impacts in GWP for the building cases are still higher than BL, but for cases B and C the GWP has decreased from 42% down to 31% and from 27% to 21% above BL. However, case A has an increase in GWP from 18% to 33% higher than BL. One of the reasons case A increases is that the insulation quantity is underestimated in ED1. This is because case A is a low energy building and the house is more insulated than a house that only complies with operational energy demands from the Danish Building Code. Another reason is that the type of insulation material used some places in case A, has a substantially higher impact than the insulation in the case building, such as rigid mineral wool.

Insulation material also gives inaccurate results in case B, where the external walls in ED1, gives an impact three times that of BL and ED2, as shown in Figure 1. This is mainly due to use of cellulose insulation in the case building, which is not an option in the component library, see table 4. Furthermore the CLT dimensions is highly overestimated in the library layer because this is designed as a load carrying element, while the case element is not. A better option would have been to choose the frame construction in library, which has the opportunity to choose cellulose insulation. While most building elements have a higher impact in the early design scenarios, this is not the case for the foundation. For all cases; the impacts from foundation are smaller in early design scenarios, due to a smaller amount of materials used for the scenarios. Overall, however, figure 1 shows that on a building element level, the impacts from the early design approach in ED1 gives a good representation of the adjusted scenario impacts in ED2.

3.2. Impact related to inventory completeness

The impact from added inventory elements shown above the dotted line in figure 1 (these are the elements layers from table 3 that were not included in BL) contribute with between 3% and 20% of the building's total GWP, depending on case building and scenario. Case B has the smallest inclusion of building elements in BL, and consequently this is where we see the largest contribution when elements are added. The added impacts from building services and doors contribute notably in case B. Case A shows the lowest impact from only adding a number of elements in building services.

If we exclude the added elements from the early design inventory, thereby only including element layers that exist in BL, we get a clearer picture of the library's difference from BL when it comes to completeness and conservative estimates. These differences can be seen in the case results for scenario ED1, and shows that GWP is 14%, 21% and 19% above BL. When adjustments have been made in scenario ED2, the results provides an understanding of just the difference in completeness between early design approach and BL; the GWP is 29% higher for case A and only 9% and 12% higher for cases B and C than baseline.

The difference in completeness for Case A is substantially higher due to impacts from finishes on internal walls and from floors and ceiling on floor deck, roof and ground floor slab as illustrated in figure 1. The higher completeness comes from including the structure in floors and ceiling, and amounts of paint to cover all internal as well as inside parts of external walls, which was not adequate in the BL scenarios for case A.

For case B and C; the higher GWP also stems from finishes on walls and floor and ceilings, and for case B; the windows were missing materials for frame.

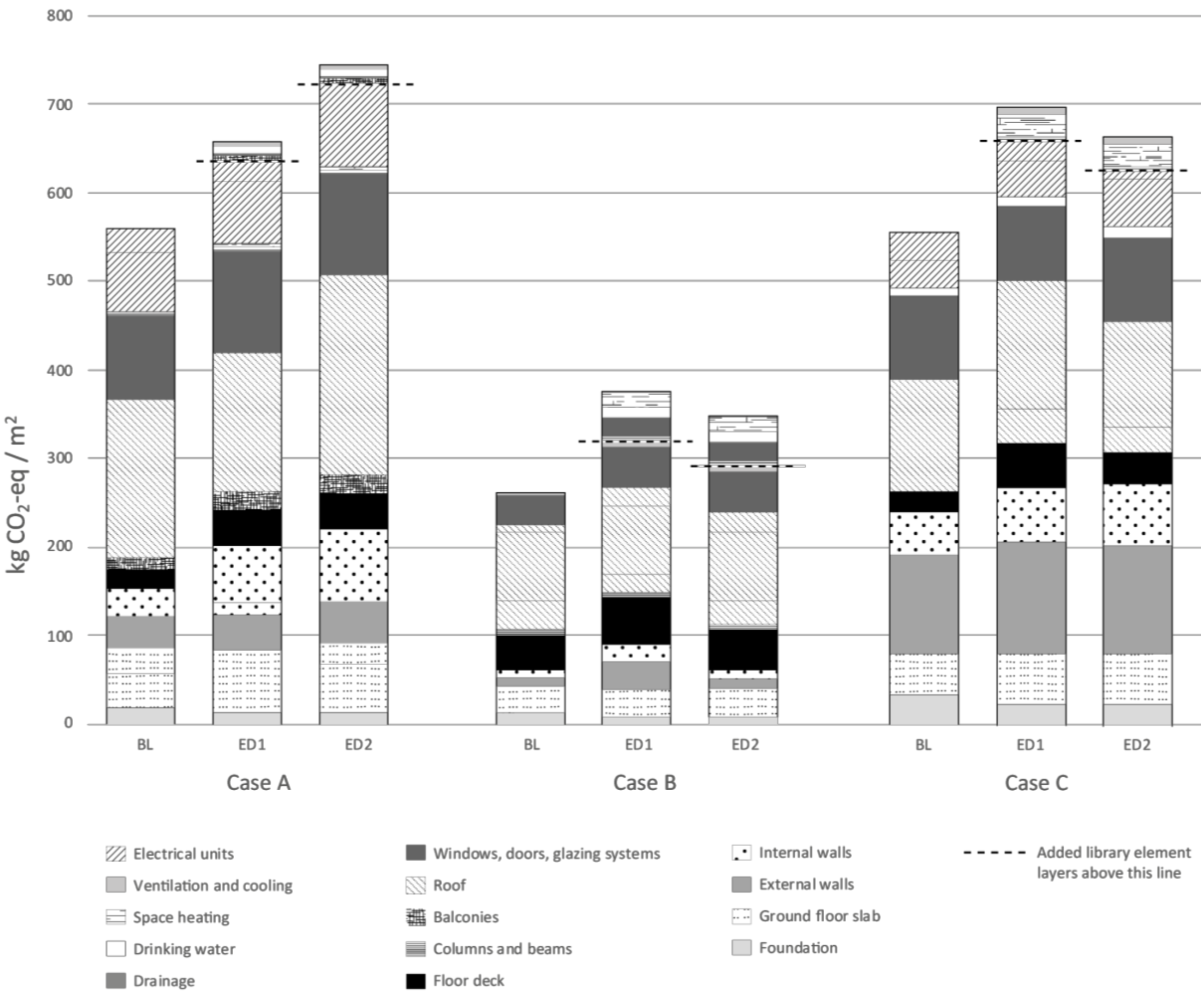

Figure 1. GWP impacts for building elements in the three case buildings for the different scenarios: Detailed approach (BL), early design (ED1), early design with adjustements of material and dimension (ED2). Included life cycle stages are A1-A3, B4 and C3-C4.

Table 4. Materials use of 1 m^2 external wall in case building B. The element has a notable difference in GWP for the three scenarios, mainly due to a different insulation type in the component library used in ED1.

BL		**ED1**		**ED2**	
260 mm	Cellulose fibre	300 mm	Mineral wool	*260* mm	Cellulose fibre
40 mm	CLT	100 mm	CLT	*40* mm	CLT
-	-	0.38 kg	Wood protection	-	-
30 mm	Pine wood	30 mm	Pine wood	30 mm	Pine wood
-	-	150 g	Screws, nails, fittings in galvanized steel	150 g	Screws, nails, fittings in galvanized steel
150 g	Aluminum profile	2 mm	Wood lists	2 mm	Wood lists
1 pcs	Plaster board, wind barrier	1 pcs	Plaster board, wind barrier	1 pcs	Plaster board, wind barrier

3.3. Correlation of mass and impact for early design scenarios

In early design scenarios both material mass and GWP is increased compared to BL scenario, the relation to BL on mass and GWP can be seen in Figure 2. For cases B and C, the GWP has increased substantially more than the mass, implying that the extra material included in the component library has a large impact on GWP compared to the existing mass. A specific example of this is the internal walls in case B: In scenario B2 the increase in mass is 7 %, while the increase in GWP is 54%. This is due to adding material elements such as paint and membrane conjoining wet rooms, which are materials with high impact in GWP per mass.

Case A shows the opposite trend with a higher added mass, and lower GWP. This is mainly due to the gravel below the ground floor slab, which was not included in BL. Gravel has relatively low GWP per mass, which explains the results. If gravel is removed from the assessment; case A will have a mass compared to BL of 116%, which is similar to the trend for case B and C (103% and 113%). The reduced GWP from removing gravel is only from 133% to 132%, thereby showing a similar trend in case A; of higher increase in GWP than in mass when using ED-scenarios.

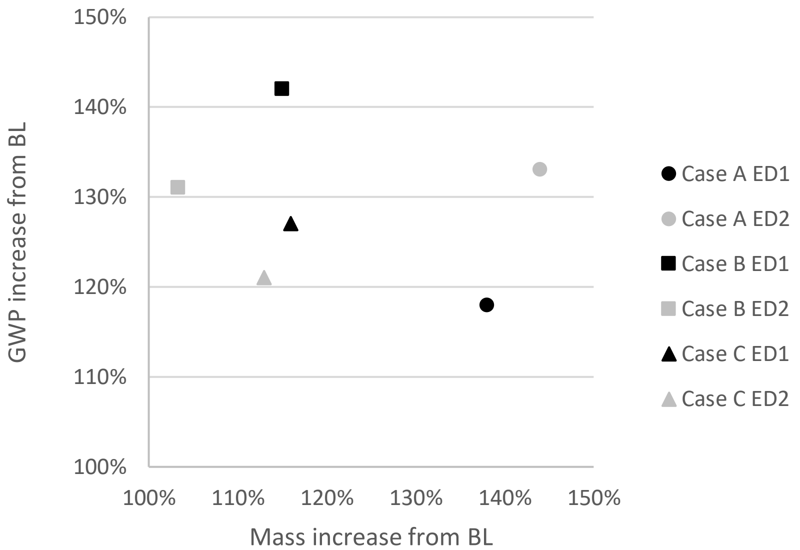

Figure 2. Mass and GWP of building cases for the two scenarios (ED1 and ED2) seen in relation to BL scenario (100 %).

4. Discussion

4.1. Component library

Differences in inventory completeness across the scenarios have shown to have a large impact on the results. The BL inventory both lack entire building elements and components or building products in the original cases. These additional materials included in the early design scenarios even shows to have a large impact on GWP when seen in relation to the building mass, making them an important part of the LCA.

The component library is conservative in estimating materials, especially insulating materials. The insulating materials is dimensioned to comply with building regulations in terms of thermal conductivity, where only the insulating material is used to dimension the thermal conductivity (without taking the remaining layers in the building element into account) [7]. However, special circumstances such as low energy buildings will likely surpass the dimension of insulating material in the component library, as was the case for case A. For low energy buildings and buildings that have special demands, the LCA practitioner must take it into account by adjusting dimensions of the insulating material first and foremost (this will likely be a natural process, because the practitioner, typically an architect or engineer, is aware of all elements that are not standard throughout designing). This will apply for all cases with special designs that are likely to make material use greater than the norm.

The same approach should apply to the material type used to insulation materials. Some of the notable differences in impacts in the component library estimates stem from the type of insulation material. The LCIA data used for rigid mineral wool has a much higher impact in GWP than normal mineral wool, and cellulose insulation, on the other hand, performs much better. When there is no cellulose to choose in the library, the results of the assessment will give a higher impact and thus a conservative estimation, which is as expected. However, when the rigid mineral wool cannot be chosen in the library, this can have a large impact on the results, giving the assumption that the building performs better than it actually does. In the component library of LCAbyg 4.0 Beta it is possible to choose elements with rigid insulation, just not for the particular structure used in Case A. A solution could be to include more types of insulation materials in the catalogue, however, a value of the catalogue is also that it is not too large.

4.2. Precision of results

The early design tool is evaluated by comparing with a detailed LCA, however, in material completeness, the early design tool can be considered even more 'detailed', than the detailed approach. Evaluating precision by comparing to the detailed approach would therefore be misleading.

The estimates on material and dimensions made in the component library, however, can be evaluated for GWP by looking at the two early design scenarios and the deviation in results from using the library (ED1) compared to the scenario where the library has been adjusted (ED2). For cases A, B and C the library shows a deviation in results of -12%, 11% and 6%, (not including the added library elements, which will only make the difference smaller). The precision of the component library can therefore be considered to be within a deviation of 12% of result, which is considered good for early design. Case A is negative due to the wrong type and quantity of insulation from the library. However, Case B and C are conservative in the estimated impact, which is typically considered a quality in early design, especially if the goal is to gain a certain amount of points for i.e. green certifications.

Only GWP was investigated in this study, however, other impact categories will be necessary for a broader approach to environmental performance.

5. Conclusion

As expected; the ED-tool gives a higher GWP impact overall than the detailed LCA. This is because the early design approach is more conservative in estimating materials and has a higher completeness in material use: both by including more of the typical building elements such as building systems and by providing a more complete bill of materials for the defined element layers, for instance by including finishes of elements such as paint as well as membranes, fastenings and structures for build-up floor, ceilings etc. These added elements in the early design approach contributed to a high increase in GWP compared to their mass contribution, which hints to the importance of including these elements for a better understanding of impacts from buildings.

The component library used in the early design approach overall gives a good representation of the building, however, in some cases it is important to the result, to specify material type and dimensions, especially for insulating materials. However, without specification, the precision of estimates made on material type and dimension in the component library is within a deviation of 12% of the result, which is considered good for early design.

Acknowledgements

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Evaluation of BIM based LCA in early design phase (low LOD) of buildings

Nilsen M, Bohne R A

Norwegian University of Science and Technology

matsnil@stud.ntnu.no

Abstract. Building Information Modelling (BIM) is a convenient tool that is capable of collecting information throughout the whole life cycle of a building in one platform. The evolution in the digital BIM model in early design stages is not standardized, but Level of Development (LOD) is a concept that systematically structures the design processes divided into five levels. LOD is assessed in this paper as an opportunity to enhance the calculation of the environmental impacts in different early design stages more efficiently, using the methodology Life Cycle Assessment (LCA). Enlightening the building elements that contribute to highest release of CO_2, permits early building material selection. This facilitates a pathway towards sustainable and environmentally friendly buildings. This study evaluates BIM based LCA in early design stages (low LOD) through literature reviews and a case study. This papers' case study executes LCAs at different LOD levels using the LCA software One Click LCA (OCL). Assessments in LOD 200, LOD 300, LOD 350 and an additional LOD 350 were utilized. The additional LOD 350 was deployed when LCA experts had implemented changes within OCL. Moreover, a concretized suggestion where today's unpredictable development of BIM becomes part of a LOD framework is proposed.

1 Introduction

There are several basic, well-established scientific links that constitute the background for this report. The UN Intergovernmental Panel on Climate Change (IPCC) states that the human fingerprint on greenhouse gases (GHGs) have risen to record levels not seen in three million years [1]. There are limitations to adaption and adaptive capacity for human and natural systems, but most adaptation needs will be lower for global warming of 1.5 °C compared to 2 °C according to the Paris Agreement [2].

The proposal of this report is to investigate which features that are required in an interaction between BIM and LCA in the early design stage (low LOD), to evaluate the environmental performance of a building. In addition, this paper research question is how an early design LCA framework corresponds to LOD.

The sustainability of buildings is depending on several aspects. This report is evaluating one of them, namely the environmental impact of buildings regarding CO_2 emission. This study focuses on the LOD in the design stage using BIM, and how a BIM based LCA can help improve the environmental impacts, limited to buildings. The study is illustrated by one case study, Valle Wood in Oslo (Norway), and one LCA tool, OCL. Cradle to gate processes for materials and services used in construction is considered as the system boundary for the study [3]. The embodied energy is the energy required to produce the building materials, and it is related to the production stage (A1-A3) of the life cycle stages. Furthermore, the in-use energy is energy consumption related to the use stage, and will not be considered in this report. Moreover, the incidence of embodied energy in building energy analyses account for the major part (50 %) of the whole primary energy demand, compared to the operational energy stages in the use stage [4–6]. The built environment have the highest potential to limit the global warming [7], and therefor an LCA framework regards to LOD is proposed.

2 Method

2.1 Conduction of LCAs

Qualitative and quantitative methods are the basis of this report's results. The qualitative methods investigate the findings regarding the interactions between BIM and LCA, as well as how BIM based LCAs can be advantageously rendered through comprehensive literature reviews. BIM models were deliberated this study through document reviews, received from NCC. The quantitative LCA calculations on the BIM models are based on using quantity take-off generated by BIM, as well as one LCA using input data retrieved from designers in Valle Wood, to obtain environmental impact in OCL.

All smc files were made available through NCC's own PortWise Access Manager 4.12. In the same portal, all relevant documents were available such as subcontractors' drawings and calculations. In addition, description of materials were listed. This study took advantage of three different smc files and distinguished the LOD levels based on [8, 9] requirements. The different BIM models (Figure 2, 3 and 4) express maturity in the design.

(i) **.smc-file published February 2017 - LOD 200**. The model is represented with approximate quantities, size and shape. There are limited objects that are similar to the planned type of materials in the project description (Figure 1). It looks like elements are generic placeholders. See Figure 2.

(ii) **.smc-file published July 2018 - LOD 300**. The model contains more specific and developed objects. Non-graphic information does also occur in this LOD level, but the size, shape and orientation of elements are located with respect to the project origin. See Figure 3.

(iii) **.smc-file published December 2018 - LOD 350**. The quantity, size, shape, location and orientation of the element as designed, can be measured directly from the BIM model. Despite that there are existing non-graphical information to the model, the model can now be used to decision making and as project guide into different locations. See Figure 4.

Table 1 describes theoretical aspects in an LCA along with OCL features, as well as assumptions made. OCL is an online LCA application that require reports, such as a BIM model inventory file from either MS Excel or gbXML. The elaboration of the LCAs that use MS Excel reports from Solibri Model Checker were based on quantity take-offs from BIM and attached automatically to EPDs in OCL. These LCAs represents three calculations, namely LOD 200, LOD 300 and LOD 350. The LCA obtained from NCC, called *final LCA*, used empirical input data because the Industry Foundation Class (IFC) convey objects to the information take-off reports that causes errors. The structural systems are better to analyze on empirical values in OCL, as they will save time compared to checking all objects from the IFC [10].

2.2 Proposed LCA framework

The proposed framework consist of three main steps [11].

(i) The definition of an evolution of LOD: The definition of element categories is the Norwegian Standard NS 3451 shown in Table 3. The definition of early design phases which appear as project delivery phases is shown in Figure 6 with respect to LOD evolution.

(ii) Consistent combination of LCA databases: EPDs are the determined LCA database. Where no EPDs are available, average values should be employed as Table 5 shows.

(iii) The link between LOD levels and LCA databases: At LOD 400, the exact quantities of each materials should be known as product specific data can be utilized.

3 Case

> "Valle Wood is going to be Norway's largest commercial building in cross laminated timber. The building will be certified in accordance with BREEAM, the world's most demanding environmental certification system, which takes a holistic view of the building's entire ecocycle" [16].

Valle Wood covers the first phase of the project. This phase is 6700 m^2, and the total site is going to be 60000 m^2 including all five phases [16].

Table 1: LCA methodology in One Click LCA

LCA methodology and assumptions made in One Click LCA	
Goal and scope definition	Evaluate the Global Warming Potential (GWP) caused by Valle Wood using OCL.
Functional Unit (FU)	FU of this LCA is Kg $CO_2 - eq$ emission per material. The reference unit is m^3. Other units like kg, kW, kWh, 1 m and m^2 could have been applied, but OCL do not possess a unit conversion factor.
Temporal- and geographical scope	OCL execute a static LCA model. It is possible to setup the service of the materials that would be preferable to include. This will have an impact on B4-B5 (Replacements) during the building life cycle and impacts associated with B6-B7 are introduced on an annual basis. At the moment OCL do not allow changes to the energy mix as this is not allowed in the standards OCL follow. Operating variables do not affect the inventory of the system. Nevertheless - this is out of the scope of the study, and mitigate the potential downsides in terms of only gather Life Cycle Inventory (LCI) data to unit processes, which is the smallest element considered in the LCI for which input and output are quantified [12]. The time period covered in this LCA is updates in the BIM model as per December 2018 [13]. Geographical scope is Oslo, Norway.
Technology coverage	The tool utilized is LCA for BREEAM NOR. The template used to export and structure information from Solibri is "One Click LCA (metric).ITO".
Change-oriented LCA	This is a change-oriented LCA that comparing three BIM models (three LOD levels), up against a modified and reliable LCA at a correct LOD 350.
Intended application	This is a LCA that can be applied to different situations; BIM-model improvement, strategic planning and public decision making.
System boundary	Consider embodied emission, cradle to gate, A1-A3 as this contribute the most to GWP.
LCI analysis and data collection	MS Excel file that imported materials from the BIM (.smc file) and grouped them based on 5 criteria: CLASS: values have to be one of the listed ones in exactly the same format (sorted in .ITO template used in information takeoff in Solibri). IFC-MATERIAL: Use the distinguishable material name to map the material to the label in the tool. Mapping is based on CLASS and IFC-MATERIAL combination. For material label, the database is EPD-Norway. When importing it for the first time, one can teach it to the tool and it will be automatically recognized in the future. QUANTITY: Number, comma as decimal separator. QTY-TYPE: Units. TRANSPORT-KM: Transport distance in km from manufacturer site to the building site (optional, can also be added later in the query).
Data quality	Cut-off criteria to this LCA is materials < 1% of the volume. Also, OCL's category 6, Building Technology, is out of the scope. The cut-off lead to the fallacy of disaggregation by splitting up processes which lower the data quality and putting flows explicitly to zero [14]. The cut-offs are related to undefined objects from the BIM model. Data information included are obtained from EPDs witch follows the same sets of standards.
Life Cycle Impact assessment (LCIA)	The impact category is global warming, characterized as per CML-IA 2012 methodology, required by EN 15978 and EN 15804 [15].
Interpretation	OCL is an transparent analysis as the tool is online and can be easily modified. As this features, this assessment is also a comparative analysis in the way the assessments comparing four alternatives to which performance at different LOD.

Figure 1: Valle Wood

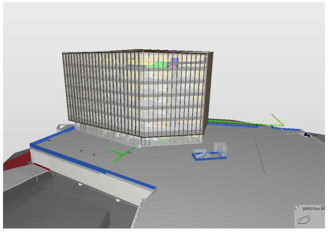

Figure 2: LOD200

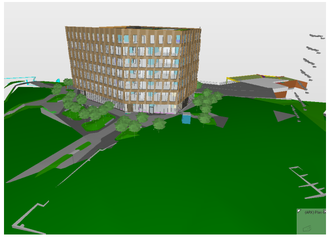

Figure 3: LOD 300

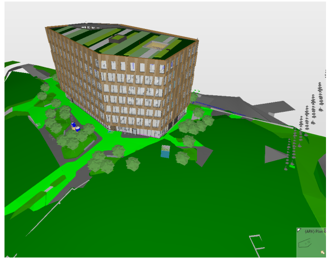

Figure 4: LOD 350

4 Results and Discussion

There are three main approaches ranging from the use of several software, the inclusion of LCA information in BIM, and quantity take-offs generated by BIM, to conduct BIM based LCAs. All approaches are seeking on reduce costs, lower the GHG emissions and increase the efficiency during early design stages of buildings [17]. Moreover, the interaction of BIM-LCA is utilized in several ways. Studies in [11, 18–27] have used several programs and LCIA databases to conduct LCAs at different stages. Some of the studies also take advantage of LOD implementation. In spite of several attempts, there is clearly a missing linkage of different databases, automatized design and impact calculation. However, the integration of LCA within the BIM is not available.

4.1 LCA of Valle Wood

The quantity takeoff information for building materials provided by Solibri Model Checker is obtained in units of volume. The mismatch between the properties in the smc files, quantity takeoff information, and OCL screening method, provides errors regarding the actual amount of materials and due to dissimilar products and EPDs. The MS Excel upload purely contains the information from the .smc file, but it is structured in a way so that the MS Excel can be read by OCL. When this occurs, a unit conversion factor is needed to evaluate the embodied environmental impacts. OCL does not possess this feature, which leads to heavier workload on the LCA performance in early design. An example can be incomplete design by architects that ignore specific requirements, regarding fire or lighting in the BIM.

4.2 LCAs Using Quantity Take-Off Generated by BIM With EPD-Norway as the LCA Database to Obtain Environmental Impact in OCL

LOD 200, LOD 300 and LOD 350 in Table 2 shows LCA results from OCL when the quantity take-off in Solibri Model Checker was used to generate the LCI report that was attached to EPDs in OCL.

The main contributors to GWP in all these designs are *horizontal structures* and *other structures*. Metals and concrete are the materials with the highest impact on the environment. Despite the fact that steel and concrete are the materials responsible for the high GHG emission, a reduction of 75% between LOD 200 and LOD 350 is present. The absence of data information through the transitional process into OCL, initiated unreliable results.

The LCA on LOD 200 indicates a low level of information in the BIM object, as the GHG emission is calculated to be more than 32000 tons of $CO_2 - eq$. Valle Wood, presented in Section 3, is going to be built in cross-laminated timber, which is not the case illustrated in February 2017 (LOD 200). Only 1% of the materials are timber. In low LOD levels, there is not a requirement to specify the type of materials, and because of the low level of information inside the BIM object, the design has not distinguished the environmental and material properties. Default settings were probably sat to materials during the early design process in BIM.

At LOD 300, the materials are not yet in accordance with the project description. Steel and concrete are still dominating the design, and no timber is contributing to the design, which contradicts to the information in the BIM model (Figure 3).

At LOD 350, [28] state that the BIM model should contain all relevant information to be environmentally assessed, but as one can see from Table 2, essential data elements are missing. This leads to errors that do not correspond to the reality of materials that should have been in the LCA. Despite the great improvement in GHG emission, the LCA is not reliable as the material distribution differs from the project description. In addition, the number of materials in OCL are incorrect compared to the BIM model in Solibri Model Checker.

4.3 Final LCA Conducted With Empirical Values

Instead of improving the quantity take-off generated by Solibri Model Checker and the transitional format (.ITO template), empirical values were added in OCL to calculate a correct value for the GHG emissions, with the right quantity for the right type of materials. This is shown in Table 2. Here, 42% of the material contribution is timber, which is in accordance with the project description.

The great reduction in GHG emission was calculated with the right type of materials, linked to the right EPD, which resulted in 2700 Tons of $CO_2 - eq$. The measurements and units were obtained from the BIM model without utilizing the quantity take-off generated by Solibri Model Checker at LOD 350 (Figure 4).

Table 2: Results from OCL related to different LODs

LOD	**Builing Element**	**%**	**Material Type**	**%**	**Material Subtypes**	**%**	**Tons of CO_2-eq**
LOD 200	Horizontal Structures (HS)	82	Steel and Metals (SM)	88	Aluminum	87	32523
	Other Structures (OS)	12	Concrete	8	Prefab. concrete walls	4	
	Vertical Structures (VS)	6	Glass	2	Concrete foundation	3	
			Timber	1	Cross Laminated Timber (CLT)	1	
			Gypsum	0	Glass	2	
LOD 300	OS	51	SM	74	Aluminum	67	9553
	HS	25	Concrete	21	Prefab. concrete	13	
	VS	24	Floor (undefined)	2	Concrete	5	
	Ground and Foundation (GF)	0	Glass	1	Steel	4	
			Insulation	1	Steel and Iron	3	
LOD 350	OS	56	SM	75	Aluminum	67	8066
	HS	27	Concrete	19	Prefab. Concrete	13	
	VS	17	Timber	3	CLT	12	
	GF	0	Floor (undefined)	2	Steel	5	
			Insulation	1	Concrete	3	
LOD 350 (Final LCA)	VS	54	Timber	42	CLT	56	2713
	HS	31	Windows and doors	14	Mortar	13	
	GF	11	Gypsum	14	Interior walls	12	
	Building technology	3	Insulation	11	Rockwool	11	
	OS	1	Floor (undefined)	8	Carpets	8	

4.4 Suggested Use of LOD in a BIM Environment With Respect to LCA Application

To support an efficient and user-friendly LCA application in early design, strategies for simplification in BIM based LCAs have been proposed by several parties. The common knowledge gap in the proposals is the need for an envelope that deprives BIM to carry out an LCA single-handily.

To minimize the carbon footprint, the writers of this report believes that early design delivery phases can help the efficiency and the automated work regarding LCAs. By using LOD as the direction-setting process in

LCA, the more environmental attention is given to the design and, the GHG emission will be considered as a determining factor through decisions. This approach and proposal desires to connect Architecture, Engineering and Construction (AEC) professionals and designers to deal with the issues through BIM based LCA in the early design stages (low LOD). The influence to alter the functionality of the building is high and the costs are low in early design stages [29, 30].

The capability of IFC's layered data structure, which has different objects with different level of details for the representation of information, should be specific regards to Model View Definitions (MVD) standard before heading to a higher LOD level. There is two distinct advantages of a standardized LOD related to the embodiment of an LCA. These are that the IFC can be imported into LCA analysis tools from any BIM authoring tools, without performing further data manipulation for mapping imported data to the used LCI database [21]. In addition, more realistic and concise results can be achieved by choosing a proper LCI database and a LCA calculation method, with respect to LOD of the elements contained in a BIM model [21].

A BIM model is a comprehensive collection of objects that are rich in information, and an LCA is a set of unit processes that are linked with each other using flows [31, 32]. It is by this required to link object in the BIM to LCI database using flows. Therefore, it can be hard for designers to handle several unit processes at a time. Henceforth, this proposal allow to break down this information into manageable and logical groups according to NS 3451 building table of building elements and OCL main distribution of building elements shown in Table 4. In addition, milestones to which LOD levels construction categories have to be developed in the BIM are expressed in the same table.

Table 3: NS 3451 - Table of building elements

NS 3451 - Table of Building Elements	
1 digit building element	**2 digits building element**
2 - Building	20 - Building in general 21 - Ground and foundation 22 - Structural system 23 - External walls 24 - Interior walls 25 - Slab 26 - Roof 27 - Building inventory 28 - Stairs and balcony 29 - Other building related parts
3 - Plumbing installations	30-39: out of scope of this study
4 - Electrical Power	40-49: out of scope of this study
5 - Telecom and automation	50-59: out of scope of this study
6 - Other installations	60-69: out of scope of this study
7 - Outdoor area	70-79: out of scope of this study

Table 4: Construction categories divided with respect to LOD and its milestones

Construction categories divided with respect to LOD		
OCL main distributions	**NS 3451**	**LOD**
1) Ground and foundation	20 21	100 150
2) Vertical structures and facade	22 23 24	175 175 175
3) Horizontal structures	25 26	175 200
4) Other structures and materials	27 27 29	300 300 350
6) Building technology	3 4 5 6	350 350 350 400
5) Outdoor area and elements on site	7	400

To systematize to which early design phase (or project delivery phase) that represents the different LOD levels is suggested in Figure 6.

A comprehensive LCA is to be done at LOD 350, building permit stage [11, 18, 21, 24, 25, 28, 33–35]. By this stage, the major elements are stated, and 80% of the 3, 4, 5, 6 and 7 categories (see Table 3) are agreed upon. The building can be stated complete in the BIM, apart from the uncertainty in the empirical, min/max or most likely values in the 80% of LOD 400 posts. Generic LCA databases can be used to obtain LCIA data when the BIM is incomplete and not considered as LOD 400. Another source to most likely values is considering conservative EPDs. An example of conservative EPD can be concrete instead of CLT.

At technical elaboration, the BIM represents LOD 400 (Figure 6), and the environmental impacts should be assessed on equal terms as the structural design issues. EPDs are the dominated LCIA database at LOD 400. Environmental impacts on different products are various, and therefore should EPDs represent the specific brand of the selected material. This will lower the uncertainty in the complete LCA. By using endpoint indicators instead of midpoint indicators in the low LOD LCAs, it would simplify the results and turn the interpretation phase into a more understandable phase for AEC professionals.

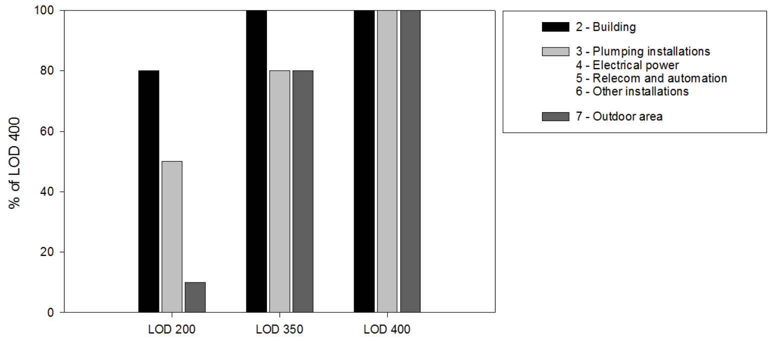

Figure 5: Degree of completeness in different stages of LOD

Table 5: Level of completeness and LCIA databases

LOD	NS 345 (1 digit)	% of LOD 400	LCIA database for building elements
LOD 200	2	80	Average values, mean values, min/max values, most likely value
	3, 4, 5, 6	50	
	7	10	
LOD 350	2	100	EPD-Norway
	3, 4, 5, 6	80	Average values, mean values, min/max values, most likely value
	7	80	
LOD 400	2	100	EPD-Norway
	3, 4, 5, 6	100	
	7	100	

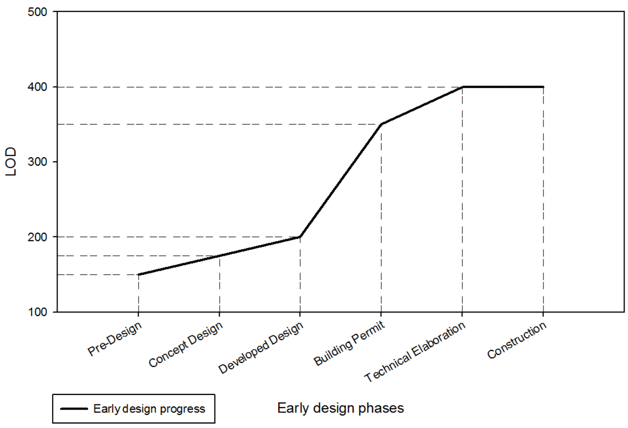

Figure 6: Design phase evolution according to LOD

Components regarding building manner should be given important effort in LOD 200, while plumping, electrical, telecom and automation and other installations are usually depending on the architectural design as Figure 5 and Table 5 shows. The building components are 80% completed at LOD 200. This is due to unpredictable issues regarding clash detection and if building elements within 3, 4, 5 or 6 categories are determinate. At LOD 350, building components is fixed as these components are the major contributors to GWP and determine the structural design of buildings. In addition, the building components determines the structural design of buildings. By clearly state these materials in LOD 350, than the majority of building materials can be assessed with high accuracy.

5 Conclusion

Main aims of a BIM based LCA is to establish a convenient decision-making method with an environmental perspective, and an ongoing environmental assessment during the early design stages. Investing more time in the design stages and utilize LOD and its requirements consistently, would enhance the level of information and detail in BIM objects. This amplifies the information within the IFC files and leads to fewer errors in BIM-LCA tools.

Therefore, we suggest the designers and design tools to be acquainted with the requirements to each LOD levels, and consequently use average, mean (±) values and best practice where the LOD level is low. The proposed LCA framework is corresponding to LOD levels, as the design delivery phases are determined by milestones of completeness in the BIM model. Designing the building project in BIM in accordance with this framework will improve the GWP, as interaction with BIM and LCA tools enables substitution of materials that contribute to the highest release of CO_2. Such automation in LCAs, and the ability for ongoing assessments will assist the decision-making processes to emphasize the environmental issues during design.

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Lessons learned from assessing life cycle impacts for an environmental product declaration: Examples for run-of-river power plant

Meili C, Jungbluth N

ESU-services Ltd., Vorstadt 14, CH-8200 Schaffhausen, Switzerland

meili@esu-services.ch

Abstract. When conducting life cycle assessments (LCA) for environmental product declarations (EPD), researchers struggle with many methodological questions. For certain products there are several standards (e.g. ISO and EN) and Product Category Rules (PCR) available which all seem applicable. These standards, however, might lead to different results. Depending on the standard, system boundaries might be drawn differently than typically done in ones preferred background database. Another common issue is a lack of a clear definition of assessment methods (version, download of factors) to be applied. Or on a more practical level, you might not know how or where to obtain certain requested figures from your LCA data or even how to start with building an appropriate model in the LCA-software. The authors of this paper explain each of these issues with an example from their practical work, provide their instant solutions and make suggestions for general improvement of the situation. In general, they call for a more precise and practical guideline and easy-to-use LCIA methods for conducting EPDs.

1. Introduction

Environmental Product Declarations (EPD) present transparent, verified, and comparable information about the life-cycle environmental impact of products. The overall goal of an EPD is to provide relevant and verified information to meet various communication needs. An important aspect of EPD is to provide the basis of a fair comparison of products and services by its environmental performance. EPDs can reflect the continuous environmental improvement of products and services over time and are able to communicate and add up relevant environmental information along a product's supply chain. EPDs are based on principles inherent in the ISO standard for Type III environmental declarations (ISO 14025) giving them a wide-spread international acceptance.

Consultants at ESU-services dealt with these questions in projects and trainings. Here, we present some lessons learned when assessing life cycle impacts for an EPD on run-of-river power plants [1], revisioning a PCR for electricity [2], reviewing of an EPD on concrete products[1] and EPD of consulting services [3]. During such work the following challenges have been identified when trying to elaborate EPD:

[1] http://www.graspointner.at/fileadmin/Prospekte/FCT_one_screen.pdf

- The choice of the correct LCIA indicators is often difficult because PCR lack details such as version of method or default characterisation factors for the methods to be used. Also, there seem to be contradictory hints in standards of different countries.
- When distinguishing between upstream, core and downstream module, relevant aspects for optimisation were hidden in background-data. Getting transparency using unit processes from ecoinvent was more helpful for this goal.
- Some indicators do not follow customary practice and logic of LCA, e.g. stating which parts of resources is used for materials or reporting on waste instead of including emissions of waste treatment.
- There are no indications on how to set findings in perspective. With bare numbers on several single emissions, the values give no order of relevance and little encouragement for improvement.

2. Goals

The main goal of this paper is to provide suggestions for the optimization of guidelines and easy-to-use methods for conducting EPDs.

The following questions are tackled:

- Which standard (ISO, EN) and Product Category Rules (PCR) to apply?
    - How to draw system boundaries accordingly?
    - Which life cycle impact assessment methods match the standard?
    - How to obtain other requested information from LCI data?
- Restrictions concerning databases to be used.
- How to build an appropriate model in the LCA-software of choice?
- How to set findings in perspective and foster encouragement improvement?

3. Example: Run-of-river power plant

3.1 Goal and scope

3.1.1 Goal

The main goal of one underlying case study was to provide insights for the optimization of run-of-river power plants to the operators. It also enables the power plant operator to make a rough calculation for the environmental impacts due to electricity production in the client's existing and prospective power plants. In order to simplify the calculation of results the approach follows the Product Category Rules (PCR) guidelines for developing an environmental product declaration (EPD) for this type of power plants.

The model provides results for the two functional units: kilowatt-hour electricity, produced in a run-of-river power plant, “at power plant” and “at final customer”. For electricity at customer, also transformation to low voltage and transmission through different grid levels is included [1].

3.1.2 Scope and system description

Modelling is done according to latest available PCR [2], in accordance with ISO 14025:2006. Data collection is based on a model for run-of-river power plants without reservoirs in Switzerland [4-6].

For the impact assessment, besides required impact categories according to PCR for EPDs also an assessment with the Swiss-specific ecological scarcity method is implemented to simplify communication with Swiss stakeholders [7].

The model is implemented in excel and allows exchange of parameterized data in the EcoSpold v1-format. Thus, it is also possible to easily import the life cycle inventory analysis in SimaPro in order to do more detailed assessments.

The following modules of the life cycle are modelled (see Figure 1):

- Upstream processes: Provision of auxiliaries for ongoing operation, mainly lubricants and corrosion protection.
- Core process, operation: Water and land use for the operation of the turbine, as well as emissions from the use of lubricants (chemical oxygen demand, COD).
- Core process, infrastructure: Materials and energy requirements for the construction and dismantling of the power plant (dams, canals, power plant, etc.) and the installation of components in the power plant (turbines, generators, etc.), including necessary material and energy consumption, e.g. diesel and explosives.
- Downstream operation: Operation of the transmission and distribution network for the supply of electricity to end customers. Includes power losses during transformation and transmission, use of SF6 and associated losses.
- Downstream operation, infrastructure: Construction and disposal of the transmission and distribution network for supplying electricity to the end customer.

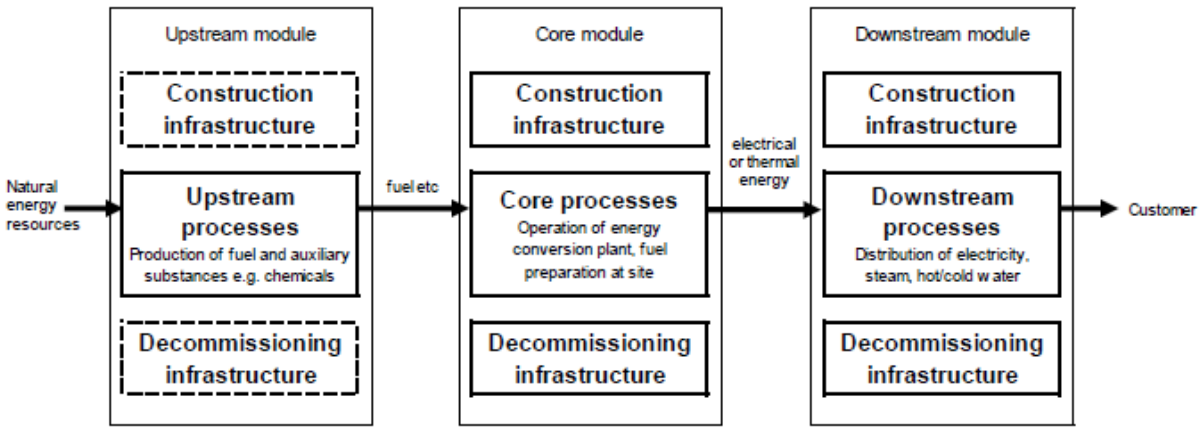

Figure 1 Illustration of the life cycle structure and rough system boundaries. Rectangles with extended lines show processes that should be included, dashed lines show processes that could be included. Construction includes necessary renewals during the technical lifetime, decommissioning includes demolition and treatment of the various waste fractions according to the polluter-pays principle (cf. PCR CPC 17 2007).

3.2 Issues identified

1. The PCR requests a distinction of upstream, core and downstream processes as described above. No clear guidance was given, if and how e.g. a lubricant used for maintenance of the turbine should be allocated to the upstream or core process. In theory, according to the structure in Figure 1, production and emissions related to production of the lubricant should be allocated to the upstream process and emissions caused in the use phase during the processing of the turbine should be allocated to the core process. Unfortunately, in several commercially available databases only "system processes" are included. They show cumulated results of the lifecycle inventory of processes and products. Therefore, it is not possible to distinguish the share of emissions from production and other upstream processes from emissions occurring during the use phase. On the other hand, also in unit processes often there is a lack of direct emission data, so these emissions would need to be assessed in an additional model.
2. Some indicators do not follow customary practice and logic of LCA, e.g. the PCR requests statements on which parts of resources are used for materials. In lifecycle inventory data, resources are accounted for in the first stage of a production process. It is not recorded for which

purpose the derived materials (e.g. mineral oil products in the production of lubricants) are used finally. From an environmental point of view, when only looking at resources, there is no difference if a resource is consumed for the provision of energy (e.g. combustion of mineral oil) or the production of a material. (e.g. use of mineral oil as ingredient substance of the lubricant). Issues of accompanying emissions etc. are covered by other indicators than the resource use. Also, the PCR requests reporting on the level of different waste categories. This is also not state of the art in the LCA practice. There, all emissions of waste treatment should be tackled in process stages looking at the waste treatment. Reporting on the amount of waste per se is not an environmental indicator as the relevance for the environment can only be assessed when knowing more about the further treatment of it (e.g. type of filters used in incineration plants, landfill sealing, recycling shares).

3. For the commissioner and especially the final target group of a report (customers of the product under study), it is difficult to set findings in perspective as they are not used to the metrics of LCA and have no feeling what the consequences of the release of e.g. 1 kg of CO2-eq would be. With bare numbers on several single emissions, the values give no order of relevance and little encouragement for improvement. The PCR and the ISO-standards give no indications on how to foster such an encouragement.

3.3 Solutions

1. For the project at hand ecoinvent unit processes were screened to determine direct emissions to the environment for lubricant oil and paint used in infrastructure and core processes. Where the emissions made more than 2% of total process related emissions according to the assessment criteria, they were included in the parameter model.
2. To get the indicator results requested according to the PCR, information was exported from the life cycle inventory data and hand-picked to be presented together with the impact assessment. To improve workflows in other consulting companies, this lack of user-friendliness was reported to the developer of a common LCA-software. They agreed to provide a more comprehensive EPD methodology with their next release. Nevertheless, it is also questionable if an extensive list of single emissions reported in an EPD can lead to better choices by the decision maker. Also, here more guidance by PCR developers would be necessary.
3. To set things in perspective it could be helpful to show results in comparison with best available technology, average technology and on an individual as well as on a national or global scale.
4. Developing a key parameter model proofs to be a valuable tool for simplifying the work on EPD for several similar products in one product group.

4. Suggestions for general improvements

It is suggested, that product category rules (PCR) include more detailed, practical guidance on how to fit a certain process into the life cycle structure as shown in Figure 1. Additionally, it is suggested, that providers of LCA software include an LCIA methodology to easily access all indicator information requested by the EPD-framework.

The PCR ideally also provides sources for information on how to put EPD results in perspective. Such sources could include a list of former EPDs and links to international environmental target values.

So far PCR do not deal sufficiently with the requirements for such simplified tools. Requirements for the review of the tool and the publication of results should be integrated in the PCR.

5. Discussion

The purpose of this paper and conference presentation is to show some shortcomings in common PCRs and initiate a discussion about the usefulness of EPD. It contains only some subjectively selected examples. The authors neither claim to deliver a comprehensive paper nor a perfect solution. In the best case, the here mentioned examples are useful as a starting point for further discussions and improvements in the general PCR-framework.

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Large scale smart meter data assessment for energy benchmarking and occupant behaviour profile development

Horváth M[1], Adams J N[2], Deme Bélafi Z[1], Czétány L[1], Szalay Z[3], Várnagy S[4], Reith A[4], Csoknyai T[1]

[1] Budapest University of Technology and Economics, Faculty of Mechanical Engineering, Muegyetem rkp. 3-9., 1111 Budapest, Hungary

[2] The University of Tennessee, Knoxville, TN 37996-2250

[3] Budapest University of Technology and Economics, Faculty of Civil Engineering, Muegyetem rkp. 3-9., 1111 Budapest, Hungary

[4] ABUD Engineering Studio, Kisfaludy u. 38., 1082 Budapest, Hungary

horvath@epgep.bme.hu

Abstract. This paper will present objectives and first results of the research project entitled "Large Scale Smart Meter Data Assessment for Energy Benchmarking and Occupant Behaviour Profile Development of Building Clusters," implemented in the geographical scope of Hungary. The project seeks to utilize a new and unique opportunity for accessing and processing an enormous dataset collected by smart meters. Recently in Hungary, nearly 10 000 buildings have been equipped with smart meters within the "Central Smart Grid Pilot Project". By means of advanced data analysis techniques, consumption trends and motivations of building users are being investigated. The aims are to help building designers and engineers design more energy efficient buildings at lower investment costs by avoiding system oversizing, and to obtain better knowledge about hourly, daily and monthly energy consumption trends. Furthermore, standard net demand values for normative energy calculations can be updated and specified more precisely since consumption habits change with time and depend on the region.

1. Introduction

There are two principal ways to analyze the energy performance of buildings. First, the asset method, which applies calculation principles and modelling tools based on the physical characteristics of buildings such as geometry, building shell attributes, features of technical systems and occupant's behavior. The asset method provides transparent information on performance indicators and details. However, it is sensitive on the reliability of input data, and information on user behavior is often missing; thus, standardized data are used instead of actual users' performance. The second, so called operational method, is based on real energy consumption analysis, which gives a reliable picture about the energy performance of a building, but only for the analyzed period under specific circumstances.

To perform energy analysis for a large number of buildings, both methods are applicable and relevant. In Hungary, there is greater proficiency in building stock analysis using the asset method, particularly in the housing sector. In 2013 the National Building Energy Strategy (NBES) [1] was expanded based on modeled building archetypes. Additionally, Hungary has joined the Tabula/Episcope project, supported by the Intelligent Energy Europe Programme. In this project, building typologies have been developed for 18 EU countries, Norway and Serbia [2]. The work was further developed within the KEOP-7.9.0/12-2013-0019 project in 2015, when a representative sample of 2 000 residential buildings [3] were selected and on-site surveys were carried out by accredited experts. As a result of the work, a national level extrapolation was implemented and energy saving scenarios were proposed for policy developers.

However, these projects did not consider real occupants' behavior, and certainly a set of simplifications were applied in the analytical model. Real energy performance can only be monitored based on the operational model, although this method does not give any information about factors influencing performance and is not applicable for modeling energy saving. Nevertheless, both discussed methods have relevance and can provide supplementary information to each other.

1.1. Brief Review on Smart Meters

Smart meters (SM) are electronic devices that record occupant energy consumption and share this information with utilities, allowing two-way communication between consumers and providers [4]. At the end of 2016, there were 700 million smart meters installed globally, with over half of those in China [5]. Aside from China, Europe is a global leader in SM implementation; a European Union directive has an 80% customer penetration goal by 2020 [6]. Additionally, from 2016 – 2020 European utility companies will invest €33.4 billion to install 182 million smart meters [7].

Given the massive uptake in SM technology, methods for analyzing such data are crucial, and there is an increased focus on profiling occupants to better understand their energy behaviors. Many researchers have begun using a data mining technique known as clustering to group occupants by similar temporal (i.e. daily, weekly or seasonal) energy use patterns [8–10]. Research in this area also supplements SM data clusters with socio-demographic data to determine how factors like age, income, employment status, appliances and building retrofit, among others, influence energy use patterns [11–14].

It is also important to note that consumers have expressed privacy concerns with SM technology. Such concerns are energy data being sold to third parties like advertisers or law enforcement, decreased privacy inside households (such as family members monitoring each other's activities), or that criminals could hack SM information and determine when residents are not at home [15,16]. Recent research also suggests that social-psychological factors like trust in utility companies, perceived usefulness of the technology and perceived risk to privacy may directly impact SM support [17]. Therefore, it is important to continually refine data analysis techniques while also addressing consumer concerns as SM use surges worldwide.

1.2. Central Smart Grid Pilot Project in Hungary

Article 8 of the Energy Performance of Buildings Directive (2010/31/EU)claims that the Member States shall encourage the introduction of intelligent metering systems whenever a building is constructed or undergoes major renovation, and the Member States may furthermore encourage, where appropriate, the installation of active control systems such as automation, control and monitoring systems that aim to save energy. Furthermore, directive (EU) 2018/844 of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings, prioritizes smart buildings and introduces the new smartness and smart readiness indicators.

Legislation related to the Third Energy Package of the EU, such as 2009/72/EC [6], and 2009/73/EC [19] required Member States to prepare an economic assessment of long-term costs and benefits of electricity and gas smart metering by 3 September 2012. In cases where the cost-benefit analysis (CBA) is positive, there is a roll-out target of 80% market penetration for electricity by 2020. The results of the CBAs are as follows [20]: for electricity smart meters, 16 states from the EU-27 have decided to roll-out smart meters by 2020, in seven states the CBAs were negative, and in four states the CBAs or roll-out plans have not been prepared; for gas smart meters, five states from the EU-27 will proceed with large-scale roll-out of smart meters by 2020, two states have plans to proceed with a large-scale roll-out but have yet to take official decisions, in 12 states the CBAs were negative, two states have no gas network at all, and in six states the assessments have not been prepared. Overall, 72% of EU consumers are expected to have smart electricity meters and 40% smart gas meters.

In Hungary, the Central Smart Grid Pilot Project (KOM) was established in 2016 to assess the possibilities of a national smart monitoring system. Within the framework of the project, 139 901 smart metering devices have been installed throughout the country in residential, public, commercial and industrial buildings. Emphasis was placed on the representativeness of settlement and building types during the selection. The evaluation of energy consumption was not an objective in the demonstration project, only installation, maintenance and continuous data collection during a 5-year period ending in 2023. Therefore, another project entitled "Large Scale Smart Meter Data Assessment for Energy Benchmarking and Occupant Behavior Profile Development of Building Clusters" was initiated by BME in October 2018 to benefit from the opportunity by accessing and processing this enormous, representative dataset.

In the past, only some segments of the building stock and building users' energy performance could be analyzed in the country due to the lack of consumption-related information. This high-resolution, detailed dataset opens new perspectives to supplement and complete the existing national building typology; it also provides building use schedules for different purposes such as building energy simulations or energy certifications using more reliable input data on users' profiles.

1.3. Objectives

The main objective of this research is to evaluate the dataset collected by the smart meters installed across Hungary within the Central Smart Grid Pilot Project. This enormously rich source of information opens new perspectives in energy pattern evaluation on a building stock level. Our intention is to obtain more advanced knowledge in the following aspects:

- a more precise picture about the real energy consumption of Hungarian building stock,
- a comparative analysis can be carried out between measured and building typology based modelled data, and hence a supplement and completion in national existing bottom-up building stock modelling,
- by means of advanced data analysis techniques it is possible now to cluster building types and occupant types to determine user profiles and energy consumption patterns,
- energy demand profiles can be developed on a large scale and utilized by energy supply and utility companies to improve their production profiles by demand side management (DSM); thus, the smart-grid concept can be realized, resulting in energy savings by peak-shifting on a national level.

The current research ("Large Scale Smart Meter Data Assessment for Energy Benchmarking and Occupant Behavior Profile Development of Building Clusters") started in October 2018 and is still in an early phase: we are working on data verification and cleaning; evaluation algorithms are being developed and tested on a small sample and supplementary data on buildings are being collected. Present paper presents the first experiences, challenges and difficulties we have faced so far.

2. Methods

2.1. Time Series Datasets

In the early stages of the project, it was decided that residential buildings would be in the focus of the research. First, the device database was filtered in order to identify the smart meters installed in residential buildings. The second step was to categorize the selected smart meter database. In the categorization process the following were considered:

- geographical diversification,

- type of settlement,
- meter type / measured consumption.

For the analysis of geographical diversification, a map was created indicating locations of installed sensors, which can be seen in Figure 1. It is apparent that the meters were mostly installed in Central Hungary and the Southern Great Plains; further, it is important to note that while there were a significant number of smart meters also installed in Northern Hungary and the Northern Great Plains, they were only in two cities (Nyíregyháza and Miskolc).

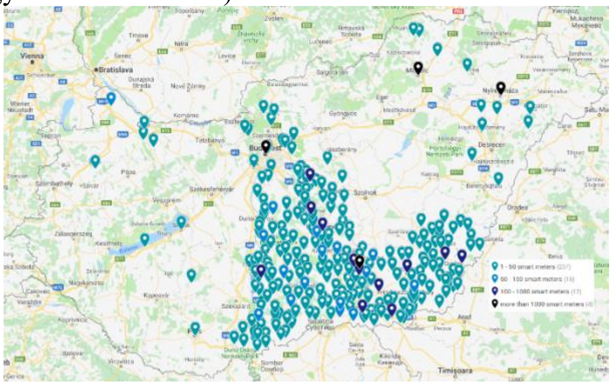

Figure 1., The geographical distribution of the installed smart meters.

The distribution of settlement types was better than the geographical distribution, which can be seen in Figure 2. While the distribution of buildings by settlement type was uniform, the number of installed smart meters by settlement type shows an uneven distribution in favour of larger cities.

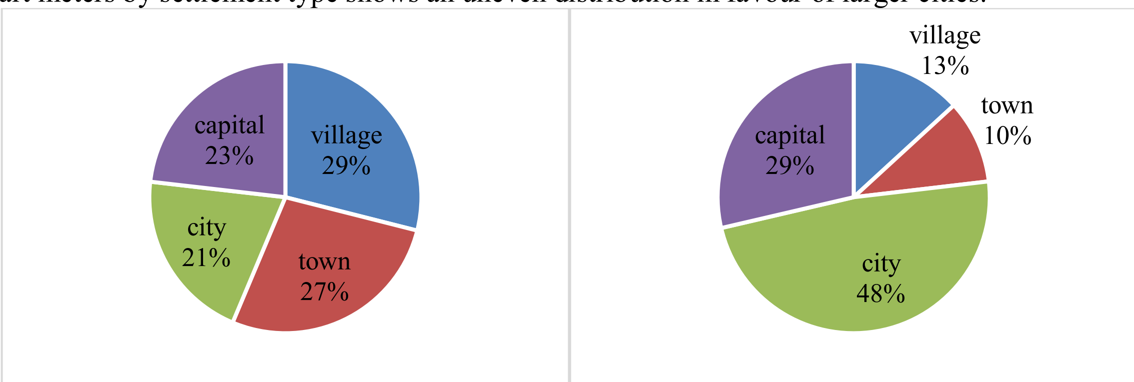

Figure 2., Distribution of residential buildings in Hungary (left) and the installed smart meters (right) by settlement type

In residential buildings a total number of 33761 smart meters were installed, measuring gas (5614), electricity (10368), heat (11715) and water (6064) consumption.

The meters were in operation between the years 2016 and 2018. For most of them, the dataset is limited to dates between 2017 and 2018 or only 2018.

It should also be noted that, depending on the sampling frequency, the possible data usage can be limited. For some meters, the sampling time was as low as 300s, but there were meters with sampling times as high as one week. Obviously, the more frequently recorded data is more suitable for daily profiles, whereas the usage of time series with high sampling time is restricted to weekly or monthly profiles. Communication problems between the smart meters and the servers result in data loss and this degrades the quality of the data. Long outages make it impossible to derive relevant observations.

2.2. Statistical Significance and Representative Sample

It is essential to ensure the validity of the results obtained from the dataset described above. In order to formulate statements on Hungarian building stock, two statistical parameters have to be investigated to determine appropriate sample size and distribution.

Firstly, the population groups were determined with the aim of having results with statistical significance. In the first round of analyses, residential apartments were tackled. Group-defining variables were: size of settlement and geographic regions of the country (see Table 1).

Table 1 - Residential apartment-based population groups used for sample-size calculations

Size of town	Nr. of apartments	Geographical region	Nr. of apartments
Villages and towns	1 227 110 (23%)	Southern Great Plain	602 819 (11%)
Cities	1 370 964 (26%)	Southern Transdanubia	409 265 (8%)
County-seat cities	925 730 (17%)	Northern Great Plain	624 091 (12%)
Capital	1 832 310 (34%)	Northern Hungary	509 790 (10%)
		Central Hungary	2 318 556 (43%)
		Western Transdanubia	435 697 (8%)
		Central Transdanubia	455 896 (9%)

Based on a national statistical dataset [21], the population of each statistical group was determined based on the number of apartments. The necessary sample size to ensure statistical significance in each group was calculated using Eq. 1 [22].

$$Ns = \frac{(Np)(p)(1-p)}{(Np-1)\left(\frac{B}{C}\right)2+(p)(1-p)} \qquad (1)$$

Where Ns = completed sample size needed (notation often used is n)

Np = size of population (notation often used is N)

p = data diversity: 50% or 0.5 is most conservative

B = acceptable level of sampling error (0.05=±5%; 0.03=±3%)

C = Z statistic associate with confidence interval (1.645=90% confidence level; 1.960=95% confidence level; 2.576=99% confidence level)

For the sample size calculations, a sampling error of 3% and 95% confidence level were assumed.

Secondly, the representativity of the sample was ensured by preserving the ratios of population groups. For example, in Hungary, 26% of apartments are located in cities. Therefore, in this project's sample, 26% of the apartments investigated were from cities.

2.3. Qualitative Information Assigned to Smart Meter Data Points

Analysis of the measured data requires some information from the buildings where the meters were installed. First, the function of the building is relevant, but parameters such as the size or construction type influence the energy consumption and may help with further analysis. Unfortunately, such data were not recorded in the measurement campaign and only the address of the buildings were available.

For compiling further building parameters, we decided to apply a 'manual' approach. As the number of meters and the number of buildings is large, a compromise had to be found between the accuracy and the time spent for data acquisition. Physical observation of the buildings would give highly reliable data, but it would take too much time as the meters are scattered all over Hungary. Using GIS mapping tools provides a relatively fast method for data collection. Based on the address, an expert identifies the building and collects relevant information by observation and some measurements.

First, we identified the relevant parameters that are important for the characterization of a building. The necessary parameters include the building function, building type, covered area, number of stories, general condition of the building, visible retrofit measures (change of windows, additional insulation on façade), type of roof (flat roof, pitched roof unused or used) and the presence of solar panels/ collectors. Buildings are first classified based on the building function: residential buildings, offices, sport facilities, restaurants, educational, healthcare, cultural, industrial, commercial, religious or agricultural buildings. There are further subcategories available, for example, educational buildings are classified into kindergartens, primary and secondary schools, universities, etc. So far, only residential buildings were examined.

As most of the measured data are from residential buildings, a more detailed subcategorization based on building archetypes developed in the framework of the KEOP-7.9.0/12-2013-0019 project was applied [3]. In this project, 23 residential building types were established and for each building type, the most typical construction materials, heating systems, typical energy consumption, etc. were provided. However, it was soon realized that such a detailed classification is difficult without further information sources, so certain categories were merged. Finally, a simplified typology with 10 classes was applied, based on the type of the residential building (detached house, small apartment building, large apartment building), the approximate date of construction and the construction type (prefabricated concrete panel or not).

According to the first experiences, this process generally worked well and fast enough to identify and classify a large number of buildings in a reasonable time frame. A major problem encountered was that streetview images are not available is some villages and in some smaller streets. Such buildings were removed from the sample and substituted with new ones. Also, the identification of the building based on the address was sometimes difficult, and external obstacles such as trees blocked the view in some cases.

2.4. Time-series Data Analysis

The preliminary analysis of the data started on the time series showing the incremental natural gas consumption of different residential buildings. It is vital to discard the unusable or false datasets as they would corrupt the conclusions of the future analysis. Therefore, some series were manually analyzed to identify the typical errors. By using the findings of these investigations, algorithms will be developed to automatically categorise the time series from the different meters and only manually investigate the minimal number of datasets.

For instance by analyzing the electricity measurements time series of the energy usage measured in kWh-s was different from the same energy usage obtained from integrating the mean power measured by the same meter. The mean power values were zero sometimes, which can be the result of some software or database failures. Thus it’s vital to check smart meter data carefully before any conclusion can be drawn.

2.5. Questionnaires and Interviews

In this project, time-series datasets are supplemented with socio-demographic data collected by questionnaires and interviews.

The following table contains independent variables derived from four models commonly used to determine social-psychological determinants of energy efficient technology acceptance. We have selected the variables from each model most relevant to our project. Each variable will be measured using reliable, previously-validated survey questions. (See Table 2)

Table 2 – Social-Psychological models and survey measures used in the project

Model	Reference	Variables
Theory of Planned Behavior	[23]	**Attitude** towards the technology

Technology Acceptance Model	[24]	**Perceived usefulness** **Perceived ease of use**
Norm Activation Model	[25]	**Personal norms (**moral obligations)
Sustainable Energy Technology Acceptance (SETA)	[26]	**Trust in technology providers** **Knowledge** **Perceived risk to privacy** **Problem perception** (awareness of consequences)

These survey measures will be supplemented with dependent, demographic variables such as age, gender, occupation, education level, perceived material status and building characteristics and retrofit. Additional dependent measures such as support for SM technology, intention to adopt SM and continued SM use in the future will also be utilized.

This forthcoming part of the project will be split into three rounds of data collection with three different categories of participants:

1. Building operators in public buildings where SM technology is not yet installed.
2. Assigned "sustainability champions" in smart buildings and potentially users who interacted with SM in their buildings.
3. Residential households with recently-installed SM.

3. Preliminary Results

3.1. Data quality check

At the present stage of this project, three common error types were found and defined. These errors will be the basis of automatic data filtering procedures.

- Type A: the sampling time is longer than a user defined value in one or more points.
- Type B: no usable data is available (the meter did not record any data, or the change in the data is almost zero –probably the building was not used).
- Type C: small or large breaks in the time series.

One example for type A errors can be seen in Fig. 3.

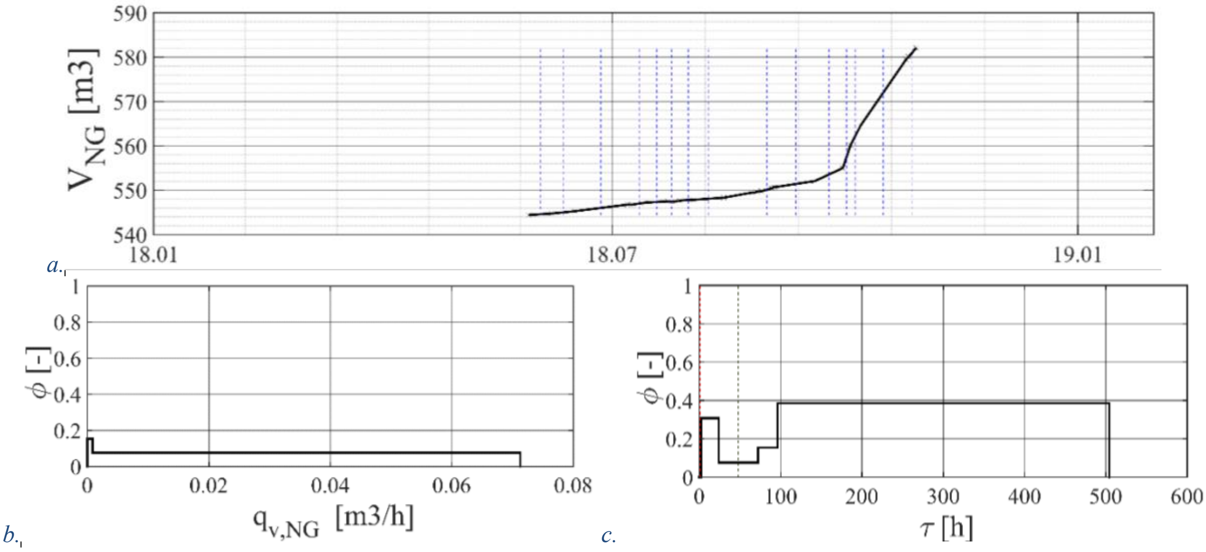

Figure 3., a.: time series, b.: histogram of $q_{v,NG}$, c.: histogram of τ. for the location code named as C00023827.

V_{NG} the incremental gas volume flown through the meter, $q_{v,NG}$ is the mean flow rate between two adjacent samplings, ϕ is the relative probability density, τ is the sampling time (the time between two adjacent points). The criteria for sampling time was 48h in this case, and at the locations where actual sampling time was higher than this value, vertical blue dashed lines were drawn at the middle between the two adjacent points (Fig. 3.a).

Fig. 3.b shows a histogram created by using the Eq. 1. $q_{v,NG,i}$ is the mean flow rate between the data point i and i+1, $V_{NG,i+1}$ and $V_{NG,i}$ are the incremental gas volumes flown through the meter at the ith and (i+1)th measurement points and τ_i is the difference in time between the two points (sampling time).

$$q_{v,NG,i} = \frac{V_{NG,i+1} - V_{NG,i}}{\tau_i} \tag{1}$$

Fig. 3.c shows a histogram of τ. It can be seen, that this time series is not suitable for any further analysis, as many points are missing.

Type B errors can be identified by only using the time series diagram. Fig. 4. show one example, for which data was transmitted, but apparently either no gas was consumed or instead of the correct numbers only zeros were recorded.

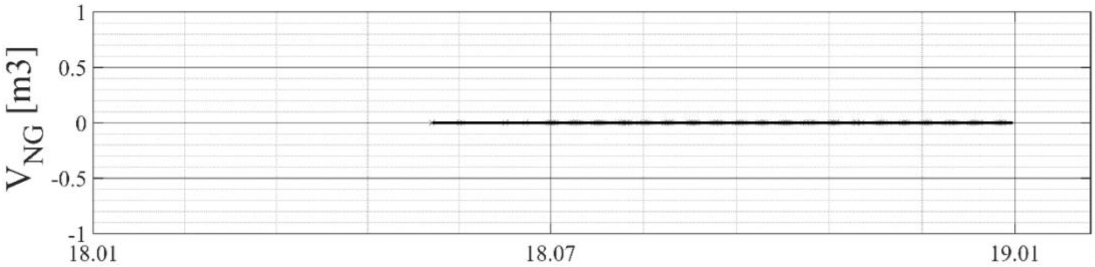

Figure 4., Time series for the location code named as C00023827.

For type C errors Fig. 5. is a good example. In this case the break or jump in the times series data can be the result of meter replacement.

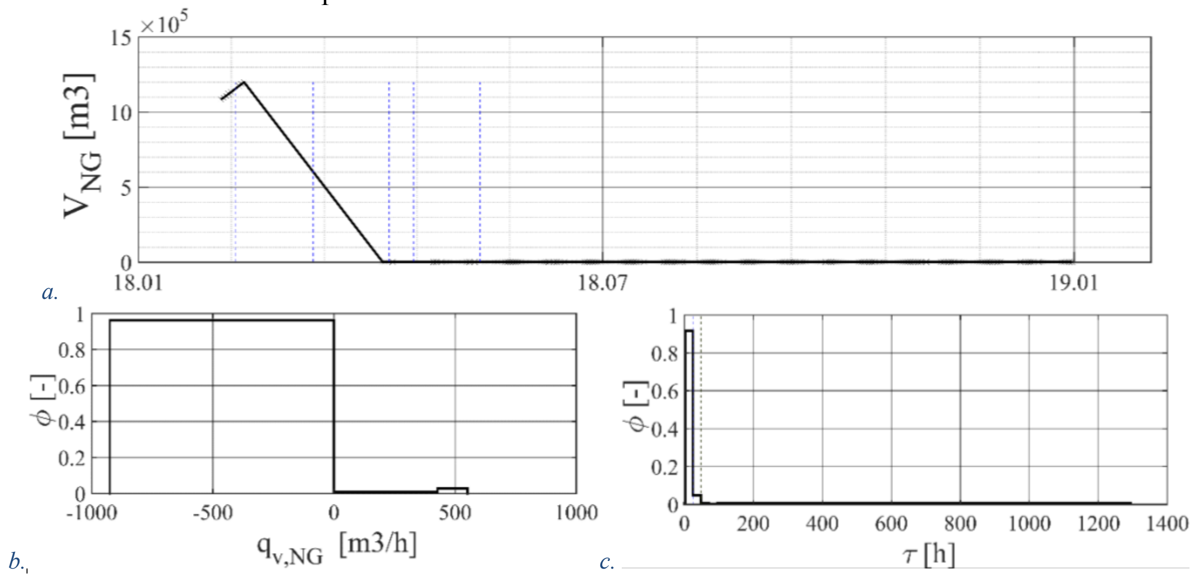

Figure 5., a.: time series, b.: histogram of qv,NG, c.: histogram of τ. for the location code named as C00028711.

Type A and C errors can most likely be corrected in some cases, but type B errors make the dataset unusable. The development of correction methods can be the subject of further research.

3.2. Natural Gas

As a preliminary step a basic gas consumption analysis has been carried out for a small selection of buildings. By carefully filtering out the datasets containing errors presented in Section 3.1, it was possible to examine the monthly natural gas consumption in 11 different locations. Fig. 6 shows locations where no gas was used during the summer season; so, it can be concluded that for cooking and domestic hot water (DHW) production electricity is used. The monthly consumption numbers were divided by the annual consumption ($V_{NG,a}$), so results are presented on a relative scale. It can be observed that the trends are within a narrow range.

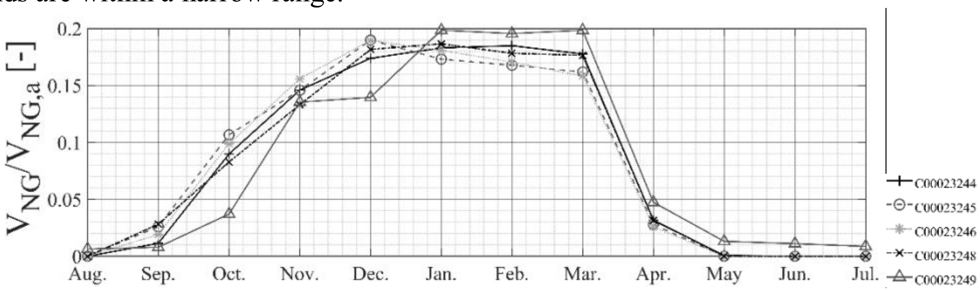

Figure 6., Monthly natural gas consumption for profiles for five different locations with almost zero consumption in the summer.

Fig 7. shows six more locations where DHW production and possibly cooking was also natural gas based, as around 12% percent of the annual gas consumption was used between May and August.

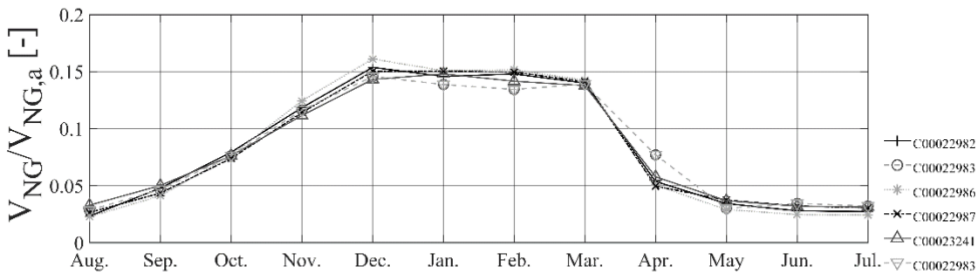

Figure 7., Monthly natural gas consumption for profiles for five different locations with gas based DHW production and cooking.

4. Conclusions and future plans

Statistical methods showed that the large dataset is suitable for selecting a sample from the smart metered buildings that produces representative results for settlement categories and building types, but not for geographical distribution, as most sensors were installed in the South-Eastern part of Hungary. The representative selection can be realized despite data errors in case of a significant number of sensors.

Data are handled with respect towards privacy issues, although GDPR rules makes it challenging to collect qualitative supplementary data about the sample buildings. All results will be anonymised.

The data evaluation process is still in the phase of methodological development and data filtering, although qualitative data collection is ongoing. Results on residential building stock is expected by the end of 2019, then public and other building types will be analyzed. In addition, there is a significant number of large residential buildings where heat cost allocator data are collected, which will be analyzed for a selected smaller number of buildings with a different, more detailed approach in cooperation with housing associations. For public buildings, GDPR is not a problem; thus, more precise supplementary data collection will be possible.

An additional part of the project will be social-psychological research based on questionnaires and interviews focusing on users' habits in approximately 20-30 public buildings in cooperation with Hegyvidék Municipality, 12th district of Budapest.

The project runs until September 2021.

Acknowledgments

Results and the determined trends are being fine-tuned and extended for other building types with a geographic scope of Hungary in another research project entitled “Large Scale Smart Meter Data Assessment for Energy Benchmarking and Occupant Behavior Profile Development of Building Clusters“. Furthermore, methods and approaches developed in the current work are being further developed for large scale data analysis. The project (no. K 128199) has been implemented with the support provided from the National Research, Development and Innovation Fund of Hungary, financed under the K_18 funding scheme.

The monitoring data subject to analysis is being collected within the "Central Smart Grid Pilot Project" by KOM Smart Meter Ltd.

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Monitoring results of innovative energy-efficient buildings in Austria

Beermann M[1], Sauper E[2]

[1] JOANNEUM RESEARCH Forschungsgesellschaft mbH, Waagner-Biro-Strasse 100, 8020 Graz, Austria
[2] Eckhard Sauper Mess-, Regel- und Steuerungstechnik, Wolfgang Pauli Straße 4, 9020 Klagenfurt, Austria

martin.beermann@joanneum.at

Abstract. The objective of this paper is to present real-world energy monitoring and sustainability assessment results of innovative energy-efficient service buildings in Austria. In the investigated buildings, the energy flows for the supply and distribution of heating, hot water and cooling energy, the object-related electricity consumption and, if available, energy generation with PV and solar thermal systems were recorded during a period of at least twelve months. The room parameters temperature and relative humidity, and in some cases the CO_2 content were also monitored. The use behavior was described based on the users of the building as well as on the operation and parametrization of mostly fully automated energy facilities. The buildings were classified in a sustainability assessment according to the Austrian Total Quality Building (TQB-) system. The buildings investigated are three office buildings, a research laboratory building, a supermarket, a hotel, a nursing home, a culture and event center and a student dormitory. The main findings presented in this paper include energy efficiency potentials identified in the automated operation of the energy facilities in the investigated service buildings. Recommendations also relate to challenges of energy monitoring itself.

1. Introduction

In Austria numerous innovative, energy-efficient buildings have been built in recent years and existing buildings renovated. Such buildings are characterized by requirements as lowest energy use, use of onsite renewable energy sources or waste heat, use of ecological building materials, ensuring adequate room comfort parameters and all this at life cycle costs comparable to conventional building concepts.

The realization of such buildings, in particular larger service buildings, includes the planning and operation of sometimes complex technical systems for heating, cooling and ventilation (HVAC). Although the planning process of complex building systems is increasingly supported by digital working methods aiming to integrate the design of buildings and their conditioning concept, the real world performance of energy efficient buildings also depends on the parametrization of mostly automated HVAC systems in larger service buildings, and on actual user behavior which can significantly deviate from standard user profiles applied in the planning phase.

Previous investigations of planned and real energy consumption of several demonstration buildings in Austria [1], [2], [3] have resulted in deviations to a varying extent. The objective of this paper is to present additional nine service buildings in Austria and to make the potential of innovative building concepts and technologies visible, but also point to possible areas of concern. The monitoring and assessment results shall serve future building projects to realize the optimization potential with regard to energetic, ecological and social aspects.

The following table 1 and figure 1 present an overview of the investigated service buildings and the main technical elements of the HVAC systems.

Table 1: Overview of the investigated service buildings

Use category	PV	Solar-thermal	Heat pump	Free Cooling	Active cooling	District heating	Steam humidifier	Component activation
Office building 1			✓	✓	✓		✓	
Office building 2	✓	✓	✓	✓		✓		✓
Office building 3			✓	✓				✓
Laboratory building	✓			✓	✓	✓	✓	✓
Nursing home						✓		
Market	✓							
Hotel			✓					
Event center	✓	✓		✓				✓
Student dormitory			✓					

Figure 1: Locations of the investigated service buildings

2. Methods

In all buildings, the generation and distribution of heating and cooling energy and hot water, the electricity demand of the HVAC system and its subsystems (e.g. heat pump, ventilation) and of other electricity consumers such as lighting were measured by using heat flow and electricity meters. The monitoring period was at least 12 months, thus covering all seasonal climatic differences, all values were recorded as 15 minute-mean values. Data management and visualization was supported by a web- and server-based professional hard- and software solution with universal interfaces to any energy and flow meters. The measurement data were evaluated in plausibility tests, specific attention was paid to the heat measurement data. Heat energy data are based on the measurement of the heat medium volume flow and the difference of flow and return flow temperatures. The measurement of small temperature differences of a few degrees, e.g. at heat pumps, is very sensitive to measurement errors of a few tenths of degrees within the class inaccuracy of the meter, which already have a major impact on the measured heat energy. Systematic errors therefore need to be corrected with appropriate factors.

Based on the measurement data, energy indicators were calculated: heating energy consumption (ambient temperature adjusted by heating degree days), warm water consumption, cooling energy consumption and final energy consumption, which is the energy supplied to the building to cover the demand of the HVAC system and of general consumers as lighting (free energy supplied by environment as solar energy, PV electricity or geothermal energy is per definition not considered as final energy).

The comfort parameters temperature, relative humidity, and in some cases the CO_2 content were measured in at least 3 rooms per building with different exposures to solar radiation. The use behavior was evaluated based on the use category of the building as well as on the operation and parametrization of mostly fully automated energy facilities.

All buildings were assessed with the Austrian sustainability rating system Total Quality Building (TQB). This rating system is based on five equally weighted criteria groups: location and facilities, economy and technical quality, energy and supply, health and comfort, resource efficiency. Criteria assessment was based on information provided by the building operators and, where available, on monitoring data. Two ecological indicators as part of TQB are explicitly presented in the results table 2 below: the life-cycle based OI3-indicator, combining global warming potential, acidification potential and non-renewable primary energy demand of the materials used in the building (system boundary BG1), and the disposal indicator EI, weighting the volume of building materials by its utilization potential after end-of-life. Detailed information on the TQB-method is provided in [4].

3. Results

Results are presented below in table 2 for the energy indicators, the comfort parameters, the TQB scores and ecological indicators. Due to the different use categories of the buildings, a comparison of results is only feasible for the three office buildings. For the other buildings the results are commented individually.

Table 2: Results of monitoring

	Office building 1	Office building 2	Office building 3	Laboratory building	Nursing home	Super-market	Hotel	Cultural and event center	Student dormitory
Gross floor area [m²]	13 051	5 535	4 878	918	3 727	1 236	1 449	1 538	1 456
Surface volume ratio [1/m]	0.29	0.42	0.81	0.41	n.a.	0.52	0.32	0.36	0.46
U-mean value [W/m²K]	0.33	0.38	0.24	0.21	0.38	0.19	0.23	0.23	0.21
Heating energy consumption [kWh/m²a]	17	44.2	25.2	163.3	47.3	32.7	30.7	12.4	30.1
Warm water consumption [kWh/m²a]	1.3	3.3	0	0	27.1	2.0	33.1	0.6	21.3
Cooling energy consumption [kWh/m²a]	12.9	20.1	9.2	102.1	0	0	0	5.3	5.3
Final energy consumption HVAC [kWh/m²a]	21.4	44.1	19.7	370.5	95.9	28.8	58.6	n.a.	26.5
Mean room temperatur (ambient T<15°C / >15°C) [°C]	22.8/23.9	24.1 / 24.8	23.5 / 24	21.8 / 22	23.9 / 25.9	20.8 / 21.3	21.3 / n.a.	21.7 / 24.1	23.2 / 24.7
Overheating hours >26°C (ambient T<15°C / >15°C) [%]	0 / 0	0 / 3-11	0 / 0-8.6	0 / 0	10-30 / 22-50	n.a.	2-11 / n.a.	0 / 0-10	0 / 15-18
Mean relative humidity (ambient T<15°C / >15°C) [%]	46.8 / 55.7	29.9 / 49.4	34.4 / 51.3	42.2 / 44.8	33.9 / 45.6	n.a.	31.9 / n.a.	n.a.	32.9 / 47.5
TQB score (range out of 1 000 points)	800-900	700-800	800-900	800-900	800-900	900-1000	800-900	800-900	700-800
OI3-Indicator (BG1)	52	176	309	117	62	211	61	244	101
EI (V1, 2012)	2.6	2.3	2	2.3	1.8	1.7	1.3	2.6	2.6

3.1. Office buildings

The three office buildings 1, 2 and 3 (OB 1, 2 and 3) have similar HVAC concepts, but completely different building shells. All three buildings supply heating energy demand by heat pumps, in OB1 using waste heat from neighboring water turbine generators, in OB2 and OB3 using groundwater, in OB3 in combination with district heating. Cooling energy is supplied by free cooling, at OB1 with water from the neighboring reservoir and in the other two buildings OB1 and OB2 with groundwater. Heating and cooling energy is distributed in OB1 by floor heating and cooling ceilings and in OB2 and OB3 by concrete-activated ceilings. The building shell of OB1 is a wood-concrete hybrid construction, and in OB2 and OB3 massive concrete construction. OB3 also has a unique stamped concrete façade. This is reflected in the average building U-value, which is particularly low for OB3 with 0.24 W/m²K compared to OB1 and OB2 with 0.33 and 0.38 W/m²K. OB1 in turn is a very compact building with an A/V value of 0.29 1 m compared to 0.42 for OB2 and 0.81 1/m for OB3.

Ambient temperature-adjusted heating energy consumption is 17 kWh/m²a for OB1, 25 kWh/m²a for OB3 and 44 kWh/m²a for OB2. In addition to the building shell characteristics U-value and compactness, solar radiation as well as the average room temperature in the heating season have an influence on heating energy consumption. Impact by solar radiation is higher in OB1 and OB2 due to large windows (east and west oriented). OB3 has smaller windows as well as the additional storage mass of the stamped concrete façade, which reduces the transmission losses of the building shell. The average room temperature during the heating season is lowest with 22.8 ° C in OB1, 23.5 ° C in OB3 and 24.1 °C in OB2.

Cooling energy consumption at OB1 is 12.9 kWh/m²a, at OB2 20.1 kWh/m²a and at OB3 9.2 kWh/m²a. The average room temperature in the summer in OB1 and OB3 is on average 24 ° C, in OB2 24.8 ° C. The percentage of overheating hours (> 26 ° C in the summer) is 0% in OB1, 0 to 8.6% in OB3 and between 3 and 11% in OB2. OB1 has overhangs in the façade on each floor as shading elements as well as daylight-controlled automated exterior blinds. In OB3, the deep, narrow window areas reduce the solar input, while the stamped concrete façade reduces the transmission losses of the building shell also in summer. In OB2, both daylight-controlled exterior blinds and specific foils on the windows provide the necessary shade.

The results of final energy consumption focus on the HCAC-systems of the buildings. Electricity consumption is 21.4 kWh / m²a in OB1, 19.7 in OB2 and 37.9 kWh / m²a in OB3. The seasonal performance ratio of the heat pumps are 3.8 in OB1, 3.7 in OB3 and 3.1 in OB2. The lower ratio at OB2 is due to a non-optimal parameterization of the heat pump in combination with district heat.

With regard to relative humidity, the measured data show the expected result that compliance with the comfort range in winter can only be ensured by air humidification in the ventilation system. In OB1 steam humidifiers are installed, resulting in an average relative humidity of 47% respectively in winter. In the other buildings, relative humidity is on average 30-34% in winter and below 20% with ambient temperatures below 0°C. However, steam humidifiers have a high power consumption, in OB1 with the highest share of household electricity consumption throughout the entire year (8.3 kWh/m²a). Electricity consumption of the steam humidifier increases the annual electricity consumption of the HVAC-system in OB1 by approximately 64%.

The range of the TQB-scores result in 800 to 900 points for OB1 and OB3 and 700 to 800 for OB2. The sub-scores for the criteria groups “location and facilities” and “economy and technical quality” are close to the maximum points in all three buildings, the differences can be found in the criteria groups “energy and supply” (described above), “health and comfort” and “resource efficiency”. The OI3-indicator is lowest (best) for OB1 with a high share of wood as construction material, whereas the massive concrete building shells of OB2 and OB3 have high OI3-indicators. The disposal indicator EI largely depends on the choice of insolation material, synthetic materials as XPS and EPS have higher (worse) results than mineral materials.

3.2. Other buildings

Results for the other buildings are commented in the following to a lesser extent than the office buildings.

A very special use category is the laboratory building. The ambient temperature-adjusted heating energy consumption is 163 kWh/m²a, cooling energy consumption is 102 kWh/m²a, final energy consumption is 370 kWh/m²a. These values result from special laboratory requirements related to room conditioning, room temperature and relative humidity must be kept in defined and very narrow ranges. Laboratory operation also requires high air exchange rates for safety reasons, resulting in additional energy consumption for the conditioning of the supply air. Steam humidification has the highest share of final energy consumption of the HVAC system (yearly average 45%, in the months of October to April up to 58%), followed by ventilation (40%). The sophisticated operation of the ventilation system with steam humidification, cooling and pre-heating and post-heating registers can therefore not be compared with other buildings and use categories. This building is nevertheless an interesting example of a building and of the high “energy investment” required to keep the room parameters within predefined and very narrow ranges throughout the year under changing ambient conditions.

The nursing home has the simplest HVAC concept in the project. The heating energy is supplied from September to May by district heating, in the remaining months by an electric boiler. The ambient temperature-adjusted heating energy consumption is 47 kWh/m²a. Compared to empirical values in the literature [5] this value is more than 50% lower calculated per care place. The relatively high average room temperatures during summer and the high proportion of overheating hours can be expected in a building without active cooling system. The supply air of the ventilation system is pre-cooled by underground collectors, which results in room temperatures of about 2-3°C lower than ambient temperatures above 30 ° C in summer.

The supermarket is another special use category. This building is known as second passive house supermarket in Mid-Europe. The heating energy consumption is 32.7 kWh/m²a. This value is higher than the maximum heating demand of 15 kWh/m²a for passive houses according to the Passive House Planning Package (PHPP-certification). However, the maximum heating demand in the PHPP refers to the energy balance of the building shell including ventilation, not including the extraction of heat by the refrigerated units. The internal heat sources are negative in this supermarket, which means that the heat extraction is higher than the internal heat sources (resulting in a so-called "cold market"). Therefore, heat needs constantly to be supplied to the building, otherwise the market would cool down. The key finding of this supermarket is that, unlike conventional supermarkets, it can be heated only with the waste heat of the refrigeration system and the compression cooling machine without using a technical heating system.

The hotel is the only renovated building presented in this paper. During renovation, the oil burner was extended by a geothermal heat pump. The monitoring result showed a surprisingly high share of 67% heat supplied by the oil burner for heating energy and warm water. It is interesting to discuss the reason as it represents a basic problem often found in heating systems that combine heat pumps with a second heating system: the heat pump feeds an energy store, which supplies the heating circuits as well as the hot water boiler. Thus, the energy storage must be maintained at the temperature level of the hot water boiler of 70 °C. In consequence the heat pump operates with a very high temperature difference between 2-3 °C temperature of the geothermal source in the primary circuit and 54- 59 °C in the secondary circuit. This results in a low efficiency of the heat pump (seasonal performance ratio 3.1). In order to keep the temperature of the energy storage at the required level for the hot water of 70 °C, the oil burner feeds the energy storage at certain times. During the time the oil burner operates, the heat pump is switched off. This is problem number two: switching on and off the heat pump leads to a lower efficiency of the heat pump, and the potential heat energy that could be generated is only half exploited, thus increases the oil consumption. The conclusion is that the heating and hot water circuits should be separated, in order to keep the temperature requirement of the heating energy storage low and to operate the heat pump with a lower temperature difference efficiently and constantly.

The cultural and event center is an interesting building since the heating energy is supplied by the solar collectors on the roof of the building throughout the year, besides one or two cold months in winter when heat is additionally supplied by the neighboring biomass heating plant of a hotel. Solar energy not consumed by the building is supplied to the neighboring hotel, and electricity from the PV plant also installed on the roof of the building is fed into the grid. Cooling energy is supplied by free cooling with water from a rainwater pool. The annual balance of energy generated by the building and final energy supplied to the HVAC system shows a surplus of 42% which is supplied to the neighboring hotel and the electrical grid.

The last building, a student dormitory, consists of 10 wood containers arranged in two floors around an atrium covered by a roof. Each box has 4 living units. Heating, cooling energy and ventilation is supplied by a combi heat pump. Heating energy demand is 30.1 which is higher than the maximum heating demand of 15 kWh/m²a for passive houses according to the Passive House Planning Package (PHPP-certification). Since the room temperature, especially in the atrium, has been relatively high with more than 23°C in winter time, there is a potential to optimize the parametrization of the HVAC system and the heating energy consumption could be reduced by about 50%.

4. Conclusions and recommendations

The following recommendations focus on project results related to the operation and parametrization of HVAC systems as well as on measurement errors of energy meters. These recommendations are relevant for building operators and owners as well as for planners and maintenance companies.

4.1. Heat pumps - temperature level and operation in an integrated HVAC system

Frequently heat pumps feed into a heat storage in conjunction with other heat generators (gas heating, solar thermal systems, district heating, etc.) to supply both heating energy and hot water, as observed in the monitored hotel and in office building 2. Due to the temperature requirement of the hot water up to 70 to 80 °C, a high temperature level is maintained, although low-temperature heating systems (underfloor heating, component activation, etc.) are frequently installed in energy efficient buildings. As a result, the efficiency of heat pumps decrease, thus losing their advantages as heat generators for low temperature heating. In integrated HVAC systems where other heat generators (for example district heating) operate to cover peak loads or extreme days parallel to the heat pump, heat pumps are often completely switched off. Thus, the heat pump does not reach the possible operation time, and the full potential of energy generated by the heat pump is not used. The recommendation is thus to disconnect high and low temperature storage tanks and maximize heat pump operating time.

4.2. Ventilation -air exchange and humidification

Excessive air exchange provides fresh air, but has the disadvantage that indoor air dries out without humidification, down to 15% relative humidity (45% would be ideal). The installation of humidifiers, especially of commonly used steam humidifiers, however, results in a very high power consumption, in the two investigated buildings in this project (in office building 1 and in the laboratory building) with the highest shares of final energy consumption. Fans for the supply and exhaust air are often operated with only one or two fixed volume settings and cannot be optimally regulated. The recommendation is to control the air volume based on CO2, adapted to the number of persons. Priority should be given to spray humidification instead of steam humidification, and retrofit frequency converters for adapted fan speed.

4.3. Pumping capacities

Frequently pumps in heating circuits are operated at constant power without taking into account the actual heat demand, as observed in office building 3. Also pumps for well water extraction for heating and cooling are often operated continuously. The result is an unnecessary power consumption for pump performance. The recommendation is to install pump controllers.

4.4. Measurement errors of heat energy meters

Heating and cooling energy meters are based on flow and return flow temperature sensors as well as on pulse or ultrasonic flowmeters. The pulse transducers are designed for different heat transfer flow rates, which results in data acquisition in too large steps if the choice is not optimal. This is a challenge for accurate heating and cooling energy measurement based on quarterly hour resolution. Another challenge is the class inaccuracy of temperature measurement in the range of 10%. With small temperature differences of flow and return flow temperatures of a few degrees (e.g. groundwater, heat pump), small measurement errors of a few tenth degrees already have a major impact on the heat energy measurement results. It is therefore important to pay attention to ambient influences on the temperature sensors, especially in retrofitted ultrasonic (clamp-on) heat meters which are externally applied to the heat pipe. For meters that can measure both heating and cooling energy, the differentiation between heating and cooling energy in the energy meter calculator is based on a minimum temperature difference of about 5 ° C (manufacturer-specific). However, with the same temperature levels in both heating and cooling energy flow (e.g. groundwater, heat pump), the heating and cooling energy needs to be calculated manually from the flow rate, flow and return flow temperature measurements. The recommendations are: careful choice of measuring instruments, installation of sensors according to standards, avoidance of external influences by insulation, plausibility check of measured data for heating and cooling energy quantity by manual recalculation based on temperatures and flow rates in the lowest possible temporal resolution, and if necessary calculation of correction factors for the temperature measurement data in the context with other measured values.

4.5. Energy monitoring

The HVAC systems are becoming increasingly complex. Often the systems are parameterized and operated based only on general knowledge regardless of the use of the building or the interaction of the technical subsystems. The result is often unnecessary over-conditioning and energy consumption, late detection of errors, as observed in most of the buildings in this project. The recommendation is to use web-based monitoring systems with automated energy reports.

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Acknowledgments

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An innovative user feedback system for sustainable buildings

Monsberger M[1], Koppelhuber D[1], Sabol V[2], Gursch H[2], Spataru A[2], Prentner O[2]

[1] Graz University of Technology, Institute of Construction Management and Economics, Lessingstraße 27/I, 8010 Graz, Austria
[2] Know-Center – Research Center for Data-Driven Business & Big Data Analytics, Inffeldgasse 13/6, 8010 Graz, Austria

michael.monsberger@tugraz.at

Abstract. A lot of research is currently focused on studying user behavior indirectly by analyzing sensor data. However, only little attention has been given to the systematic acquisition of immediate user feedback to study user behavior in buildings. In this paper, we present a novel user feedback system which allows building users to provide feedback on the perceived sense of personal comfort in a room. To this end, a dedicated easy-to-use mobile app has been developed; it is complemented by a supporting infrastructure, including a web page for an at-a-glance overview. The obtained user feedback is compared with sensor data to assess whether building services (e.g., heating, ventilation and air-conditioning systems) are operated in accordance with user requirements. This serves as a basis to develop algorithms capable of optimizing building operation by providing recommendations to facility management staff or by automatic adjustment of operating points of building services. In this paper, we present the basic concept of the novel feedback system for building users and first results from an initial test phase. The results show that building users utilize the developed app to provide both, positive and negative feedback on room conditions. They also show that it is possible to identify rooms with non-ideal operating conditions and that reasonable measures to improve building operation can be derived from the gathered information. The results highlight the potential of the proposed system.

1. Introduction

Energy efficiency plays an important role in the building sector. Aspects such as user behavior [1] or optimal operation of heating, ventilation and air-conditioning (HVAC) systems [2] have a significant impact on the energy consumption of buildings. Moreover, achieving a high level of user satisfaction is an important goal of building operation. Although standardized comfort models (e.g., Fanger [3]) provide a basic framework for the operation of HVAC systems, meeting the specific needs of building users is often a tedious and time-consuming process. In many cases, user dissatisfaction goes hand in hand with inefficient operation of building services, for example, if HVAC system set points or control strategies are wrong. In such cases, it is beneficial to determine optimum system settings in order to achieve both, a high degree of user satisfaction and energy-efficient operation. While many research activities focus on the analysis of sensor data to optimize building operation, so far only limited attention has been given to the immediate capture of user perceptions by means of individual user feedback and the use of such feedback for optimizing building operation. Field studies of mood-tracking applications have shown that techniques for reporting mood feedback are well accepted and can improve performance if the application is well integrated into the work processes [4]. For this reason, the research project FEELings (User Feedback for Energy Efficiency in Buildings) aims to develop an integrated user feedback system which allows building users to report their mood and personal perception of room conditions via a mobile app. In this paper, we will introduce the basic concept of the novel user feedback system and the design of the developed user feedback app. We also present initial results obtained from a first test period (roll-out phase), which show that the system provides the necessary functionalities to capture user feedback and to deliver relevant information to improve building operation.

2. Description of the integrated user feedback system

2.1. Overall system design

Figure 1 shows the overall concept and structure of the investigated user feedback system. The main system components are a mobile app representing the interface to building users and a database for storing the feedback along with measurement data.

Users are able to give feedback on room conditions via the app by specifying their mood and comfort level. Each feedback is tied to a specific location or room in the building. Users can set a default location such as their own office. If users want to give feedback on other rooms or buildings, they can enter a different location manually or semi-automatically via a QR code. In the future, localization may be done automatically by means of indoor positioning.

The user information is stored in a database together with measurement data (temperature, humidity, CO_2 concentration, light intensity etc.) and building service system data (HVAC operation parameters) of the corresponding room. Data analysis methods are subsequently used to identify room and operating conditions which are perceived as pleasant. In a first step, favorable conditions are reported to facility management staff who can manually adjust settings of building services systems for the rooms. In an advanced stage, the adjustment should be done automatically. This would lead to building services systems adjusting themselves according to the user feedback, meaning that system operation matches the user needs.

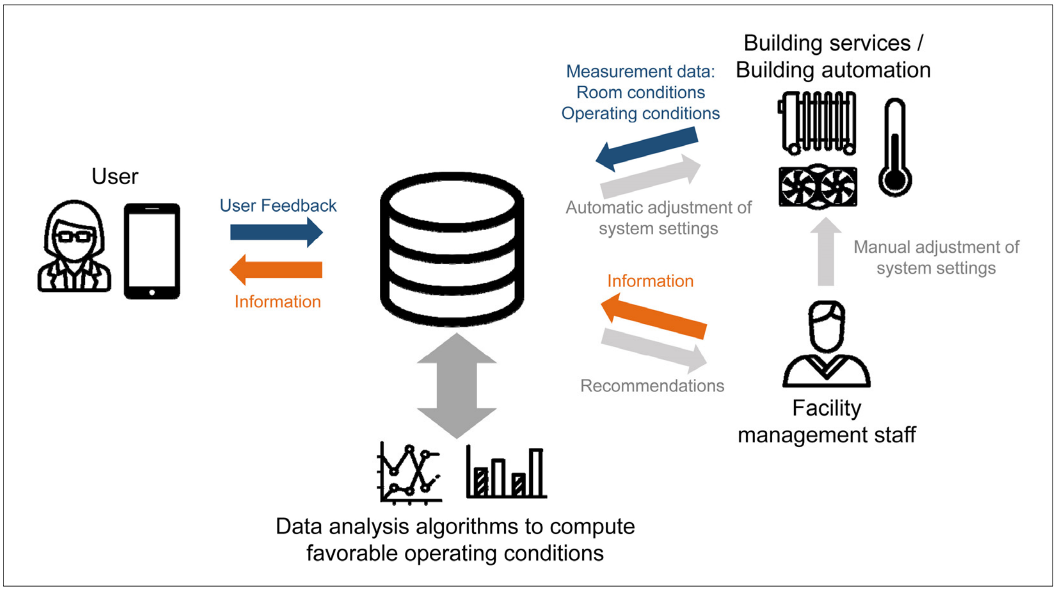

Figure 1. Concept of the user feedback system connecting building users, building services and facility management staff by means of data analysis.

Besides mood and comfort reporting, the app also provides additional functionalities in order to motivate people to use it. Users can report issues such as damages or failures of technical equipment to facility management staff (e.g., power or water failure, broken heating or air-conditioning etc.). In addition, the app can be used by facility managers to communicate with the building users, for example, to announce maintenance works. Finally, users can access statistical information based on the obtained feedback (e.g., frequency of feedback, building rating based on the feedback etc.). This information is very important to keep people interested in the app and consequently keep them as active users.

So far, the mobile app, a web portal and the database for storing user feedback and measurement data have been implemented and evaluated in an initial test phase. The development of data analysis algorithms to automatically detect preferable operating states has not yet started and is subject of the second phase of the FEELings project.

2.2. Design of the user feedback app

The developed user feedback app was implemented using the Ionic HTML5-based cross-platform framework [5]. Ionic was selected to cover Android, iOS and the desktop browser with one code base, drastically reducing development effort of the app.

After installing the app on a smartphone (or after opening the app in a desktop browser), users register with their e-mail address and select a default location by choosing the building and the room from a pull-down list or by scanning a QR code at the room entrance. Once registered, users can submit mood and comfort ratings and report issues.

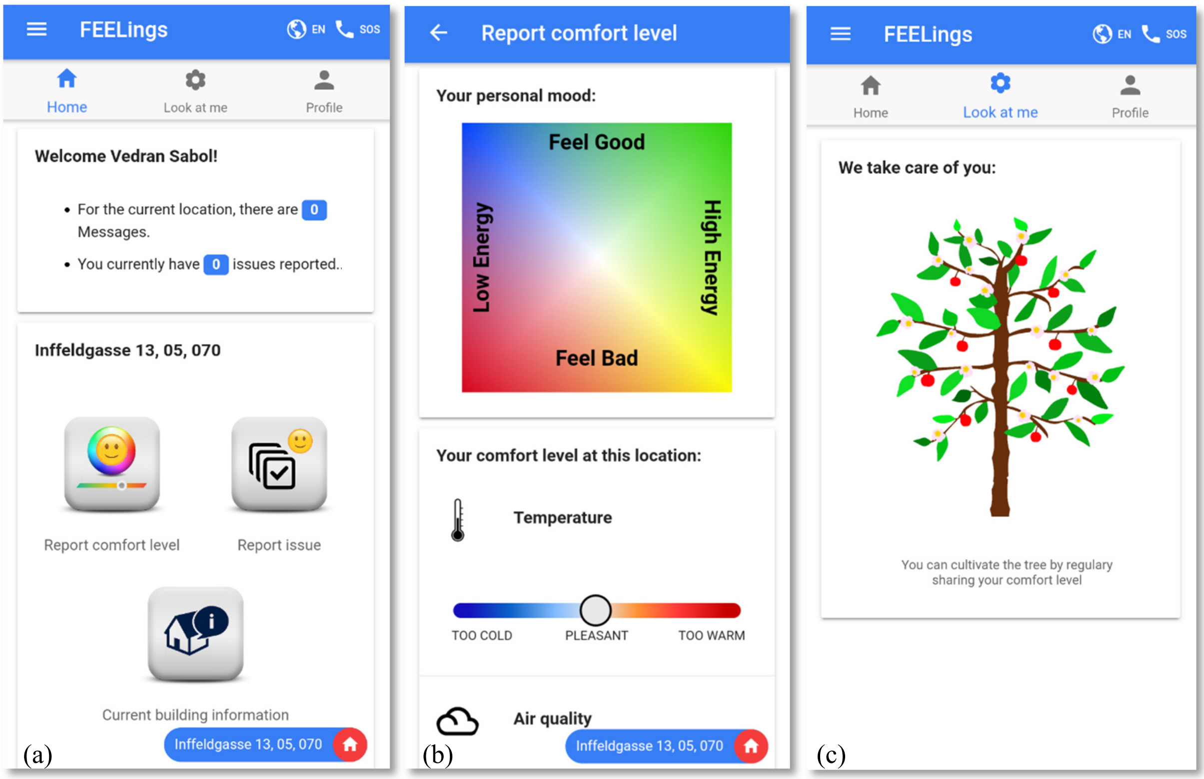

Figure 2. Design of the app: (a) home screen for navigating the app; (b) mood map and sliders for reporting user's comfort level; (c) a motivational widget which responds to the user's activities of submitting feedback.

Figure 2a shows the home screen displaying the user's name, the location, the number of reported issues and the number of messages from facility management related to the user's building. From here, users can select one of the three major functionality blocks of the app: (1) submit the current mood and comfort level; (2) report an issue specific to the room, building or environment; (3) obtain information on reported issues concerning the user's building.

Figure 2b illustrates the screen for submitting the personal mood using a mood map. The mood map is a rectangular area where the y-axis corresponds to how the user currently feels (*bottom – feel bad, top – feel good*), while the x-axis represents the user's energy level (*left – low energy, right – high energy*). By simply touching (or clicking) a specific position in the mood map, users can express their mood along these two dimensions. Furthermore, the comfort level can be specified more precisely using sliders representing temperature (*too cold – pleasant – too warm*), air quality (*fresh – ok – bad*), noise level (*quiet – lively – noisy*), light intensity (*too dark – pleasant – too bright*) and the type of activity (*sitting, standing or moving*). Optionally, users can submit a short message of up to 300 characters.

Figure 2c shows a motivational widget in the form of a tree: if a user submits feedback frequently, the tree will grow green; otherwise the tree starts losing leaves until the branches remain naked. We believe that using a natural metaphor, such as a growing tree, could motivate users to nourish the tree by reporting their mood and comfort level more frequently. Moreover, users may opt to receive bi-weekly or daily reminders to submit feedback.

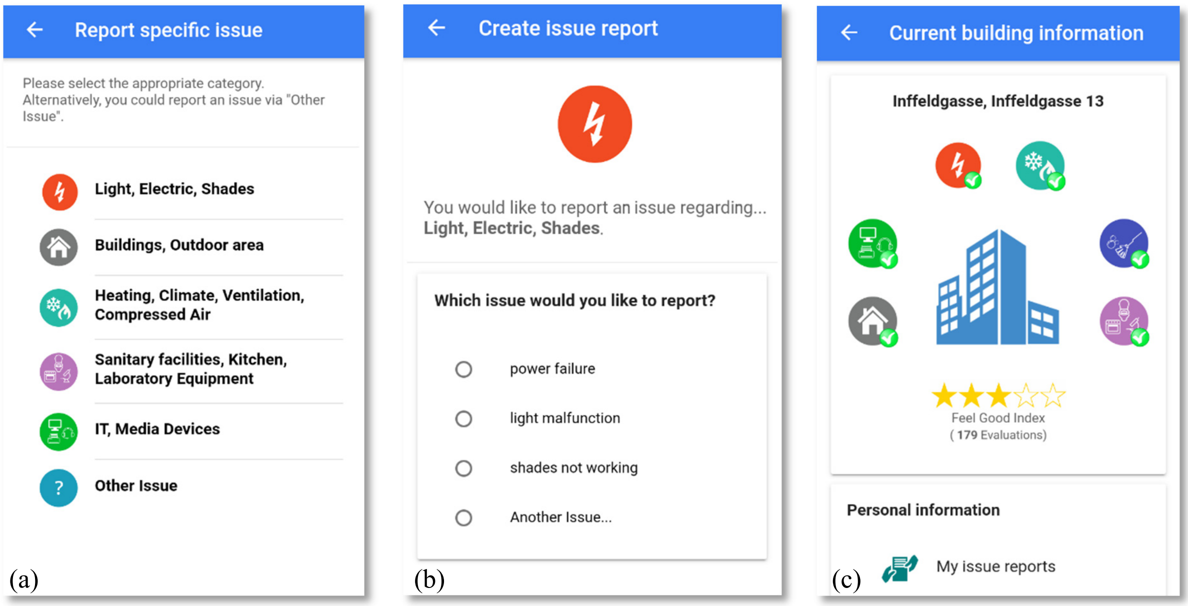

Figure 3. Mechanism for reporting issues: (a) selection of issue category; (b) more detailed specification of the problem; (c) overview of the state of a building in six categories.

Figure 3 shows the possibilities to report and monitor issues related to the room, the building or the outside environment. After selecting an issue category (figure 3a), users can choose from a list of predefined options to specify the issue in more detail (figure 3b). If no option describes the issue well enough, users can select the option "Another issue…" where it is possible to provide a textual description and to upload a photo of the problem. For later reference, users have access to all issues they reported. A reported issue is immediately sent to the maintenance service per e-mail, including a link to a web page containing all information submitted for that particular issue. The maintenance team can take action or, if necessary, request further information from the user.

Finally, figure 3c shows a status overview of the user's building for each of the six issue categories and a star rating calculated based on the submitted mood and comfort ratings.

3. Initial test results

3.1. Description of the first use case

The novel user feedback system is evaluated over a period of one year in four different use cases. A use case represents a monitored building in which users are asked to use the app. The use of the app, and therefore participation in the project, is voluntary. A building at the campus of Graz University of

Technology was selected as first use case. The seven-story building was put in operation in 2012 and accommodates offices, laboratories and seminar rooms. About 250 people currently work in this building. The building is equipped with a floor heating system operating in heating mode in winter and in cooling mode in summer. The temperature is controlled via four zones on each floor (i.e., no single room control). While a central ventilation system is available in all laboratories and seminar rooms, the ventilation of office rooms takes place manually by means of window ventilation.

The roll-out of the user feedback system for this first use case took place in December 2018 with an information event for the building users. The first two and a half months of operation are used as trial phase in order to test the basic functionality of the system, to get user feedback to improve the app and to eliminate bugs. After successful completion of this initial test phase, the system will be rolled out to the other use cases. The following results were obtained from this initial test phase which lasted from December 10, 2018 until February 28, 2019. A total of 55 users, i.e., about 20% of all building users, participated in this initial test phase.

3.2. Frequency of comfort ratings

Figure 4 shows the accumulated number of comfort ratings over time; sections with a high growth indicate an active use of the app, while constant sections correspond with no use (e.g., Christmas break with no app usage at all). Sharp increases correspond with information events (e.g., during roll-out) and e-mail reminders (e.g., on January 24, 2019) or with times with poor room comfort.

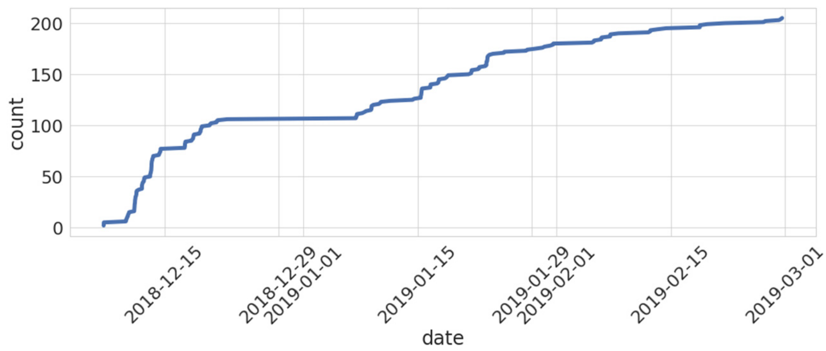

Figure 4. Accumulated number of comfort ratings over time.

The total of 205 app ratings can be broken down into specific feedback categories as shown in table 1. Part of the feedback was sent with default values preset by the app. There are two possible explanations for this. First, the default value matches the user's perception, or, second, the user did not want to provide feedback in a specific category and simply kept the default value. The number of default values varies significantly between the different categories. Table 1 shows that the mood map most often has a value different to the default setting, followed by air quality, temperature, noise, light and the work profile.

Table 1. Number of non-default feedback values per input category. Percentages relate to the total of 205 comfort ratings.

	Mood	Air Quality	Temperature	Noise	Light	Work Profile
Count	167	148	111	106	57	39
Percentage	81%	72%	54%	52%	28%	19%

3.3. Distribution of mood ratings

The feedback from the mood map (figure 2b) provides a first indication about the well-being of building users. Figure 5 shows the result (i.e., non-default feedback values) obtained for the selected use case building during the initial test period. The two-dimensional mood map was divided into nine areas of equal size in order to categorize and compare the user ratings. The overall mood feedback for the use case building is positive. A total of 114 mood ratings have at least a rating of *FEEL OK* and *ENERGY OK,* which corresponds to 68% of the overall number of non-default ratings. Moreover, 61 ratings belong to the *FEEL GOOD* and *HIGH ENERGY* group (upper right corner). On the other hand, 15 reported mood ratings fall into the *FEEL BAD* and *LOW ENERGY* category (lower left corner). A more detailed look at the data shows that the poor mood ratings come from eight specific rooms. An obvious conclusion from this result is that people generally feel comfortable in the building except certain rooms. The user feedback from these rooms was thus analyzed in more detail. First results for one particular room are presented in the next section.

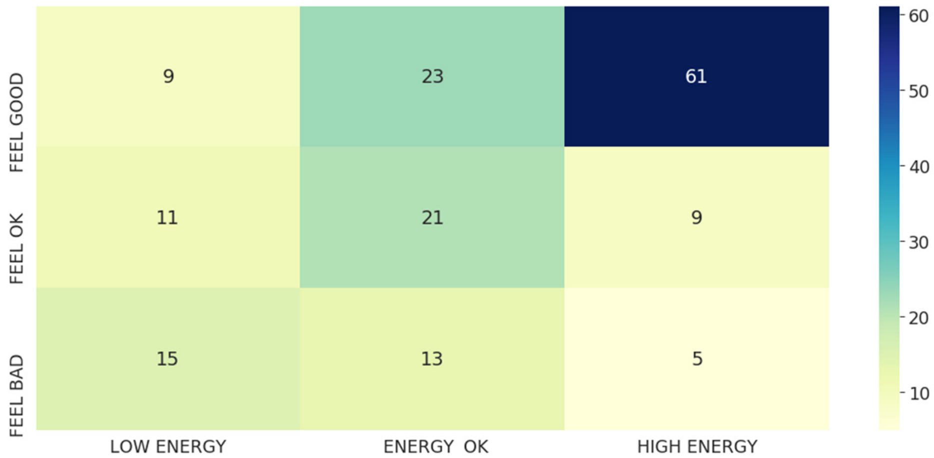

Figure 5. Heatmap encoding the number of ratings for nine mood groups of equal size.

3.4. User feedback on room temperature for an office room

Figure 6 shows the measured room temperature and the reported room temperature feedback over the initial test period for an office room with 14 occupants. The mood map feedback for this room was poor (FEEL BAD and ENERGY LOW) in comparison with other rooms. The room is equipped with two sensors (brand Tinkerforge, type Temperature Bricklet v1.1) positioned in the longitudinal axis of the room at one-third points at a height of approximately 1.4 m. The upper part of figure 6 shows the temperature profile measured by one of the sensors. Temperature values are recorded every five minutes. User feedback is illustrated in the lower part of figure 6. Each point corresponds with a reported temperature feedback using the temperature slider of the app (see figure 2b). The points' vertical positions in figure 6 coincide with the slider positions, covering the range *too cold – pleasant – too warm*. Five of the 14 room occupants participated in the test and provided feedback. One user only submitted one rating; the other users gave multiple ratings over the test period.

The average room temperature is around 26 °C as apparent from the temperature profile. This is a comparatively high value in winter months. The profile has downward spikes showing significant temperature decreases for short times. These spikes are caused by manual room ventilation. People who work in the office regularly open the windows when they arrive in the morning. This explains the absence of spikes during the Christmas break from December 22, 2018 until January 6, 2019 when the office was not occupied.

The amount of feedback of the four users is declining over time as figure 6 shows. While 25 room temperature ratings were received between December 10 and 22, 2018, only 15 ratings were received between January 6 and February 28, 2019. One possible reason is that people lost interest in the app, potentially because no action was taken to improve the temperature level in the room.

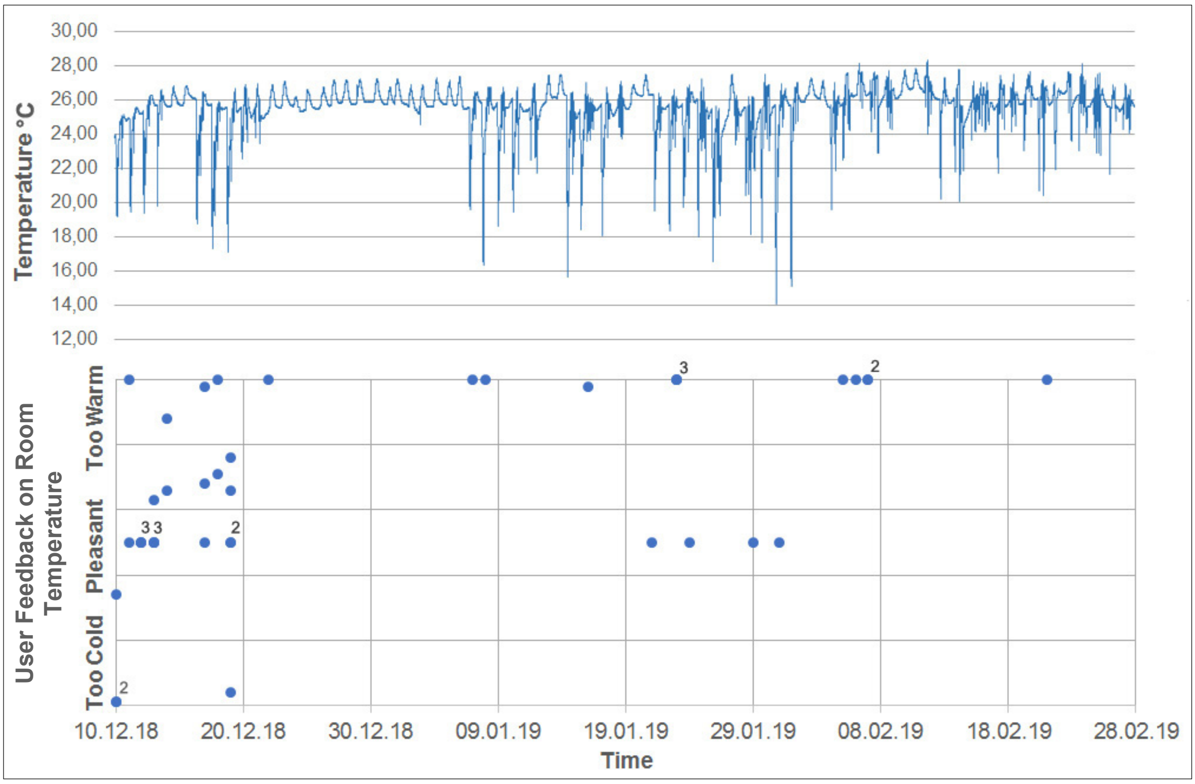

Figure 6. Measured room temperature and reported feedback on the temperature for an office room.

Figure 7 shows the temperature ratings against the measured room temperatures at which these ratings were submitted. Temperatures above 26 °C are rated as *too warm*. Ratings submitted between 25 °C and 26 °C vary between *pleasant* and *too warm.* The majority of ratings in the temperature range between 20 °C and 25 °C is *pleasant*.

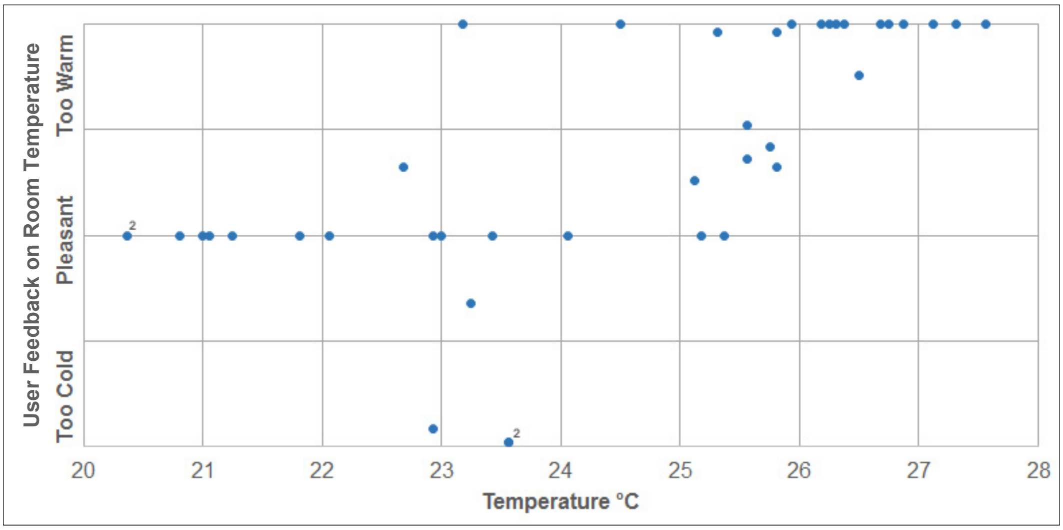

Figure 7. Feedback on the room temperature vs. measured room temperature for an office room (data from the test period between December 10, 2018 and February 28, 2019).

The results presented in figure 6 and figure 7 indicate that the average room temperature of around 26 °C is too high. A reasonable measure would hence be to adjust the set point of the heating system in order to reduce the temperature of this room. Such an adjustment would also reduce energy consumption for room heating. The practical implementation of this measure will be evaluated with the facility management staff. The impact of this step on the personal sense of users' comfort can in turn be monitored with the app. These initial results already highlight the potential for identifying non-ideal room conditions by using the proposed user feedback approach.

4. Conclusion and outlook

In this paper, we introduced a novel feedback system for building users and presented results of its initial test phase. The principal idea is to capture perceptions of building users about room conditions with an app and to compare the obtained user ratings with measurement data. The immediate user feedback makes it possible to determine whether given room conditions correspond with user requirements. The generated information is used to optimize the operation of the building with respect to both, user satisfaction and efficiency. In a first phase, the overall system was designed, set up and evaluated in an initial two-and-a-half-month test in order to prove the basic functionality. The results of this initial test have shown that users utilize the app to report both, positive and negative feedback. Based on this feedback, it was possible to identify rooms with non-ideal room conditions. In one example, users rated room temperatures during winter months as too high. This is an indication for facility managers to reduce the room temperature by adjusting the heating system. This example shows that the generated information can support decision making of facility managers. It can be concluded from the initial test results that the system provides the basic functionalities for capturing user feedback and delivering relevant information to improve building operation. In a next step, data analysis methods will be developed in order to automatically detect non-ideal room conditions. Information about such conditions will be provided to facility managers so they can optimize system settings. In an advanced stage, this optimization process should be done automatically by computing set points based on data analyses and by directly applying them to building automation systems. The proposed approach should help to increase the efficiency of building operation and the quality of building use.

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Hook-and-Loop fastener – application for the technical building equipment

Oswald F[1], Riewe R[2], Raudaschl M[2]

[1] University of Auckland, School of Architecture and Planning, 16 Symonds Street, 1010 Auckland, New Zealand

[2] Graz University of Technology, Institute of Architecture Technology, Rechbauerstr. 12, 8010 Graz, Austria

ferdinand.oswald@auckland.ac.nz

Abstract. The Hook-and-Loop fastener (better known for its commercial name Velcro®) is omnipresent in many fields today. Astonishingly it is far from utilizing its full potential in the construction industry although its properties could have a variety of positive effects on the industry.

Contents and Objectives

Commonly the building installation lines (such as electricity, water or ventilation, to name just a few) are walled-in, screwed, or glued at the construction site. Would these instead be assembled and mounted using the hook-and-loop similar fasteners, the following effects with corresponding consequences could arise:

- Simplified assembly processes: They would decisively accelerate the construction phase of a building and would additionally be less prone to performance-related quality deficiencies.
- Flexible mountings and adaptability: They would enable the building to react to short-notice planning changes as well as to adapt to a new spatial program more efficiently.
- Damage-free connections - both for the base-surface and for the component to be fastened to it - would enable a pure separation of different materials and thus easy re-use. The possibility of easy re-use of specific components could prolong the component's in-use phase of the lifecycle, which would contribute to sustainable usage of resources.

The aim of this exploratory project was thus to develop concepts for the production of surfaces with hook-and-loop-compatible surfaces in buildings, which could serve as a base-surface for simplified mounting of building`s installation lines.

1. Starting point/Motivation

The Hook-and-Loop fastener (better known for its commercial name Velcro®) is omnipresent in many fields today. Its potential lies in the astonishing strength of the bond between two compatible layers, which can in addition be loosened and re-fastened tool-free for several hundred times with very little influence to its strength and durability. Astonishingly it is far from utilizing its full potential in the construction industry although its properties could have a variety of positive effects on the industry.

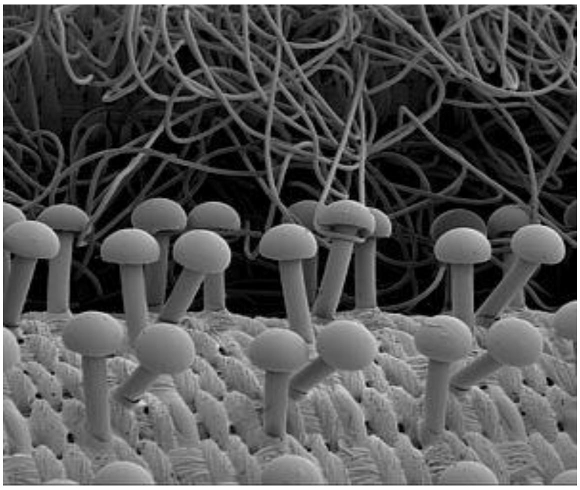

Figure 1. Hook-and-loop fastening principle [1].

The project facade4zeroWaste which includes the development, architectural design relevance, grants of patents, results of pre-certification testing's and the product publication in the time frame from 2009 till now ongoing. Aim of the research project facade4zeroWaste was the idea of a recyclable facade insulation system that can easily be dismantled after its lifetime and reused thanks to an innovative grip fixing system consisting of mushroom-shaped heads and loops - Grip fixing instead of adhesive. The project won numerous prices and awards like the EQAR - Recycling Prize 2015 or the Innovation Award for Architecture and Building 2017. The project is a contract research project tasked by Sto SE & Co. KGaA, Germany and Sto GesmbH, Austria and the Institute of Architecture Technology, Austria. The façade system was presented to the public in January 2017 as the product Sto Systain R (R = render: seamless plaster layer surface) on the building fair BAU 2017 in Munich. StoSystain has been developed by the authors of this paper.

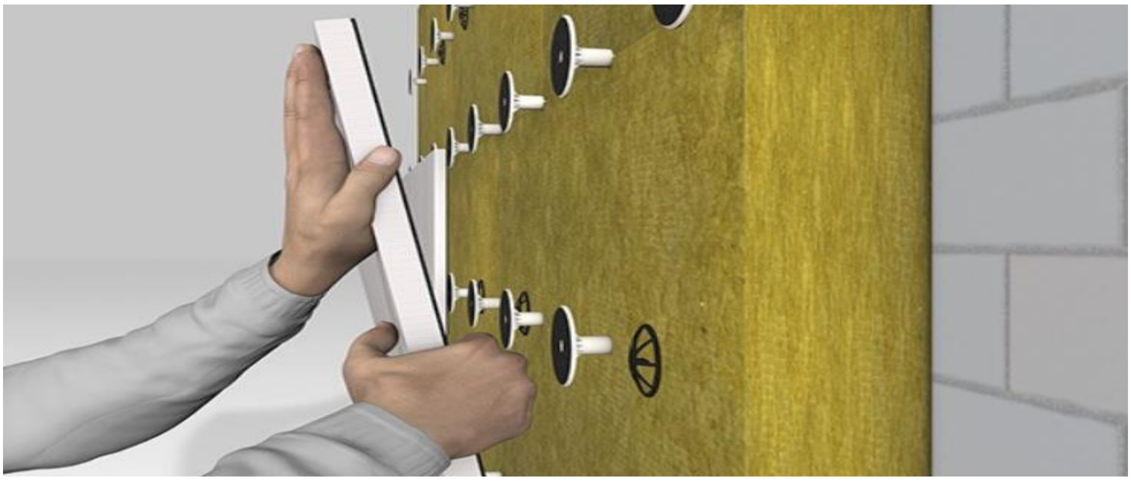

Figure 2. Façade panel and mechanical fixation element (round shaped) during assembly [2].

Figure 3. StoSystain R on the building fair BAU 2017in Munich [2].

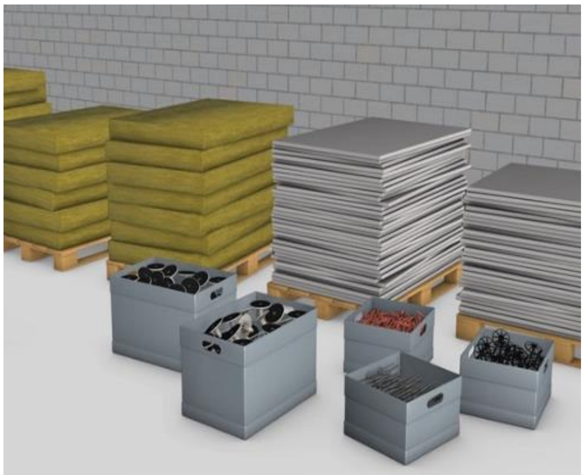

Figure 4. Sorting by component-type for recycling + reuse and Transportation, StoSystain façade system [2].

2. Contents and Objectives

Commonly the building installation lines (such as electricity, water or ventilation, to name just a few) are walled-in, screwed, or glued at the construction site. Would these instead be assembled and mounted using the hook-and-loop similar fasteners, the following effects with corresponding consequences could arise:

- Simplified assembly processes: They would decisively accelerate the construction phase of a building and would additionally be less prone to performance-related quality deficiencies.
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- Damage-free connections - both for the base-surface and for the component to be fastened to it - would enable a pure separation of different materials and thus easy re-use. The possibility of easy re-use of specific components could prolong the component's in-use phase of the lifecycle, which would contribute to sustainable usage of resources.

The aim of this exploratory project was thus to develop concepts for the production of surfaces with hook-and-loop-compatible surfaces in buildings, which could serve as a base-surface for simplified mounting of building`s installation lines.

Figure 5. Polyethylene-pipe insulation, self-adhesive [3].

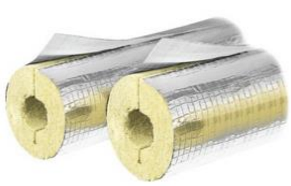


Figure 6. Stone wool pipe shell aluminium-laminated, self-adhesive [4].

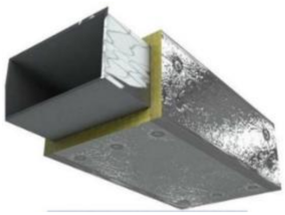


Figure 7. Mineral fibre aluminium-laminated [5].

Figure 8. Damage of insulation at ventilation ducts as a result of fixation [6].

Figure 9. Drilling and chiselling work on the construction site for electrical installations and water pipes with popular tools [7].

Figure 10. Dirty tools on the construction site [8].

3. Methods

The exploratory project was not limited to the consideration of a single material or a trade, but aimed at the widest possible field of view in order to uncover potentials that could lead to more extensive and more product-specific research projects in the near future.

The development of conceptual connections between different construction base-surfaces and hook-and-loop components was carried out by a thorough investigation and professional assessment of existing connections. Two innovation matrices were created. The developed concepts were then evaluated by means of evaluation sheets and team discussions. Promising concepts have been physically tested by the Laboratory of Structural Engineering at Graz University of Technology.

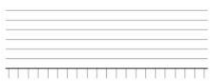
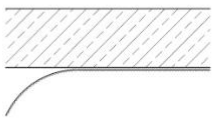
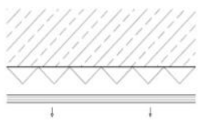
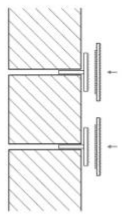
A – Shell Construction Material				
wood	concrete		steel	brick
H1.8 - Fasern 	B1.1 - Kleben 	B3.5 - Einlegen 	S2.2 - Klemmen 	Z3.4 - Einspannen 
Substance to substance bond	Substance to substance bond	Frictional connection	Interlocking connection	Frictional connection

Figure 11. Promising concepts - Connections between different construction base-surfaces and hook-and-loop components [9].

Figure 12. Experimental Setup of the peeling and pull-out tension test with Loop-Fastener. The width of the test strip is 5 cm. [10].

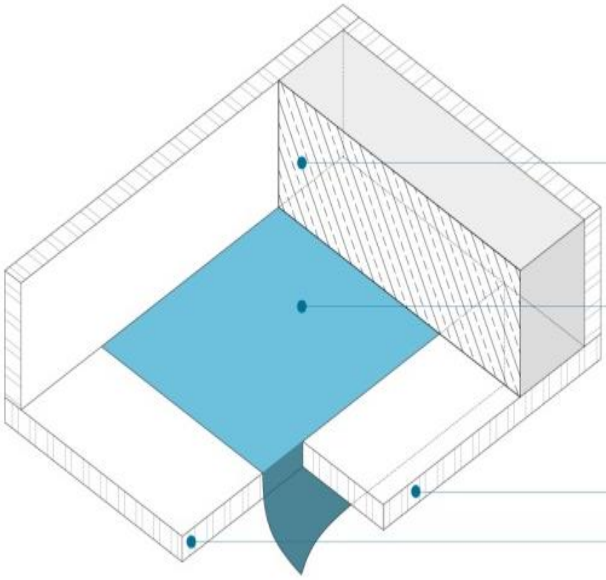


Figure 13. Testing concept, Fixations of the inserted Hook-and Loop-fastener [11].

4. Results

Based on the innovation matrix, a total of 143 concepts for connections between Velcro and building materials were developed. Due to their particularly high innovation content, five of these concepts were handed over to the Research & Technology House at the Graz University of Technology, which is currently examining their patentability.

Two key findings form the basis for further research projects. On the one hand, to achieve the envisaged flexibility, the aim is to provide a large hook-and-loop-compatible base-surface of a building (e.g. wall or slab). To achieve the hook-and-loop compatibility, the material of choice here would be either velour or fleece, because they are both webbed materials and thus more economical and available in large rolls. The specific properties of the material and its processing specifics must be taken into account for further development.

Secondly, the timing of production of hook-and-loop-compatible base-surfaces is of crucial relevance. Whether during prefabrication, during the construction phase, or during reconstruction / remodelling, each intervention requires a different approach.

During the construction phase of reinforced concrete walls or slabs for example, the hook-and-loop-compatible base-surface could be achieved in a variety of ways. Following the manufacturing logic of reinforced concrete, velour or fleece mats could be inserted into the formwork before the concrete is poured. Challenges, such as precise position fixation during the pouring process, or the protection of mats from contamination, need to be addressed. However, completely different approaches are required when the load-bearing construction is already finished or when refurbishment of an existing building is in question. In the last two cases, largely independent of building materials, we found out, that production of hook-and-loop-compatible base-surfaces is the most efficient when it is done with one of the various available gluing techniques. They are relatively easy to handle, but with disadvantages when it comes to dismantling a building. Namely, the ability to separate building materials at the end of their life-cycle (ideally the velour or fleece mat could be completely separated from other materials), is of great importance for the evaluation of the different concepts.

In addition to these considerations, building materials and construction composites were examined for their potentially inherent hook-and-loop compatibility. First and foremost, these include various fibrous materials which, due to their structure, could under certain circumstances form loops. Such concepts are convincing in terms of material homogeneity and thus complete purity. Nevertheless, tests have shown that the strength of such bonds is far from that of commercially available hook and loop fasteners, which limits, but does not preclude their potential use and development.

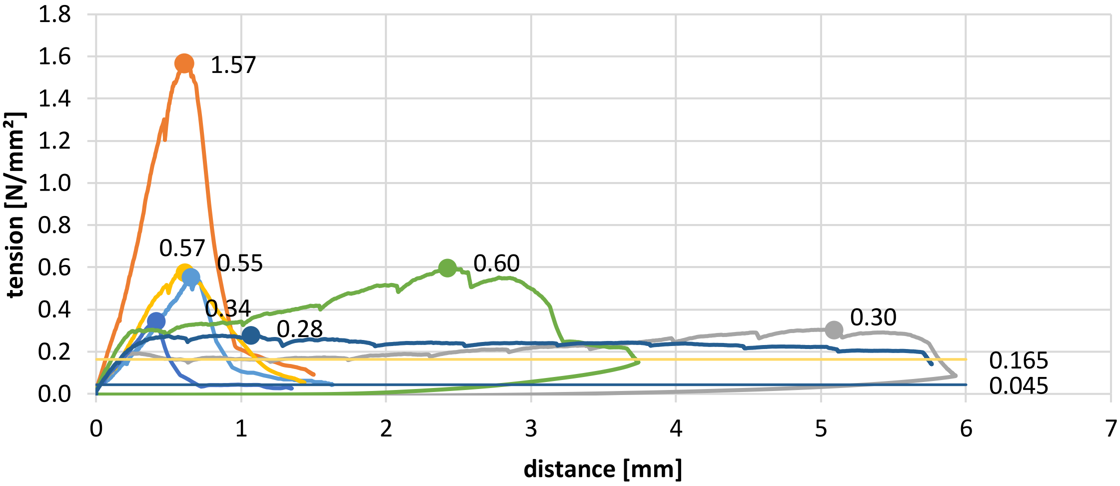


Figure 14. Complete overview of the results pull strength test „Insert Loop-fastener into concrete" [12].

5. Prospects / Suggestions for future research

The exploratory project has shown that it is possible to produce large hook-and-loop-compatible base-surface areas in buildings. This represents a solid foundation for the future achieving of the formulated objectives. Within the institute an in-depth basic knowledge has been created, which provides optimal conditions for further research and development work on the way to the damage-free assembly and disassembly of building's technical installations. The entire project team gained new knowledge in the field of building services, connection and fastening types, and the production & application of hook-and-loop products.

Great potential lies in the exploration of the following topics: Concrete and hook-and-loop surfaces, hook-and-loop-compatible fiber insulation, and alternative connection systems for conventional hook-and-loop-fasteners. The further development either in the form of a state-funded project or together with corresponding and well-known partner companies will therefore be the focus of the future research work of the Institute of Architecture Technology.

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[8] https://www.123rf.com/photo_15436870_dirty-shovel-and-masonry-tools-on-a-construction-site.html, 01.08.2018, 10:05

[9] Source: Institute of Architecture Technology, Graz University of Technology, Austria

[10] Source: Test report „Hook-and-Loop fastener-application for the technical building equipment“, Laboratory for Structural Engineering, Graz University of Technology, Austria.

[11] Source: Institute of Architecture Technology, Graz University of Technology, Austria

[12] Photo: Test report „Hook-and-Loop fastener-application for the technical building equipment“, Laboratory for Structural Engineering, Graz University of Technology, Austria.

Image-obfuscation as a means for privacy-conscious visual data acquisition from building systems

Subramaniam S[1], **Hoffmann S**[1]

[1] Department of Civil Engineering, Technische Universität Kaiserslautern, Germany

sarith@rhrk.uni-kl.de

Abstract. In the last two decades, numerous studies have demonstrated the viability of using High Dynamic Range Imaging (HDRI) to quantify lighting conditions in the built environment. Several human factor studies have demonstrated correlation between visual comfort perceived by occupants and glare metrics calculated by analysing HDR images. However, the use of HDRI in real-world applications has been severely limited owing to privacy concerns. This research investigates the feasibility of employing obfuscated (i.e. deliberately distorted) HDR images for analysing glare. The authors present a pilot study where visual conditions inside an office-space were simulated and captured as HDR images using a validated, physically-based renderer. The images were then obfuscated to various degrees by application of blur filters. Glare metrics calculated for the obfuscated images, when compared with the metrics generated for the original HDR images, were found to be within 2%-12% relative error. The proof-of-concept demonstrated through this study provides the framework for field-testing of an HDR-based lighting control system in a real office space.

1. Introduction

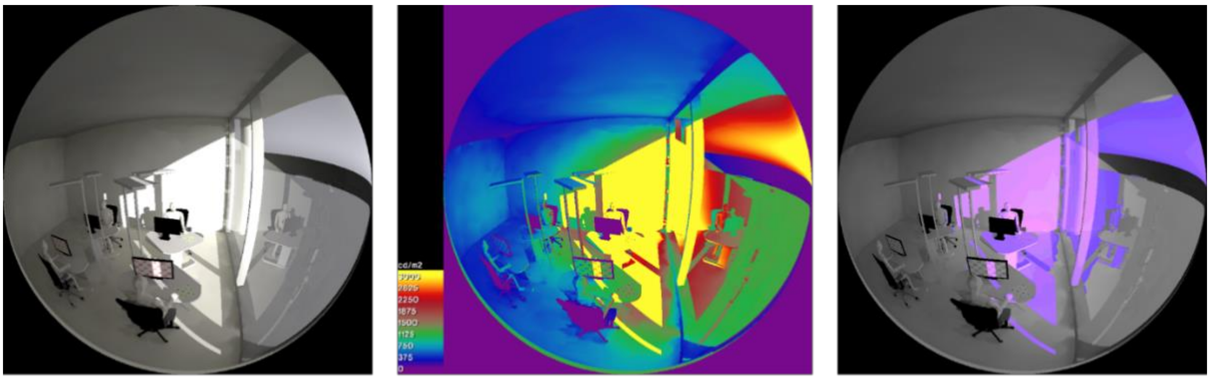
The availability of daylight in commercial workspaces has been associated with improvement in occupant well-being and productivity. In surveys, occupants have indicated a preference for locations with a view of the outdoors than in closed spaces with no external views[1, 2].

An effective daylight control strategy is one that will ensure task-adequate brightness inside a space and minimize visual discomfort due to glare [3]. Active strategies for glare control include the use of devices such as blinds, adjustable shades, and more recently, electrochromic glazing. Owing to the temporal variations in daylight during a typical day, such devices need to be adjusted periodically to minimize glare and optimize useful daylight. While automated lighting control systems have been commercially available for many years, there exists a gap between the purported and actual performance of these systems. Studies have shown that in spaces where such automatic systems are installed, the automatic control is often overridden by the occupants. Additionally, meta-analyses have indicated a significant disparity between the projected and realized benefits of daylighting control systems [4, 5].

The shortcomings in the performance of daylight responsive lighting control systems are attributable to the way in which they estimate the lighting conditions in a space. These devices are automatically actuated by microcontrollers or building management systems whose control algorithms rely on photosensor-derived vertical and horizontal illuminance/irradiance measurements to account for lighting conditions in a space [6-8]. Illuminance, especially of a single representative location in space, while easily measurable, is not always a reliable predictor of visual comfort. The lighting metrics that have demonstrated high correlation with perception of visual discomfort typically take into account luminance of potential glare sources, their size and vertical illuminance[9]. Several field studies conducted since early 2000s have demonstrated that images acquired from commercial cameras can be reliably employed to measure luminance and illuminance data through High Dynamic Range Imaging (HDRI) [10-13]. The process of image-acquisition involves capturing multiple images at different exposure levels and then fusing them together to create a High Dynamic Range image. Unlike standard image formats like JPG or PNG, which usually store 8-bit data per pixel, HDR images store between 24 to 48 bytes per pixel, thus facilitating the storage of a wide range of brightness values encountered in natural lighting conditions [14-16].

HDR images can also be generated through physically-based rendering engines like Radiance. Radiance, a command-line ray-tracing tool developed primarily by Greg Ward at the Lawrence Berkeley National Laboratory [17]. It employs a 32bit/pixel RGBE data format capable of storing the wide range of luminance values encountered in daylit spaces. Based on the numerous validation studies conducted on the accuracy of Radiance in simulating daylighting conditions, and resulting glare, the use of Radiance for predicting glare through HDR images during design stages is widely advocated and practiced [18-21].

Currently, the most commonly used tool for glare assessment from HDR images is a command line program called Evalglare [22-24]. Among the several glare-based metrics calculated by Evalglare, Daylight Glare Probability (DGP), is the most prominent and is widely used [25-27]. Evalglare requires fisheye HDR images for analysing glare. Figure 1 shows a scenario where the luminance captured through an HDR image has been evaluated using false-colour mapping as well as Evalglare.



(a) (b) (c)

Figure 1. Image (a) shows an HDR image generated through Radiance. Image(b) shows the corresponding false colour mapping of luminance values and image (c) shows the location of potential glare sources identified by evalglare. The colours assigned to the glare source by evalglare are arbitrary.

2. Motivation and working hypothesis

Although HDRI has proven to be a reliable means of acquiring data that can be used to quantify the luminous conditions existing in space, its applications in real-world applications have been limited. The photographs captured for generating HDR images can compromise the privacy of individuals and/or reveal sensitive information about the photographed space [28-30].

The research underlying this paper investigates whether glare analysis of low-quality or deliberately distorted HDR images can produce results comparable to those obtained through high resolution HDR images. The rationale behind distorting the HDR images is to obscure the activity and identity of occupants, thus alleviating, to some extent, privacy-related concerns. An example of distortion using blur filters is shown in Figure 2. The authors hypothesize that, if an obfuscation technique is uniformly applied across the entire image, the values of DGP derived through obfuscated HDR images will be comparable to those derived through original HDR images. The subsequent sections describe the methodology and results from a simulation-based pilot study conducted for testing this hypothesis.

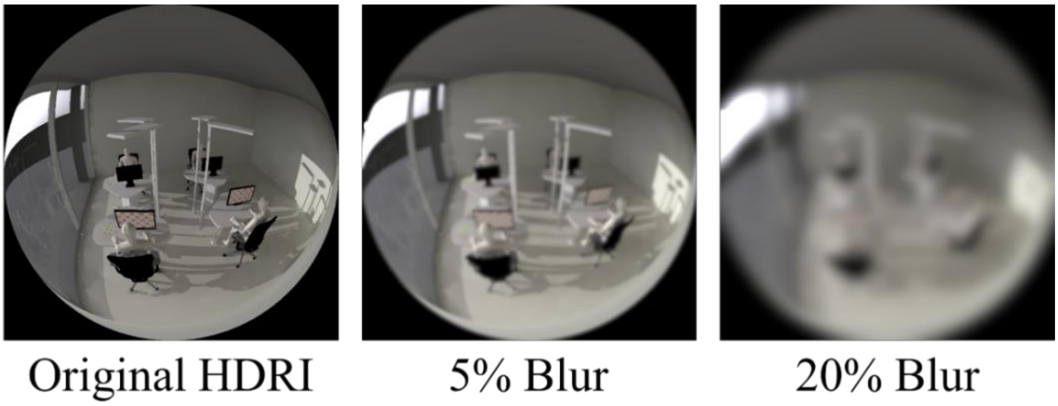


Figure 2. Obfuscation of an HDR image using Gaussian blur filters.

3. Methodology

The goals of the pilot study described in this paper are to identify an obfuscation method that allows for progressive distortion of HDR images, establish automated glare analysis workflows from images and finally ascertain the feasibility of such images as a replacement for standard HDR images.

Figure 3 shows the room considered for the simulations. This room, which is modelled after an actual office space in Germany, consists of a south-facing full-height glazing. The occupants are subject to direct insolation, and consequently visual discomfort, especially during the winter months when the solar profile angle is low. The 3D model shown in Figure 3 was created in SketchUp® software from physically measured dimensions at the site. The model was then exported to a format compatible with the Radiance rendering system using a plugin called Su2Rad [31].

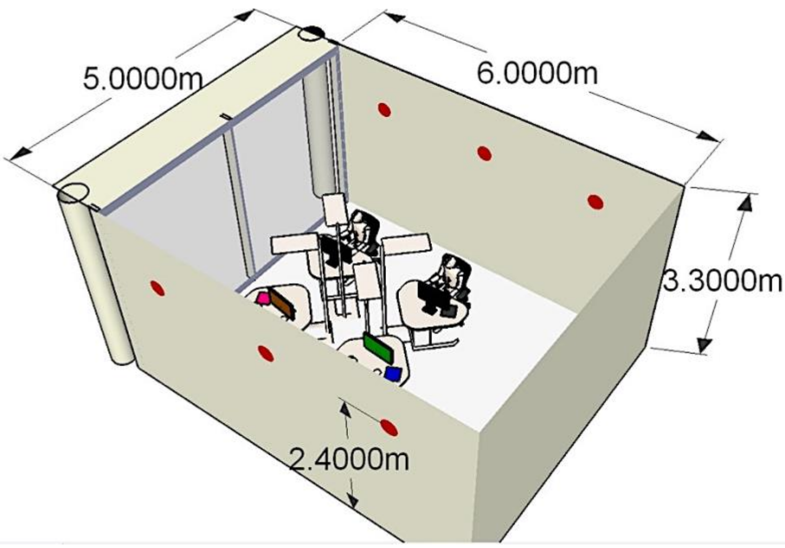


Figure 3. Overall dimensions of the space modelled for the study. The glazing faces towards south. The six virtual cameras used to generate HDR images were placed 2.4 m above the floor level and are highlighted with red circles in the image.

Figure 4 shows two typical HDR images generated with Radiance from the exported model. For the purposes of generating HDR images for glare analysis conducted in the study, six camera locations were chosen, three each on east and west wall, at a height of 2.4 meters from the floor level. The location of the cameras is highlighted in Figure 3 and Figure 5 shows HDR images generated for these camera locations at a single point-in-time. A total of 426 such images were generated for 71 sky conditions the purposes of the pilot study.

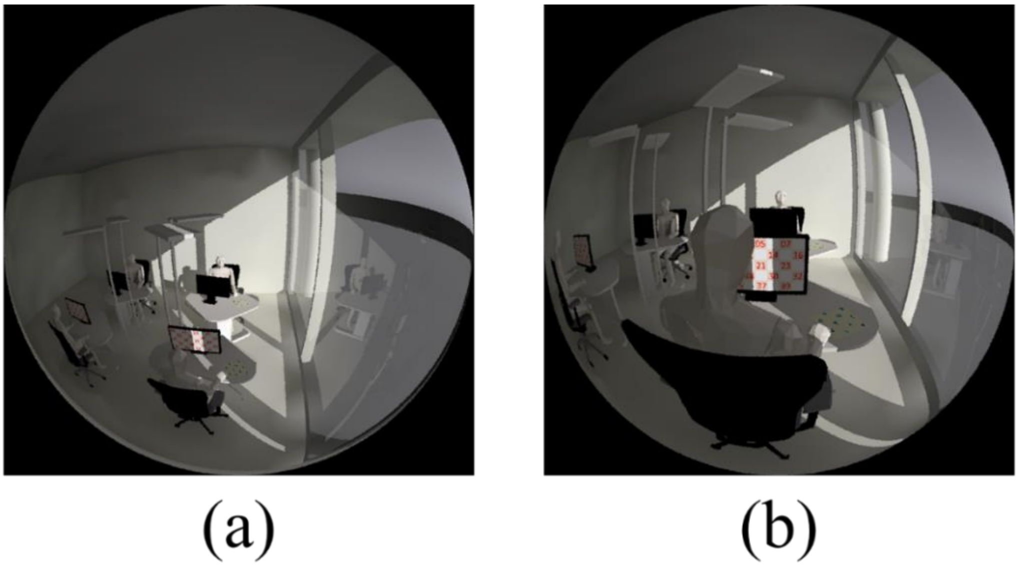


Figure 4. Fish-eye HDR images generated with Radiance for the same daylighting condition at two camera settings.

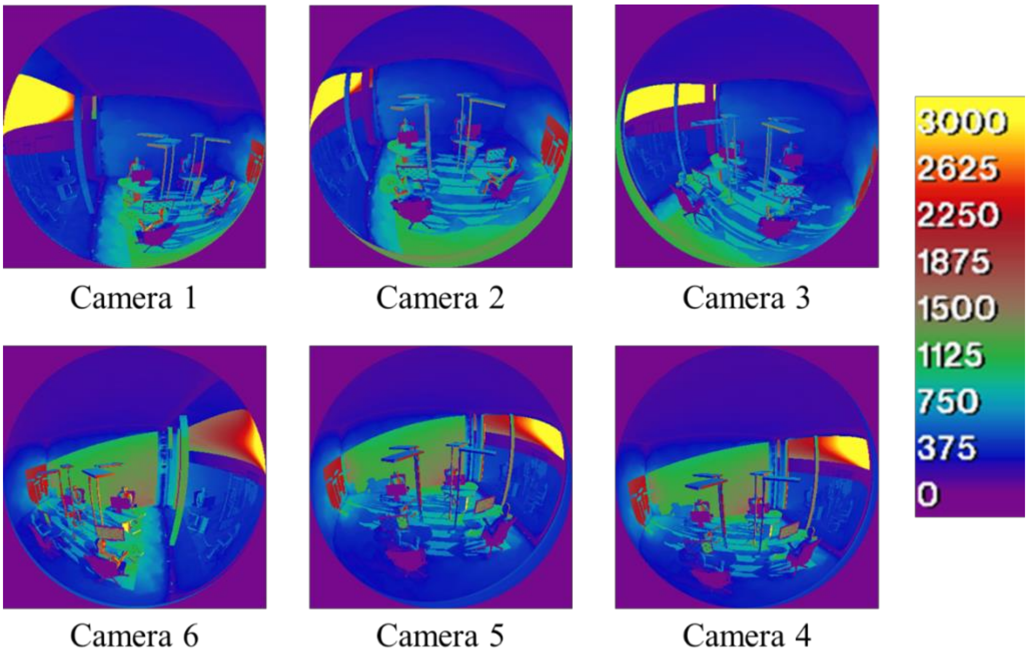


Figure 5. Falsecolour mappings of HDR images generated for the same daylighting condition at the six virtual camera positions. As is apparent from the images, the cameras are placed on either side of the room and at variable distances from the glazing. The value mapped through falsecolor is candela/m^2, the unit of luminance.

The sky conditions considered for the simulations were created using the Perez Sky Model implemented in a Radiance tool called Gendaylit [32, 33]. The location details and hourly radiation values required for the Perez Sky Model were obtained from Typical Meteorological Year (TMY) data for Berlin, Germany. The rationale for choosing the 71 conditions is explained further through Table 1.

Table 1. Timesteps considered for generating the HDR images considered in the study.

Detail	Quantity	Comment
Total timesteps considered	120	Hourly, from 9AM to 4PM (inclusive), between 1st November to 15th November
Timesteps with direct sun	71	The 49 hours that were filtered out consisted of overcast conditions.
HDR images generated	426	1 image/hour for 71 hours, captured by 6 cameras

An example of HDR images generated for different sky conditions is shown in Figure 6. The entire set of HDR images generated for the specified daylighting conditions and camera settings were then obfuscated to various levels by using procedural software filters. The authors initially tested image interpolation algorithms involving linear, bicubic and Lanczos filters. Since the interpolation algorithms usually reduce the size of the resulting image, they were found to drastically underestimate the luminance of glare sources in the HDR images. Subsequently, Gaussian blur filters were tested and were found to provide a reasonable balance between distortion and retention of useful luminance data. Figure 7 provides an example of the level of distortion achieved through progressively higher levels of blurring. As is evident from the general shape patterns and the magnitude of luminances mapped through false-colour, details relevant to the analysis of visual discomfort are retained to a certain extent even in distorted images. The next section provides a summary of the glare data obtained through the obfuscated images.

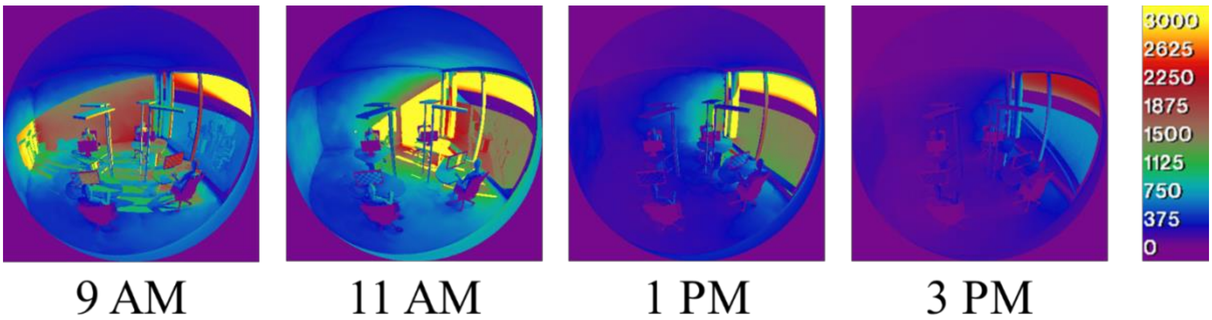


Figure 6. Falsecolour mappings of images generated for the same camera position for alternate hours on 3rd November. The value mapped through falsecolour is candela/m^2, the unit of luminance.

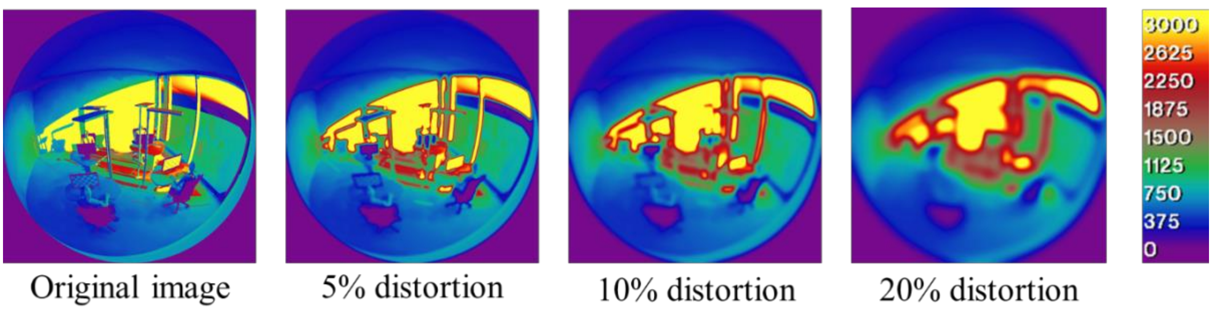


Figure 7. Progressive obfuscation of a single HDR image using a Gaussian blur filter. The value mapped through falsecolour is candela/m^2, the unit of luminance.

4. Results

Of the 426 HDR images generated for this study, 115 images contained daylight luminance and vertical illuminance levels lower than the threshold at which they could be effectively analysed. This threshold is based on the minimum vertical illuminance and minimum qualifiable DGP level assigned in Evalglare. 34 images yielded DGP values higher than 0.59, a value above which glare is characterized as intolerable. The remaining 277 images yielded DGP levels where the glare could be characterized as either imperceptible or perceptible. The obfuscated derivatives of these 277 images were also analysed with Evalglare to determine the DGP levels obtained after obfuscation.

Table 2. Categorical summary of the DGP values calculated for the 426 original HDR images generated for the study.

Scenario	Instances	Comment
DGP<0.2	115 (27%)	DGP is not defined for low lighting conditions
0.2<=DGP<=0.35	190 (45%)	Imperceptible glare
0.35<DGP<=0.59	87 (20%)	Perceptible to intolerable glare
DGP>0.59	34 (8%)	Beyond intolerable glare

Figure 8 summarizes the relative error in DGP calculation as a function of obfuscation level. Relative error for an individual image was calculated as:

Error%= Abs((DGP from Original Image – DGP from obfuscated Image)/(DGP from Original Image))

As indicated by the Figure 8, for all the distortion levels considered in this study, the mean error in the calculation of DGP was less than 5%. The box-plots in the figure also show that the error increased

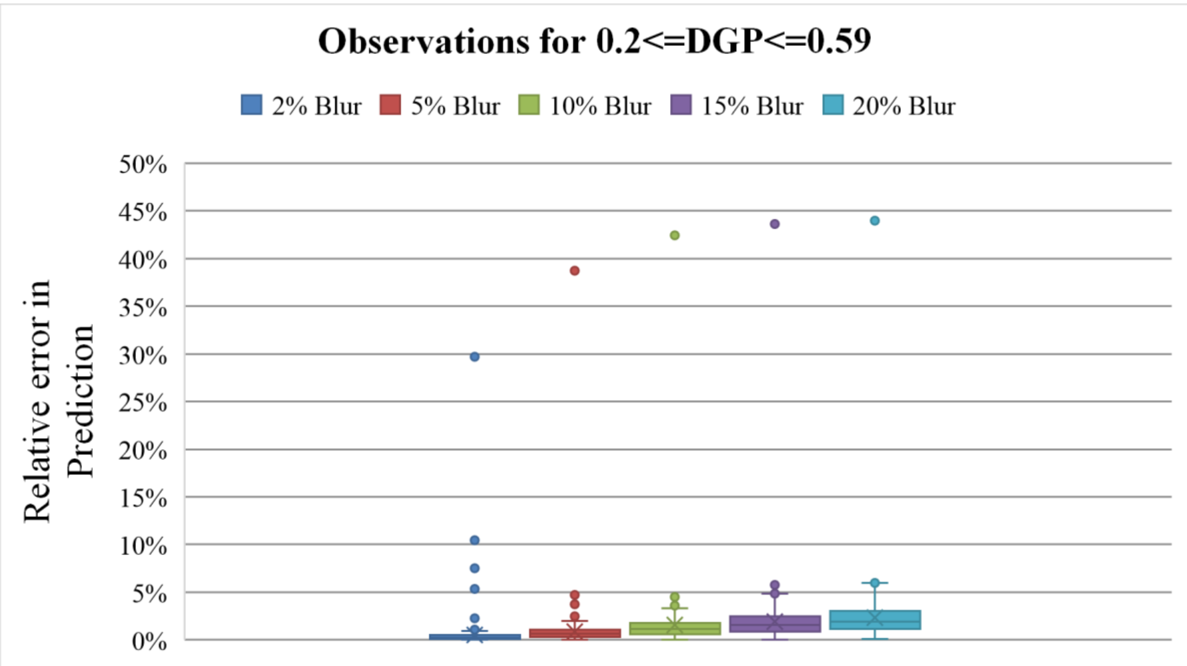


Figure 8. Box-plots of relative-error in DGP values calculated with HDR images that were obfuscated using Gaussian blur filters.

slightly and progressively as the order of distortion was increased. The one major outlier in Figure 8 relates to an instance where the blurring resulted in the erasure of several potential glare sources from the blurred images. The HDR images, both original and blurred, for this instance are shown in Figure 9. As can be noticed by the coloured patches on the original and blurred HDR images, progressive blurring resulted in a reduction of the number of identified glare sources and caused the retained glare sources to shrink in size.

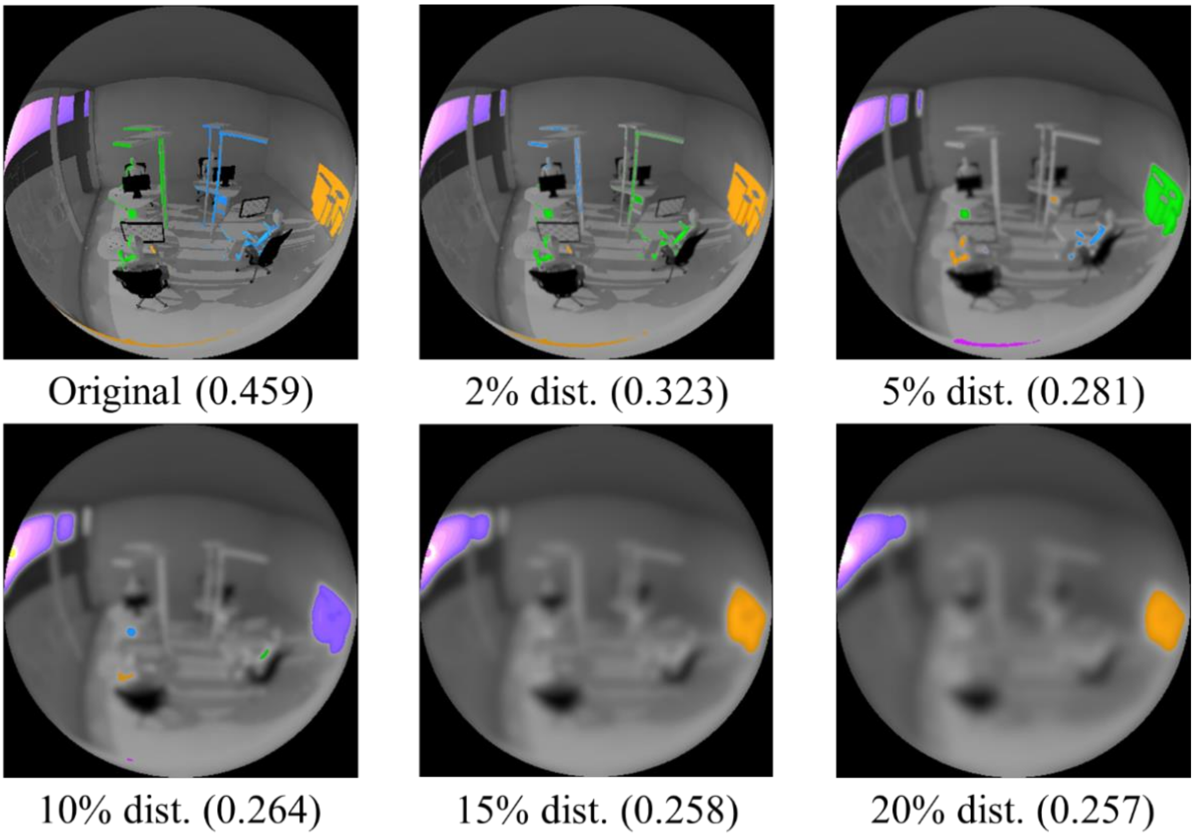


Figure 9. Glare sources identified in the outlier scenario in Figure 8. Distortion has been abbreviated to dist. The value of DGP calculated for each of the images is provided in parenthesis.

DGP values calculated within the range of 0.35 to 0.59 can be further categorized according to perceptible, disturbing or intolerable glare as shown in Table 3 [23]. A higher relative error in DGP calculation will lead to the glare being incorrectly categorized. Assuming that an automatic lighting control system will be actuated based on these glare categories, it is possible that larger values of relative errors in calculation of DGP will cause the control system to perform incorrectly. Figure 10 provides a relative comparison of the obfuscation levels as a function of the accuracy with which glare was categorized. For the 87 instances when the glare was categorized between perceptible to intolerable, images that were distorted using blur filters of up to 15%, led to incorrect categorization in 11 or less instances.

Table 3. Glare categorization within DGP range of 0.35 to 0.59.

Range	Category
0.2<=DGP<=0.35	Imperceptible
0.35 <=DGP<=0.40	Perceptible
0.40<DGP<=0.45	Disturbing
0.45<DGP<=0.59	Intolerable

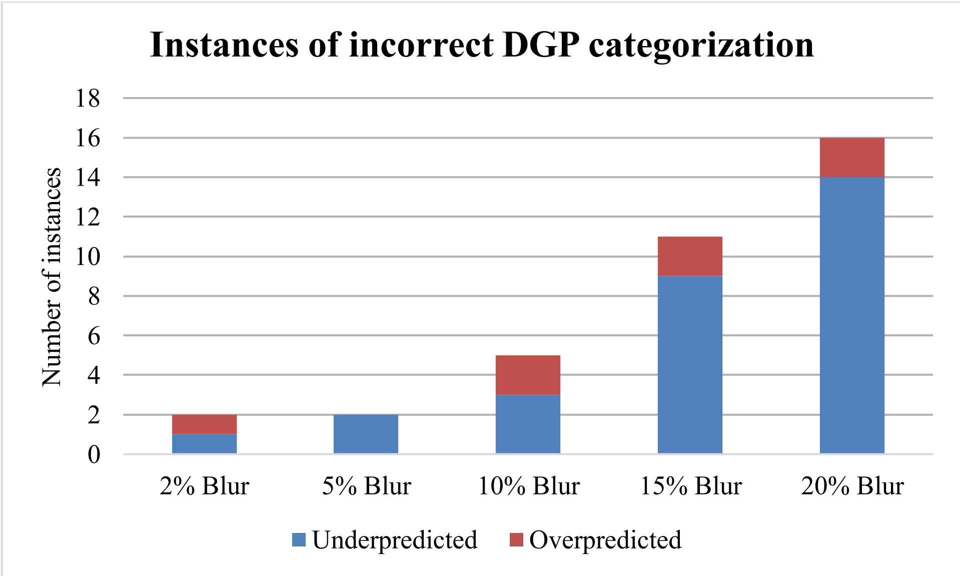


Figure 10. Number of instances, out of a total of 87, when the DGP values were incorrectly categorized.

5. Discussion and conclusion

The results summarized in the last section indicate that the error associated with the DGPs calculated through obfuscated images is usually within a relative error margin of 5%. In cases where the errors were encountered, the incorrect categorization of error was within a single category. Furthermore, the DGP values were more often underpredicted than overpredicted. For example, in Figure 10, for the 20% blur scenario, of the 16 (out of 87) instances when the glare rating was miscategorized, the glare rating was underpredicted in 14 (87.5%) instances. The underprediction of DGP values can be partially attributed to the fact that potential error sources with smaller solid angles are typically obscured during blurring.

In conclusion, the results from this pilot study indicate that obfuscated images can be employed for glare analysis, especially in cases where the results from such an analysis is intended to categorically actuate a lighting control system. As is logically expected, higher levels of obfuscation were associated with greater margins of error in DGP calculation. So, any real-world applications of obfuscated HDR images for glare analysis will require the selection of an obfuscation level that can strike a balance between privacy of occupants as well as accuracy of data acquisition.

Future initiatives planned for this research relate to a field study involving the use of miniature cameras mounted on a single-board computers for the purposes of HDRI acquisition.

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The Three Sisters, klimaaktiv object of the month 12/2018

Kranzl M

Dr. Pfeiler ZT GmbH, Wielandgasse 36, 8010 Graz, Austria

M.Kranzl@zt-pfeiler.at

Abstract. In the lakeside city of Aspern in the 22nd district of Vienna, the homebuilding association for private employees has established the residential complex “The Three Sisters” on the construction site D22, a plot of land measuring 5,200m². When planning the building envelope of the three buildings which range from four to six floors, the responsible persons consciously decided to use the Wienerberger “Porotherm 50 W.i. Plan” brick. Thus, the first multi-storey residential building project has been constructed using the latest brick generation. The use of a mineral and monocoque construction method makes a significant contribution to eliminating the need for petroleum-based full heat insulation. Therefore, the building complex can throughout be categorized as a low-energy building. Further notable advantages of the applied construction method and building design include the use of an exterior wall system without additional insulation (upgraded insulation on the outside) to obtain a U-value of 0.12 W/m²K which corresponds the passive house standards. The high demands of the construction design in terms of ecological, economical and socio-cultural quality of the three building components are reflected in the ecological selection of construction materials, the persistence of the building complex and the stability of value, as well as apartment sizes, assisted living, smart-start-apartments, integrated green space concepts, roof terraces, urban gardening, etc. The TQB certification with 769 out of 1000 points has been obtained and the project has been awarded with klimaaktiv GOLD to prove the quality of the project and ensure quality assurance and management.

1. Goal to establish more sustainable buildings for the future of the urban development district lakeside city of Aspern

The substantial requirement for a sustainable building is to consider the holistic contemplation of a building (construction, operation and demolition) in the first planning-phases (ideally already included in the preliminary design/design). In the lakeside city of Aspern this is an aim resp. a prerequisite for every building to be constructed. The coordination of planning and implementation, execution of legal requirements, energy efficiency, sound insulation, ecological material-selection, user comfort, quality management of the building envelope by the means of BlowerDoor-tests, quality management of the room air by the means of internal space hygiene measurements can be observed throughout the project at hand. The achieved TQB-certification (with 769 out of 1000 points) and the klimaaktiv-certification with the highest possible rank “gold” and being the klimaaktiv object 2018-12 speaks for itself.

2. Implementation of sustainability-topics

In the course of the implementation of a sustainable building the responsible party purposely decided on the use of the Wienerberger “Porotherm 50 W. i. Plan” brick. It is the first multi-story residential building project to use the new generation of bricks during its construction. Due to the continuously in mineral and single layer type constructed structure in nearly zero energy building quality, an essential contribution was being made in order to relinquish from using crude oil-based heat insulation. Further benefits of the construction material brick lie in the easy separability of the material (mineral wool as cuttings in the tubular body) [1] at the end-of-life of a building and the recycling-ability of the brick fragments [2].

2.1. Heat insulation

With this exterior wall-system, a u-value of 0.12W/m2K (passive house standard) can be reached without the use of additional insulation (upgraded insulation on the exterior). The values of the energy performance certification are respectively positive:

- Heating demand: 21.31 kWh/m^2 gross floor area and year
- Primary energy demand: 48.04 kWh/m^2 gross floor area and year
- CO_2: 5.7 kgCO_2/m^2 gross floor area and year

The monolithically wall with integrated heat insulation (cuttings made of water-repellent mineral wool located in the tubular body) distinguishes itself due to optimal structural-physical and biological performance and therefore presents itself as a timely and sustainable exterior wall solution.

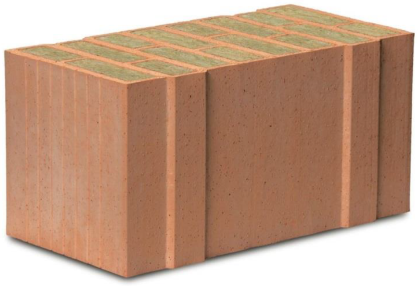

Figure 1. Wienerberger "Porotherm 50 W. i. Plan" (W. i. Wärmedämmung inklusive) [3].

a. Heating system

Building A and building B

Radiator: Individual room control with thermostatic valves, individual heat consumption calculation, radiator (60 ° C / 35 ° C)

Building C

Floor heating: room thermostat zone control with time control, individual heat consumption calculation, surface heating (40 ° C / 30 ° C)
Radiator: room thermostat zone control with time control, individual
Heat consumption calculation, radiator (60 ° C / 35 ° C)

b. Sources

Central space heating is provided by District Heating Vienna – "Fernwärme Wien" and is combined with a water tank in order to provide also hot water.

2.2. Requirements for the airborne noise insulation of the exterior components

According to the executed airborne noise measurements (for the W. i. series – 42,5, 38, etc.) at the acoustic testing facility of the TGM Vienna, a sound reduction index RW of 48dB can be reached with the Porotherm 50 W. i. Plan, bilaterally plastered. This corresponds approximately with a conventional Porotherm brick with a VWS-system, hence it accomplishes the legal minimum requirement for airborne noise insulation of exterior components until the category R'res w = 43dB. Therefore, generally the requirements for the airborne noise insulation are being met by the W. i. brick.

2.3. Requirements for the airborne noise insulation in the interior of the building (divider walls)
Indoor units resp. apartment divider walls at residential constructions are to be measured in a way that provides that between both neighbouring utilization units/apartments (conditioned by the sound transmission through the separating component and the acoustic vertical transmission of the flanking constructions) a minimum requirement for the airborne noise insulation according to legal basis resp. OIB directive 5 and ÖN B 8115-2 is being adhered to (minimum requirement for the residential divider walls -> evaluated standard sound level difference DnT.w > 55dB).

Considering the acoustic vertical transmission topic, the flank of the exterior wall brick W. i. presents a certain sonically weak spot due to the hole pattern and the meagre mass. Regarding this, a detailed design by the means of a sonically separation at the divider wall connection has been acquired by the cooperation with the company Wienerberger, to improve resp. solve this topic.

3. Result of sustainable planning and-topics

The optimized planning resp. implementation concerning power demand, selected construction material, construction, comfort and room air quality can be observed through the achieved awards:

Point statement of the main categories for KlimaAktiv GOLD:

PLANUNG UND AUSFÜHRUNG	137
ENERGIE UND VERSORGUNG	500
BAUSTOFFE UND KONSTRUKTION	150
KOMFORT UND RAUMLUFTQUALITÄT	115

Figure 2. Point statement for the KlimaAktiv-certification [4].

Point statement of the main categories for TQB:

Figure 3. Point statement for the TQB-certification [5].

4. "The Three Sisters"

Building A(NNA) / assembly house: This component with a total of 33 flats is designed as an assembly house for the group "Que[e]rbau". Que[e]rbau stands for self-chosen identity, self-chosen form of life and thinking outside the box, independent of propagated norms. In the assembly house, a five-storey central atrium assumes the function of opening up as a meeting place.

Building B(ELLA): There is something for everyone here: from the SMART start apartment with two rooms right up to five-room apartments. Two thirds of the apartments are oriented to the east and west. This component is comprised of 40 flats, and designed as a 6-storey building with recessed open-space zones and is accessible through two staircases. On the upper floors, the development is partly via an open access balcony.

Building C(LARA) / assisted living: This component is designed as a whole for assisted living with several operators and different care concepts.

On the ground floor, Diakoniewerk rented three apartments for the accommodation and care of migrants. On the 1st and 2nd floor, HABIT - Haus der Barmherzigkeit - runs a dormitory for children and adolescents with multiple disabilities. Furthermore, on the 3rd floor the association Integration Vienna operates a living community "Lebe bunt", for disabled and non-disabled young people.

An integrated green space concept connects the adjacent building plots into a coherent whole. Roof terraces, a communal sauna, a club café and an "urban gardening" field in the middle of the area complete the offer for the community.

4.1. Contributions to user satisfaction

Each of the 78 subsidized housing units has been supplemented by its own open space (terrace, balcony, loggia) and an additional storage room. In addition, all apartments have above-average room heights of about 2.63 m to 4.00 m and are therefore higher than required by the Vienna Building Code. Wherever possible, "French windows" have been installed that extend from floor to ceiling, visually increasing the space and allowing in more light and sun. The larger units are oriented and illuminated at least on two sides and therefore easy to ventilate, which provides great added value, especially in summer. Furthermore, each apartment is equipped with a controlled fresh air supply.

5. Conclusion

The requirements for the regionality of the materials (<200km linear distance to the construction site) for the primary structure resp. insulation could be met, as could be the application of low-pollution and low-emission construction products, which were implemented by the means of product management (separated approval before the installation of the materials).

Supplementary equipment like a playground, a roof terrace, a sauna, club- resp. common rooms and a community garden are available for the occupants of “the three sisters”.

The correct choice of ecological materials, validation-measurements of the airtightness (which prove the quality of the building envelope) during the construction progress resp. measurements of the room air quality (which ensure the innocuousness of the superficially installed materials) guarantee for the appropriate quality of this project.

Consequently, it can be guaranteed that “the three sisters”, due to the excellent cooperation of the architecture- and the sector planning team, the building owner; executing companies and urban development, was not only developed as an outstanding project but also put into action as such.

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Reducing water footprint of building sector: concrete with seawater and marine aggregates

Arosio V[1], Arrigoni A[2], Dotelli G[1]

[1] Dipartimento di Chimica, Materiali e Ingegneria Chimica, Politecnico di Milano, Piazza Leonardo da Vinci 32, Milano, 20133, Italy
[2] Department of Civil and Mineral Engineering, University of Toronto, 35 St. George Street, Toronto, Ontario M5S 1A4, Canada

valeria.arosio@mail.polimi.it

Abstract. Freshwater resources are currently under great pressure all over the world due to many factors, such as climate change and growing urbanization. Industrial products like concrete pauperize a significant share of available freshwater during their life cycle. Therefore, cutting down the amount of freshwater consumed by these products might be a solution to reduce the stress in regions affected by water scarcity. In this study, the potential freshwater savings linked to the adoption of innovative concrete mixtures were investigated via the Life Cycle Assessment (LCA) method. In particular, the use of marine aggregates instead of land-based ones and seawater rather than freshwater in the mixing process of concrete were examined. To improve the validity of the analysis, the applicability to the Italian context using geo-referenced data for the distance to the coastline and the availability of freshwater was explored. Results confirmed the positive effect that the use of seawater and marine aggregates might have in reducing the water footprint of the Italian construction sector, leaving freshwater available for human consumption. Mixing concrete with seawater would lead to a reduction of its water footprint up to 12%. Moreover, if land-won aggregates were replaced with marine ones, an 84% reduction of the water footprint could be achieved. In both cases, possible burden shifting (e.g. increase of greenhouse gases emissions) should be investigated.

1. Introduction

Freshwater resources are currently under great pressure all over the world due to many factors: climate change, population growth, higher standards of living, increased industrialization and widespread urbanization [1]. Water consumption grew twice as fast as population in the last century [2], and nearly half of the global population already live in areas that are potentially scarce in water at least one month per year [3]. The industrial sector accounts for approximately 19% of the total water withdrawals [4], and the construction industry is among the main users. Urbanization boosted, indeed, the demand for construction materials [5], with concrete reaching an annual production of more than 32 Gt in 2017 [6]. Besides the large demand for natural aggregates, concrete production also requires a lot of water. For instance, a standard concrete batching plant withdraws on average 100 m^3 of water each day just for the mixing process [7]. However, concrete demand for water goes well beyond this process. Water is required to process all the raw materials and to produce the energy and the fuels used along the concrete production chain [8]. However, inventory data for water demand throughout the life cycle of concrete are limited and inconsistent [9]. Miller et al. tried to estimate the global amount of water consumed to produce concrete at a global scale and concluded that, on a cradle to gate analysis, concrete production was responsible for a global water consumption of 16.6 Gm^3 in 2012, equivalent to the annual domestic use of 145 million US residents [10].

To avoid the corrosion of the steel rebars used in reinforced concrete structures, mixing water must be free of chlorides and therefore, the use of seawater is forbidden and freshwater is currently used [11]. However, the use of reinforcement elements resistant to corrosion (e.g. stainless steel, glass fibre reinforced polymers) has been investigated over the past few years, opening up the opportunity to the use of alternative types of water. For instance, results of the SEACON project showed that the properties of concrete could be preserved and even improved when seawater was used in the mixing process if reinforcing elements resistant to corrosion were used [12]. Moreover, using rebar that would extend the durability of the structure could also reduce the life cycle environmental impacts [13] and the life cycle costs of the structure [14]. Nevertheless, the actual implications of using seawater and, possibly, chloride contaminated aggregates on the Water Footprint (WF) of concrete produced in a specific geographic context were not investigated.

The goals of the study were: (1) to assess the life cycle water consumption and the WF of a generic concrete mix produced in Italy, identifying the most impacting stages of the life cycle, and (2) to assess the variation in the WF if seawater was used instead of freshwater in the mixing process and marine aggregates were included in the mix in place of land-won aggregates. To reach this goal, the WF of the different concrete mixes was evaluated with a GIS-based approach considering both the direct and indirect water consumption in the different life cycle stages of the production of concrete.

2. Materials and methods

The WF of the different concrete mixes was assessed following the ISO 14046 guidelines, which provide a metric to assess the potential impacts associated to the life cycle use of water for an activity [15]. The methodological steps, in line with the standardized life cycle assessment procedure, are presented in the following sections.

2.1. Goal and scope definition

The goal of the analysis was to assess the water footprint of a generic concrete produced in Italy and to investigate whether the use of seawater and marine aggregates could reduce it. Hence, three different mix designs were compared: 1) concrete with Land-won Aggregates (LA) mixed with Fresh-Water (FW), representing the base case scenario and referred to as "LAFW" in the analysis; 2) concrete with Land-won Aggregates mixed with Sea-Water (SW), referred to as "LASW"; and 3) concrete with Marine Aggregates (MA) mixed with Sea-Water, referred to as "MASW".

2.1.1. Declared unit. The declared unit was one cubic metre of unreinforced fresh generic concrete delivered to the construction site. Except for the type of aggregates (land-won or marine) and mixing water (freshwater or seawater), the same concrete mix was used for all the scenarios. Recipe for the mix (i.e. 200 kg of Portland cement, 1280 kg of gravel, 720 kg of sand and 170 litres of water) was taken from the Ecoinvent database [16] and represents a general unreinforced concrete. All mixes were assumed to have the same mechanical properties and service life.

2.1.2. System boundaries. The approach of the study was from cradle-to-gate, where the gate of the study was the construction site. Transportation to the construction site (i.e. stage A4 according to ISO 14046*)* was included in the analysis. The different unit processes considered for the analysis and their relative inputs of direct water are illustrated in 'figure 1'. Direct water refers to the water consumed in a specific process (e.g. water for mixing concrete). Although the component was not shown in the figure, indirect water (i.e. water consumed in preceding processes such as the one consumed in the generation of energy used to mix concrete) was also included in the assessment.

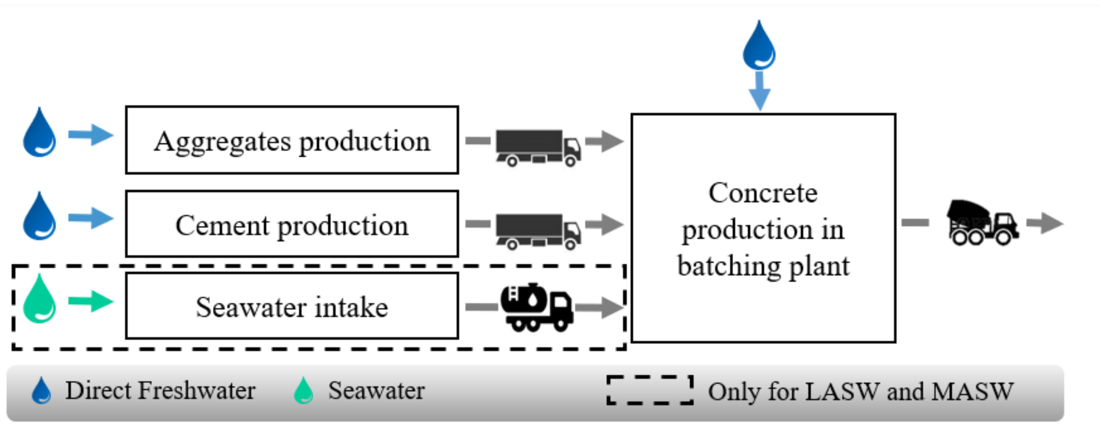

Figure 1. Unit processes considered in the study and their relative direct inputs of water.

2.1.3. Geography. Three different Italian regions (i.e. Abruzzo, Eastern Sicily and Lombardy) were considered for the analysis to investigate the influence of the geographical context on the WF. In fact, the three regions (in the central, southern and northern part of the country respectively) differ in terms of climate, freshwater availability, distance from the sea and type of quarries.

2.2. Life Cycle Inventory (LCI)
Different studies, databases and tools were used for the LCI: studies available in the scientific literature and the Ecoinvent database [16] were used as sources of secondary data; ArcGIS was used for the geolocation of quarries, cement factories, batching plants and seawater intake facilities; finally, the Distance Matrix API of Google was used to calculate the road distances between different points. The electricity consumed in quarries, cement factories and batching plants was modelled using the Italian electricity mix. A focus on the inventory for aggregates and water considered in the different scenarios is presented in the next sections. As for the quality of the data, primary data were collected for energy consumption and water withdrawals in a land quarry and a in a concrete batching plant, while secondary data were used for the other unit processes.

2.2.1. Aggregates. Aggregates, in Italy, are sourced from three different types of land quarries: wet, dry, and rock quarries. Wet quarries are open-pit mines characterized by the presence of a lake, formed when the excavations of sand and gravel penetrates the aquifer's water table. Conversely, in dry quarries the excavation process never reaches the water table. Finally, aggregates from rock quarries are produced from blasting and crushing rocks in mountainous areas. A hypothetical scenario where marine aggregates were used instead of land-won aggregates was also considered in the present study. Although the extraction of aggregates from the seabed is not currently practiced in Italy, this activity is common in other European countries such as the UK and the Netherlands [17]. For this scenario, aggregates were assumed to be dredged from the seabed off the Italian coast and transported by ship to the shore.

In wet quarries, water is used to wash the aggregates and the machinery on site. Aggregates are washed to separate the different sizes, while machineries are washed for productivity reasons. Although not directly used, freshwater is consumed in quarries due to evaporation. Water evaporates not only during the washing process, but also from the extracted aggregates (before and after washing) and from the quarry lake. If aggregates were not quarried, the evaporating water would remain in the aquifer and it would be available for other purposes. For this reason, evaporating water was included in the assessment. On the other hand, not all the water used to wash the aggregates and the machineries is consumed: most of it, in fact, either leaches back to the aquifer or it is conveyed to settling tanks, where silt deposits and decanted water is re-used for washing. For this reason, the only water that is actually consumed in the washing process is that which is adsorbed by the aggregates or that evaporates. Based on a previous study, the amount of evaporating water was assumed to be 10% of the withdrawn water [18]. As for the water evaporating from the quarry lake, it was calculated using the Visentini formulas, which correlate the evaporation rate from small water surface to the average temperature and the elevation [19]. A wet quarry located in Northern Italy was used as reference case study, and the annual evaporation from the quarry lake was then multiplied by the surface of the lake and the rate was divided by the annual production of the quarry in order to allocate the amount of evaporated water to the produced aggregates.

Water is used to wash aggregates and machineries in dry quarries too. However, since no lake is present in this case and water used for washing is collected and reused for the same purpose, the only water consumed is the one adsorbed by the aggregates or the one evaporating during the activity. Primary data collected by Rigamonti et al. were considered in this case [20].

In rock quarries, aggregates are not washed since there are not fine particles (i.e. silt) to be removed. Nevertheless, water is consumed to control dust and to wash machinery. Data were collected from another Italian study investigating this type of quarry [21]. Decanted harvested rainwater and new freshwater withdrawn from the well were used in the quarry; however, since not enough information was available on the amount of harvested rainwater, only the withdrawn component was considered.

Finally, in case of off-shore extractions, it was assumed that marine aggregates were washed with seawater to remove the fine particles and that no additional washing was required to remove the chlorides contamination. Therefore, direct consumption of freshwater was considered null in this case.

2.2.2. Batching plant. Primary data were collected for water consumed at the batching plant: total direct consumption was equal to 0.50 m^3 per cubic meter of fresh concrete, split between the water for mixing (equal to 0.17 m^3 based on the Ecoinvent recipe) and the one for washing the truck mixers and the area. For the base case scenario, water for mixing was assumed to be withdrawn from a well located at the concrete mixing plant. On the other hand, seawater was assumed to be collected from an open intake facility on the coast and then transported by truck to the concrete mixing plants.

2.2.3. Cement plant. Primary data from one of the main Italian cement manufacturers were used for the study and 0.24 m^3 of FW resulted to be used on average per metric ton of cement, mainly for gas conditioning and cooling activities.

2.2.4. Geolocation, distances and transports. Location of the active quarries in the different regions was retrieved from the official regional websites while location of batching plants and cement factories were provided, respectively, by the Italian Technical Economic Association for Ready-Mixed Concrete [22] and the Italian Association of Cement manufactures [23]. Coordinates of each plant and quarry were then imported to ArcGIS and, for each batching plant, it was assumed that cement was supplied from the closest producer and that aggregates were sourced in equal amounts from the closest four quarries. Finally, fresh concrete was assumed to be transported for 10 km with a truck mixer to reach the construction site [24].

Seawater intake facilities and marine aggregates extraction site were assumed to be located along the coastline, at a minimal linear distance to each batching plant. SW was considered to be transported by tankers from the intake facility to the concrete batching plant.

2.3. Life Cycle Impact Assessment

The AWARE method, developed by WULCA, was used for the impact assessment [25]. The AWARE characterization factors account for the Available WAter Remaining in a watershed after the demand of humans and aquatic ecosystems is met. The metric provides characterization factors both at the river basin scale and aggregated at national level. In the present study, basin scale factors were used for direct water consumptions, while aggregated national factors were considered for the indirect uses.

Characterization factors were then imported to ArcGIS and applied to the different plants based on their location.

3. Results and discussion

The actual amount of freshwater consumed to produce 1 m^3 of concrete in Italy and the water footprint for the different mixes assessed with the AWARE method are both presented in this section.

3.1. *Water consumption*

Direct and indirect freshwater consumption for each process unit are listed in 'table 1', where all the numbers are referred to the declared unit in the base case scenario (i.e. 1 m^3 of fresh concrete delivered to the construction site). An average distance was considered for transportation from the quarry and the cement plants to the concrete mixing facility. Water consumption to produce 1 m^3 of fresh concrete ranged between 1.7 and 5.5 m^3, according to the type of aggregate used in the mix. The minimum value corresponds to concrete containing aggregates from a rock quarry, while the maximum is referred to the case with aggregates from a wet quarry. The high value of direct consumption for the wet quarry was due to a large extent (i.e. 94%) to the water evaporated from the quarry lake.

Table 1. Direct, indirect and total freshwater consumption for the base case scenario.

Process unit	Indirect water consumption ($m^3_{water}/m^3_{concrete}$)	Direct water consumption ($m^3_{water}/m^3_{concrete}$)	Total Water consumption ($m^3_{water}/m^3_{concrete}$)
Aggregates production – dry quarry	0.03	1.68	1.71
Aggregates production – wet quarry	0.06	4.49	4.55
Aggregates production – rock quarry	0.04	0.71	0.75
Cement plant	0.30	0.05	0.35
Batching plant	0.05	0.50	0.55
Transport	0.03	0.00	0.03
Declared unit	0.41 - 0.44	1.26 - 5.04	1.65 - 5.48

3.2. *Water footprint*

3.2.1. Base case scenario. WF results for the Italian base case scenario (i.e. LAFW) are summarized in 'table 2'. In the table, the WF (expressed in world-equivalents m^3 of water) of each unit process is reported for the three regions investigated. The *mean* represents the calculated average WF for the concrete produced in the region, while the *range* represents the potential minimum and maximum for each region. Cases where all the aggregates were sourced from only one of the four closest quarries was also included in the analysis. The larger WF in Sicily (up to 300 m^3-eq. per m^3 produced) was due to the limited remaining available freshwater in the region; conversely, the larger availability of freshwater in Lombardy resulted in lower impacts. The ranges for cement production, batching plant and mixing water are related to the different characterization factors of the river basins where the plants are located. The range for aggregates production depends not only on the characterization factors, but also on the type of quarry. Finally, the range for transportation is related to the transport distance and does not depend on local water availability, since there was no direct water consumption involved in the process. For indirect water, national aggregated characterization factors of the producing countries based on the information available on Ecoinvent datasets were used.

Table 2. Water footprint of each unit process for the base case scenario in the regions investigated.

	Abruzzo			Eastern Sicily			Lombardy		
	Mean (m^3-eq.)	Range (m^3-eq.)	Share (%)	Mean (m^3-eq.)	Range (m^3-eq.)	Share (%)	Mean (m^3-eq.)	Range (m^3-eq.)	Share (%)
Aggregates prod	46	13-98	61	126	49-256	74	10	4-15	46
Cement prod	10	9-11	13	12	12	7	8	8	37
Batching plant	13	7-21	17	16	15-17	9	3	3	12
Mixing water	6	3-10	8	15	14-16	9	< 1	< 1	2
Transport	< 1	< 1	1	1	1	1	< 1	< 1 - 1	3
Declared unit	65	32-141	100	171	91-303	100	21	15-27	100

3.2.2. Alternative scenarios. A comparison of the WF for the different scenarios considered (i.e. LAFW, LASW and MASW) is presented in 'figure 2'. Error bars indicate the minimum and the maximum WF in the different batching plants. Differently from 'table 2', the minimum and maximum considered here do not consider the cases where all the aggregates were sourced from a single supplier. Since the AWARE characterization factor for seawater is null, the WF of the water used for mixing in the LASW and MASW scenarios was only due to its transportation from the coast to the batching plants.

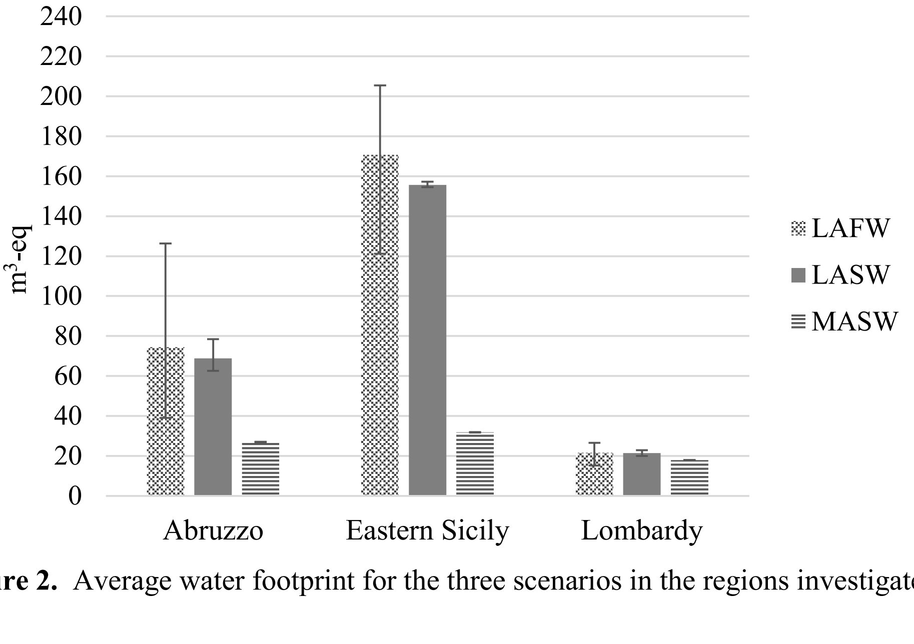

Figure 2. Average water footprint for the three scenarios in the regions investigated.

Replacing FW with SW resulted in a reduction of the WF of concrete from less than 2% in Lombardy to 9% in Eastern Sicily. Using MA instead of LA resulted in a further reduction of the WF in almost all the batching plants analyzed. In Abruzzo and Eastern Sicily, the reduction would be extremely significant (i.e. always larger than 45%) thanks to the avoided direct freshwater consumption in areas affected by high water stress. In Lombardy, on the other hand, the WF implications depend on the type of aggregates that would be substituted. Given the long distance from the coast, the benefits of using MA in terms of WF were clear (up to a 36% reduction) only when aggregates from wet quarries were replaced.

4. Conclusions

In the present study, the amount of freshwater consumed to produce 1 m^3 of fresh concrete and its WF were assessed for three Italian regions differently affected by water stress. Moreover, the implications on the final WF of substituting land-won aggregates with marine ones and using seawater instead of freshwater for mixing the concrete were investigated. The following conclusions could be drawn:

- Aggregates production proved to be the determining parameter on the final overall freshwater consumption, while water used to mix the concrete resulted to be only a fraction of all the freshwater consumed along the production chain (i.e. from a minimum of less than 2% to a maximum of 12%). Freshwater evaporating from quarry lakes could considerably increase the amount of water consumed in case aggregates from wet quarries were used, with a contribution that could reach 4.2 m^3 per m^3 of concrete (i.e. up to 77% of the total consumption). Moreover, cement production and water consumed in batching plants in addition to that used for mixing, contribute significantly to the overall consumption. On the other hand, the indirect water consumed to transport the different materials resulted to be trivial.
- Similarly, water physically incorporated in the fresh concrete was only partially responsible for its WF (i.e. 8 to 9% of the total WF in areas affected by high water stress and 2% in Lombardy, where the direct water consumptions are less impacting). Accordingly, using seawater could reduce the WF of concrete up to 12% in Eastern Sicily and would negligibly affect the WF in Lombardy.
- On the other hand, replacing land-won aggregates with the marine counterpart could reduce to a great extent the pressure of concrete on freshwater availability in areas affected by water stress, leaving freshwater available for human consumption. In Eastern Sicily, for instance, using marine aggregates and seawater could reduce the WF up to 80%. However, if aggregates need to be transported for a long distance and the area has a large availability of freshwater, using marine aggregates might be detrimental for the WF.

5. Further investigations

The present study was a first attempt to assess the implications of using alternative sources of water and aggregates on the WF of concrete. Even though the study showed positive outcomes, before promoting their use further research is necessary to investigate a possible burden shifting (e.g. implications on greenhouse gas emissions and aquatic ecosystems, which fell outside the scope of the present work). Moreover, the durability of the concrete designs and the water consumption in the manufacturing of the reinforcing elements should be included in the analysis to extend the present results to the whole life cycle of the building material. Furthermore, some assumptions made for the present analysis should be further revised to improve the robustness of the study. For instance, water evaporating from the quarry lake resulted to be a decisive parameter in the WF of concrete in regions with wet quarries. However, the dimension of the lake, the temperature in the region, the productivity and the service life of the quarry would greatly affect the amount of evaporating freshwater that should be allocated to the aggregates. Finally, an additional sensitivity analysis considering different strengths and water-to-binder ratios for concrete should be performed to investigate variations in the role that water for mixing and mixture components might play in the overall WF of the material.

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Sustainability assessment in Cuban cement sector- a methodological approach

Sánchez S[1], Cancio Y[1], Sánchez I R[1], Martirena J F[2], Rosa[3] E R, Habert G[4]

[1] Faculty of Economic Sciences, Central University "Marta Abreu" of Las Villas (UCLV), Carretera a Camajuaní km $5^{1/2}$, Santa Clara, Villa Clara, Cuba.

[2] Center for Research and Development of Structures and Materials (CIDem), UCLV, Carretera a Camajuaní km $5^{1/2}$, Santa Clara, Villa Clara, Cuba.

[3] Faculty of Chemistry and Farmacy, Central University "Marta Abreu" of Las Villas (UCLV), Carretera a Camajuaní km $5^{1/2}$, Santa Clara, Villa Clara, Cuba.

[4] Chair of sustainable construction, ETH Zurich, CH-8093 Switzerland.

ssanchez@uclv.edu.cu

Abstract. The search of sustainability is a need for human activities in general. Particularly, cement sector as a significant contributor to climate change has to implement strategies to reduce its environmental impacts. But, effective strategies have to be complemented by adequate methodological techniques to assess, guide and certificate sustainability. Amongst all the techniques developed by the scientific community in recent years, life cycle techniques highlight as one of the most used one due to its integrated and holistic philosophy. In Cuba, a new cement based on a combination of calcined clay and limestone to reduce clinker to 50% (Low Carbon Cement, LC^3) is been developed as part of an international collaboration project. The main goal of this research is to assess sustainability of cement sector in Cuba using life cycle techniques such as: Life cycle assessment (environmental-LCA), Social Life Cycle Assessment (S-LCA), Life Cycle Costing (LCC), Economic Life Cycle Assessment (EcLCA). As part of the assessment LC^3 is compared with traditional produced cements in Cuba OPC and PPC. Results show that LC^3 introduction allows increasing sustainability in cement sector by reducing carbon emissions, energy consumption, costs and reporting positive effects on society.

1. Introduction

One of the most intensive industries in capital and energy is the cement industry [1]. This industry constitutes the base for the sector producing construction materials, as cement is the main ingredient of concrete, and have multiple interrelations with all sectors and economic activities that exist or must exist for the proper functioning of the economy. However, the high production volumes of this industry make it responsible for approximately 6-10% of global CO_2 emissions of anthropogenic origin and about 5% of energy consumption in the industrial sector [2].

The increase of the energetic efficiency, the use of alternative fuels, the decrease of the clinker ratio by using supplementary cementitious materials (SCM), besides the sequestration and capture of carbon, are the main strategies developed to reduce the emissions of CO_2 and energy costs associated with cement production [2].

Low Carbon Cement (LC^3) is a cement with high level of clinker substitution with addition of 30% calcined clay and 15% limestone [3]. Several articles have been published proving the technical viability of this new product [4]–[6]. Although the lower clinker content in LC^3 is supposed to reduce energy consumption, associated costs and emissions and extend existing productive capacities; these assumptions need to be proven.

The Life Cycle Sustainability Assessment (LCSA) is one of the most modern tools applicable for the evaluation of investment impacts and programs oriented towards sustainability [7], [8]; nevertheless, its methodological structure is in development and its application is still limited [9-11]. In the solution of these limitations the proposal, selection and guidance for the use of indicators play a fundamental role; the availability of data and experience for its application, among others, that allow achieving the organicity of the three methodologies that make up the LCSA: Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Analysis of the Life Cycle Assessment (S-LCA).

2. Method for sustainability assessment

According to UNEP/SETAC (2011) the Life Cycle Sustainability Assessment considers all stages of the product and service life cycle and the complete study of its production and value chain. First ideas that guided LCSA approach can be attributed, according to Finkbeiner (2010), to the German Oeko-Institut for its method called "Product Line Analysis" (*Produktlinienanalyse*) [12]. Later, UNEP published several documents that serve as a methodological guide for the discussion and implementation of this tool [13].

In formula 1, proposed by Kloepffer (2008) [14], the LCSA is conceptually defined:

$$LCSA = LCA + LCC + S\text{-}LCA \quad (1)$$

Where:

LCSA = Life Cycle Sustainability Assessment LCC = Life Cycle Costing

LCA = Life Cycle Assessment (environmental) S-LCA = Social Life Cycle Assessment

The environmental life cycle assessment (environmental LCA) looks at the potential impacts of products and services in the environment. ISO standards for LCA guide these studies in four phases: (i) definition of objectives and scope; (ii) inventory analysis; (iii) impact assessment; (iv) interpretation of results; with close interrelation between the phases.

Life Cycle Costing (LCC) and financial analysis are combined with the economic analysis of the life cycle from the methodological guide proposed by Neugebauer et al. (2016) [16], understanding that the economic analysis comprises a number of variables that allow holistic evaluation of the impacts of an activity or service beyond the cost category [15], [16].

Social Life Cycle Assessment (S-LCA) were published by UNEP/SETAC in 2009 [17], then in 2013, methodological sheets for impact categories and indicators by stakeholder groups were published [18]. In this investigation the subcategories and indicators are adjusted to Cuban conditions to be evaluated. From the UNEP proposal (2013) 14 indicators are identified and 2 proposed for evaluation.

According to [14] there are at least two options to include LCC and S-LCA as part of LCSA. Option 1 is based on performing three separated life cycle assessments with identical system boundaries. Its graphical representation matches with formula 1. Option 2 is based on "a new life cycle assessment" where costs and social assessment are included as additional impact categories to the LCA (environmental). This option includes a life cycle inventory with the *inputs* and *outputs* needed to assess the three areas simultaneously and possibly to get the same protection areas.

The advantage of this option is that greater integration is achieved by having a single LCI associated with a single analysis system. However, there are reservations as to the compatibility of this variant with the ISO 14040 standard, since the standard in its introduction states that the LCA "does not usually consider the economic or social aspects of a product [...] but should be used as part of a much more complete decision process". This clearly favours the application of option 1 in the short term, while the international standards ISO 14040-44 are revised and modified so that they comply with option 2.

For its part UNEP (2011) clarifies that although standardization, aggregation and weighting are optional steps in accordance with ISO 14040, any aggregation and weighting of the results of the three techniques used in the ASCV is not recommended because the research and implementation of this approach is at an early stage and the results of each applied life cycle technique are not yet comparable to each other.

In order with previous ideas, in this paper final results are shown throughout a methodological proposal of pared indicators following eco-efficiency philosophy. These indicators are presented in a radial chart that allows to perform a combined interpretation and decide among several alternatives.

2.1. Choice of functional unit and system boundaries

The main objective is to evaluate the environmental, economic and social impacts of the introduction of low carbon cement in Cuba comparing LC3 with cements currently produced OPC and PPC. Table 1 shows material composition of the cements compared. The analysis is performed from cradle to gate, mainly focused on the production and transport of the cement constituents, as shown in [19]. According to the system boundaries, the functional unit selected in the study is 1 ton of cement. This functional unit is commonly used for cradle to gate LCA but one if its limitations is not being directly related with cement quality, this aspect remains as an extra task for evaluators in order to get an integral assessment of this construction product. When assessing concrete performance other units suit better to explain its performance like m^2 of wall, m^2 of built surface, m2 of usable floor area, etc. [20].

Table 1. Composition of the assessed cements.

Cement	Constituents (%)				
	Clinker	Limestone	Gypsum	Calcined Clay	Zeolite
OPC	0,88	0,05	0,07	-	-
PPC	0,75	-	0,05	-	0,20
LC^3	0,48	0,15	0,07	0,30	-

2.2. Data collection

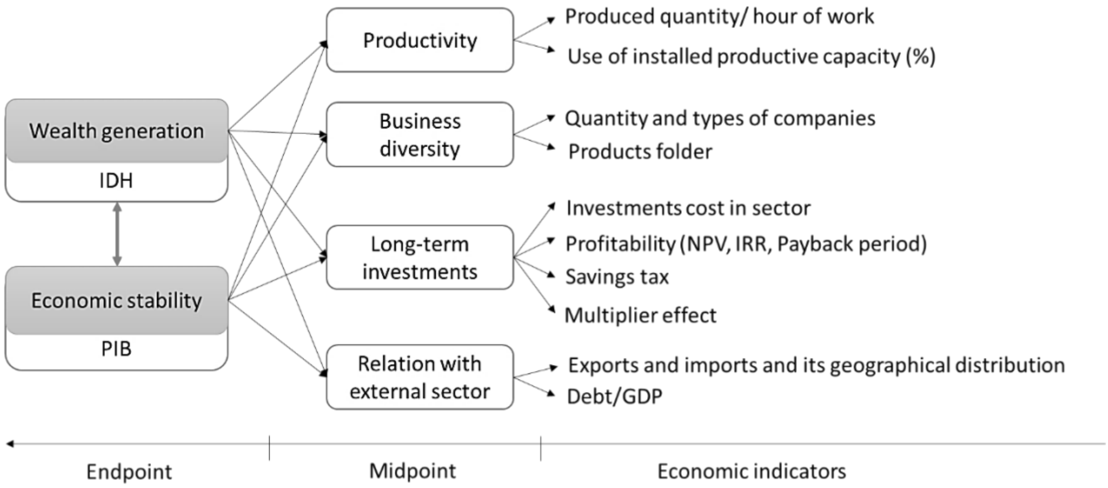
Data collection for the performed LCA has been published in [21]. The economic assessment used data collected from Siguaney cement factory relative to salary, consumption indexes, cost of energy, raw materials distances, depreciation, amongst other. Data from social area was obtained from several sources like official documents like statistical year book, production reports, accounting books of industry, interviews with workers and directives of different companies. To warranty liability of data, the triangulation of obtained information in interviews was performed by reviewing official documents related to the topic.

2.3. Impact assessment

In this study environmental assessment is performed applying ReCiPe impact assessment method. Specifically, for Cuban cement sector 11 midpoint categories are selected: Climate change, Ozone depletion, Chemical oxidants formation, Human toxicity, Particulate matter formation, Terrestrial acidification, Fresh water eutrophication, Marine eutrophication, Fresh water ecotoxicity, Marine ecotoxicity and Fossil fuel depletion. Three endpoint categories are analysed: Human health, Ecosystems and Resources.

Costs assessment is performed following life cycle of the product and its productive chain. Production process is divided into 5 stages: raw materials extraction, fuels extraction, transport, clinkerization and grinding plus other processes. Assessment of economic impacts (E-LCA) complements costs analysis with financial analysis of different investment scenarios, productivity and macro-economic variables analysis. Midpoint, endpoint and indicators proposed to Cuban cement sector and its interconnections are shown in Figure 1.

Figure 1. Proposal of categories and indicators to perform E-LCA in Cuban cement industry.



Source: Proposed following [16].

Social impact assessment is performed as Social Life Cycle Assessment following UNEP/SETAC methodological proposal [17], [18]. From the proposal of UNEP/SETAC 14 indicators, 9 midpoint and 3 endpoint categories were selected to assess cement industry in Cuba as shown in Table 2.

Table 2. Sub-categories and indicators selected to social assessment in Cuban cement sector.

Categories	Sub-categories	Indicators
1. Workers	1.4 Hours of work	No. hours of work/t cement
	1.7 Health and security	*Incidence of diseases related to cement production/ worker*
3. Local Community	3.3 Cultural patrimony	No. of buildings with patrimonial value restorable/year
	3.5 Local employment	Percentage of labour work employed in locality
		No. employees
	3.7 Access to material resources	No. of infrastructure projects developed with access and benefit of community
	3.8 Living conditions healthy and secure	*Incidence of diseases related to cement production/ community inhabitant*
5. Society	5.1 Public commitment to sustainability aspects	Presence of documents available publicly such as agreements in sustainability topics
		Implementation/firm of principles or conduct codes internationally conciliated
	5.3 Contribution to economic development	% GDP relative to construction sector
		Number of houses built/year
		Changes in acquisitive power of population
	5.5 Technological development	Sectorial efforts for technological development
		Relation with programs or projects of technological transfer

2.4. Integration of results

To be able of develop the final process of integrating economic, social and environmental results, a set of paired indicators is proposed allowing to combine the three dimensions of sustainability taking into account the main findings in the evaluations carried out separately and the efficiency of them characterizing each evaluated dimension. This facilitates the integration of the results without complicating the evaluation process. It was decided to calculate the indicators for those categories of considerable magnitude and that show greater impact for cement sector. Table 3 shows the proposed indicators, the unit of measurement in which they are expressed and their classification.

Table 3. Proposed indicators and its classification.

Indicator	Unit	Type
Production cost/ MPa*	Pesos / MPa	Technic-Economical
Investment cost/ MPa*	Pesos / MPa	Technic-Economical
Energy consumption/ MPa*	MJ/ MPa	Technic-Economical
Reduced emissions/ investment	tCO_{2eq}/ Peso (MT)	Economic-Environmental
Dust emissions/ hour of work	kg MP10/ h	Social-environmental

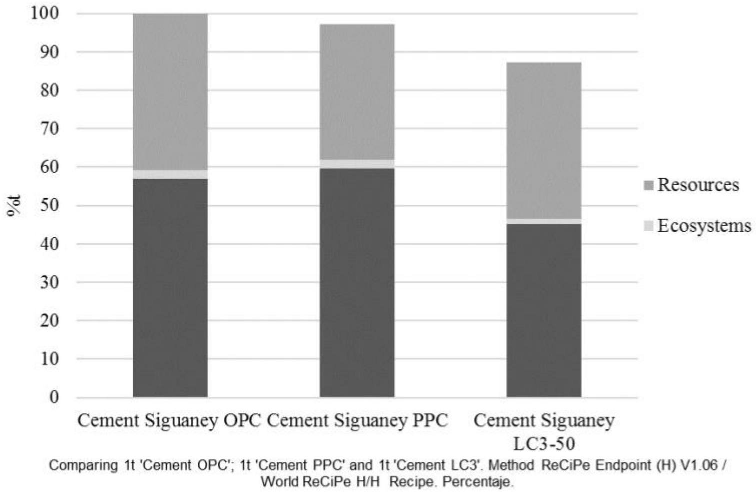
*MPa of compressive strength at 28 days

3. Results

3.1. Life Cycle Assessment

The comparative life cycle analysis of the OPC, PPC and LC^3 cements is performed to evaluate 11 intermediate categories and 3 final categories of the ReCiPe methodology. The calculations are performed using the professional software Simapro vs- 8.0.3.14. LC3 presents lower impact in 8 of the midpoint categories reporting higher impact in eutrophication and ecotoxity indicators. From the endpoint categories, the most affected category is human health, due to the damage caused by the gases emitted in the production process related to CO2 and particulate matter. The P-35 causes greater damage to human health and the ecosystem, as shown in Figure 2. The production of LC3 is the one that most affects resources by the calcination of kaolinitic clay with Cuban crude oil which is more polluting that pet-coke assumed to clinker production.

Figure 2. Results of endpoint categories of damage OPC vs. PPC vs. LC3.



The analysis of the energy consumption shows that with the introduction of LC3 can reduce in approximately 900 MJ the energy consumption per ton of cement produced. The main savings are obtained in the processes of clinkering, extraction of fuels and grinding.

3.2. Life Cycle Costing and Economic Life Cycle Assessment

Through the LCC, the cost composition of each cement is analyzed. The main costs are reported by the extraction and transportation of energy resources, raw materials and equipment depreciation. LC3 production reports a considerable decrease in production costs mainly related with reduction of clinker factor. Costs saving of 10-15 % are reported in Cuban conditions if LC3 is compared with PPC and OPC respectively [21].

To evaluate the profitability of the technological alternatives, 2 alternatives are compared with Business as Usual using a capital cost of 12%, discount rate of 35% and time horizon of 15 years. The results are shown in table 4.

Alternative 1: proposes the strategy of introducing the LC3 in the Cuban cement industry as the partial substitution of traditional cements from the conversion of kilns to calciners. Four calciners with capacity of 300 000 tons / year of calcined clay are estimated.

Alternative 2: Under this alternative, calcination of the clay should be done through flash calciners. Flash technology must be imported. The same amount of calciners is estimated as in alternative 1.

Table 4. Financial results for each of the investment alternatives.

Alternatives	**Indicators**		
	NPV (MPesos)	**IRR (%)**	**Payback period (Years)**
LC^3_Retrofitted calciners	$227.34	58%	3 years, $8^{1/3}$ months
LC^3_ Flash calciners	$123.53	33%	5 years

The internal rate of return and the payback period show that the conversion of kilns to calciners is the best alternative in the short-term. The cost of this conversion is taken from [22], where is establish a maximum retrofitting cost to produce calcined pozzolana of 12M€. Same results should be obtained if an industrial calciner is installed since recent investment costs are quite similar to this scenario [23].

Analyzing productivity aspects is expected that the introduction of Low Carbon Cement increases the productivity since a better use can be done with the same amount of clinker. In other words, decreasing clinker ratio Cuban cement industry will be able to offer a higher amount of cement to market with minor changes in its technology. This could have a positive impact on the business diversity and could stimulate exports to countries of the Caribbean and Latin American areas but this fact depends on several factors besides the level of cement production. Moreover, the reanimation of this sector would lead to a reanimation of Cuban economy due to the multiplier effect of construction as key sector for and investments and development.

3.3. Social Life Cycle Assessment

The assessment of social impacts is carried out mainly by assessing the potential for change in the selected indicators. When possible, quantitative analysis is performed. The following levels are proposed to evaluate the potential for change: a: Negligible, B. Minor, C. Moderate and D. Significant. The results of the evaluation show that 79% of the impacts present moderate or significant change potential [21].

Table 5. Potential of change (PC) of proposed social indicators

Sub-categories	PC	Indicators	PC
1.4 Hours of Work	A	No. of hours worked / t cement	A
1.7 Health and Safety	D	Incidence of diseases attributable to cement production/ worker	D
3.3 Cultural Heritage	C	No. of buildings with patrimonial value restore / year	C
3.5 Local Employment	B	Percentage of labor force contracted in the locality	A
		No. Of jobs	B
3.7 Access to Material Resources	C	No. of infrastructure projects developed with access and benefit to the community	C
3.8 Safe and Healthy Living Conditions	C	Incidence of diseases attributable to cement production / community residents	C
5.1 Public Commitment to Sustainability Issues	C	Presence of publicly available documents as agreements on sustainability issues	C
		Implementation / signature of principles or other internationally reconciled codes of conduct	D

5.3 Contribution to Economic Development	C	% GDP relative to the construction sector	C
		Number of houses / year	D
		Changes in the purchasing power of the population	C
5.5 Technological Development	C	Sectoral efforts for technological development	D
		Relationship with technology transfer programs or projects	C

3.4. Integration of results

For the integrated evaluation of the results in the economic, social and environmental dimensions, the combined analysis is proposed through scatter plots of the most significant variables of each sphere. The significance of the chosen variables is determined taking into account results of the assessment, literature review and expert's opinion (detailed information available in [21]). In this way, decision-makers can be offered a brief and simple analysis of the most sustainable investment variant. The indicators for the case study in the cement industry are shown in Table 6.

Table 6. Indicators selected to integrate and interpret the results

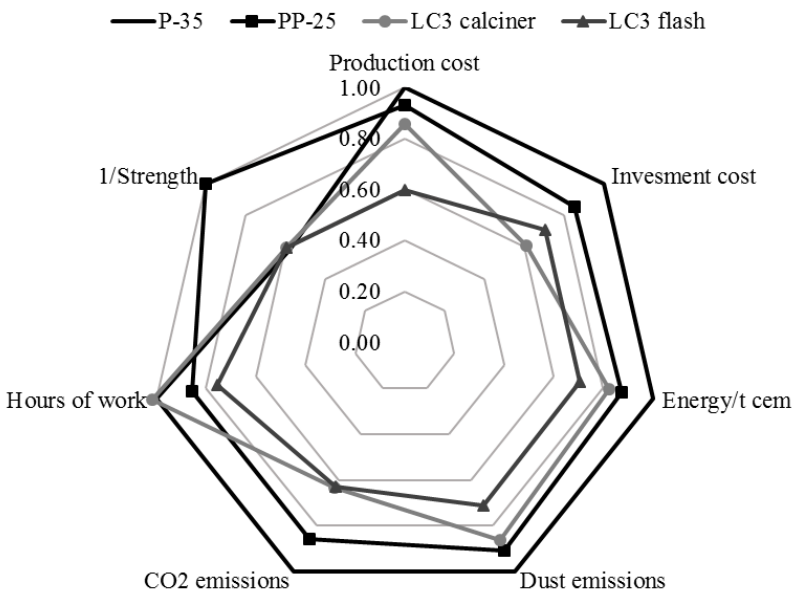
Indicators	UM	OPC	PPC	LC3_Calciner	LC3_Flash
Production cost	Pesos	187,70	174,55	160,86	112,12
Investment cost	USD	159,57	135,99	97,39	112,54
Compressive strength 28 days	MPa	43,07	25,00	42,08	42,08*
Energy consumption	MJ	5292,38	4626,33	4367,53	3254,22
Dust emissions	kg PM10eq	15,10	13,69	13,00	9,75
Carbon emissions	kg CO2eq	890,63	764,92	564,39	559,73
CO2 emissions reduced	kg CO2eq	-	125,71	326,24	330,90
Time of labor	Hour	0,035	0,030	0,036	0,027

* to LC^3_Flash is assumed equal compressive strength than obtained in the industrial trial with the calciner.

Source: [21]

To analyze results in an integrated way figure 4 is proposed, showing all indicators together.

Figure 3. Integrated assessment of impacts. Case study: introduction of LC^3 in Cuba.



The results of the economic, social and environmental evaluations show the positive impacts (see figure 3) of introducing low carbon cement in Cuba. The main impacts are associated with the reduction of emissions of greenhouse gases and dust, which could influence in the reduction of diseases associated with the production of cement; the saving of energy that influence in the reduction of the cost of production and the consequent impact on the purchasing power of the population. A revitalization of the cement production in Siguaney and consequently in Cuba, that would allow to satisfy the internal demand and increase the exports of this good, and the increase of the productive capacities through small investments with high profitability and short period of recovery.

4. Conclusions

The results of the Life Cycle Sustainability Assessment carried out show that the main impacts are associated with the reduction of greenhouse gas emissions and dust, which in turn influences the reduction of diseases associated with this type of production; the energy saving that is translated in the reduction of the cost of production and the consequent impact on the purchasing power of the population; the revitalization of the cement production in Cuba and in particular in Siguaney, which would allow to satisfy the domestic demand and to increase the exports of this good; in addition to the increase of productive capacities through small investments with high profitability and short recovery period.

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Eco-efficiency assessment of conventional OPC/PPC replacement by LC3 in Cuban residential buildings

Cancio Díaz Y[1], Sánchez Berriel S[1], Sánchez Machado I R[1], Martirena Hernández J F[1], Habert G[2]

[1] Central University of Las Villas, Cuba
[2] Chair of Sustainable Construction, Swiss Federal Institute of Technology, ETH Zurich

yudieskycd@uclv.edu.cu

Abstract. This paper aims at assessing the sustainability of replacing conventional OPC/PPC by Limestone Calcined Clay Cement (LC3) in Cuba. Authors conducted an eco-efficiency (E-E) analysis supported by E-E ratios, which in turn are rooted on the environmental assessment (Life Cycle Assessment, LCA) and the economic analysis (Economic Value Added, EVA). Taking case studies in Villa Clara province capital district, three construction methods were compared and further conclusions emerged with regard to economic and ecological criteria. A square meter of built area was employed as functional unit. According to main results, Grand panel technique appears to be the benchmarking method, followed by Forsa system and, finally, concrete block technique. LC3 blend outperforms OPC/PPC from both economic and environmental perspective. Furthermore, productive efficiency potentials were found on the field of material selection and raw material procurement. Authors provided decision-makers with some policy recommendations in order to contribute enhancing the sustainable use of LC3 in Cuban construction sector.

1. Introduction

The building materials sector is the third-largest CO2 emitting industrial sector worldwide [1]. This sector represents 10% of the total anthropogenic CO2 emissions, most of which are related to concrete manufacture: about 85% of these CO2 emissions come from the provision of cement [2]. Due to the responsibility of construction activities on climate change, the global concern has been focused on the production of concrete structures. Modern civilisation construction is mainly built of concrete, the most consumed material in the world, after water. For emerging economies —where the building stock is still under construction and the potentials for renewable energy transition are not already proven— the need for alternative materials is increasingly recommended.

LC3 —Limestone Calcined Clay Cement— is a blended cement innovation proposed by an international team led by the Swiss Federal Institute of Technology, EPFL-Lausanne. LC3 is a combination of clinker (50%), calcined clay (30%), gypsum (5%) and limestone (15%). The calcined clay of this newly developed technology is metakaolin. Metakaolin has been gaining attention among cement producers as a supplementary cementitious material [3]. Abundant information is readily available on the literature, i.e., [4],[5],[6]. LC3 advantages not only lie on the energy reduction field and emission savings; moreover, it leads to approximately 15% cost- cutting.

This paper aims at assessing the sustainability of replacing conventional OPC/PPC by LC3 in Cuba. Three construction methods has been taken into consideration: (i) concrete block technology, (ii) Grand panel system (mainly prefabricated concrete elements) and (iii) Forsa system (mainly RMC-intensive). The aforementioned building systems were analysed along the following three scenarios: (i) Business As Usual (BAU scenario), which means producing/using conventional OPC/PPC cements, (ii) the country only replaces PPC by LC3, (iii) LC3 substitutes both existing cements. All the alternative choices are scrutinised by taken into account the eco-efficiency index early proposed by [7],[8],[9]. The ratios were built upon the results of Life Cycle Assessment (LCA) and Economic Value Added (EVA) as two so-called and so-accepted ways of looking at sustainability pillars.

Authors looked at the economies of scale coming from different building sizes, as well as the transportation distance breakeven point for building materials costing. Finally, some policy recommendations arisen from the results of four case-studies, were reached.

2. Methodology and data

The eco-efficiency index was calculated by means of the Equation 1, as proposed in the sustainability literature. Data sources for calculating LCA are twofold: background data took impact factors from previous researches [10],[11],[12] and foreground data is reported in table 1. Figure 1 shows the breakdown of material consumption according to the four case-studies under assessment in this paper.

$$Eco-efficiency\ index = \frac{EVA\ (Economic\ Value\ Added)}{CO_2\ (Carbon\ Dioxide\ Emissions)} \qquad (Eq. 1)$$

Table 1

Foreground data for the case studies under assessment

		Blocks	Grand Panel		Forsa
Building materials/Building system	Unit	Two-storey	Two-storey	Five-storey	Five-storey
Ready-Mix Concrete	m^3	30,6	10,9	40,1	397,0
Prefabricated concrete	m^3	9,5	52,0	277,8	14,3
Blocks 15 cm	u	7560,0	770,0	2381,0	2140
Cement	t	29,3	8,6	40,2	27,7
Sand	m^3	42,9	30,1	79,3	55,0
Gravel	m^3		0,37	0,9	
Calcium hydrate	t	4,92	2,25	9,9	6,8
Steel	t	2,83	0,86	2,6	31,5
Usable floor area	m^2	168,74	161,42	863,6	806,9

Data on table 1 stands for the data inventory needed to conduct LCA as well as the economic assessment. The amount of cement reported in row 4 is the cement used for mortar in masonry applications. The cement consumption per unit of building materials listed on the above table, behave as follows: 450 kg per cubic meter of ready mix concrete, 360 kg per cubic meter of precast concrete and 1,62 kg per block. Figure 1 reports the breakdown of construction materials consumption by construction technology type, expressed in percentage. It shows that Grand panel system is prefab. intensive while Forsa method is quite RMC consuming. Concrete block technique is mainly based on masonry applications, which require a great amount of cement in the construction site. The later system is labour-intensive and needs to mobilize the transportation of a huge amount of building materials.

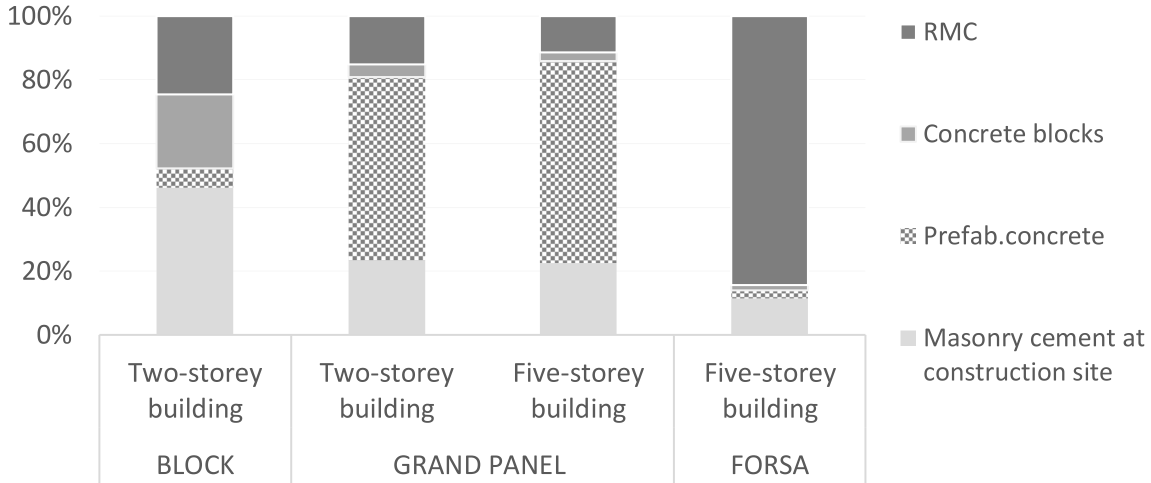

Fig. 1. Material consumption breakdown, by construction technology type (percentage).

3. Results

Figure 2 summarizes the eco-efficiency outputs of this study. Some concluding insights would be drawn from the results:

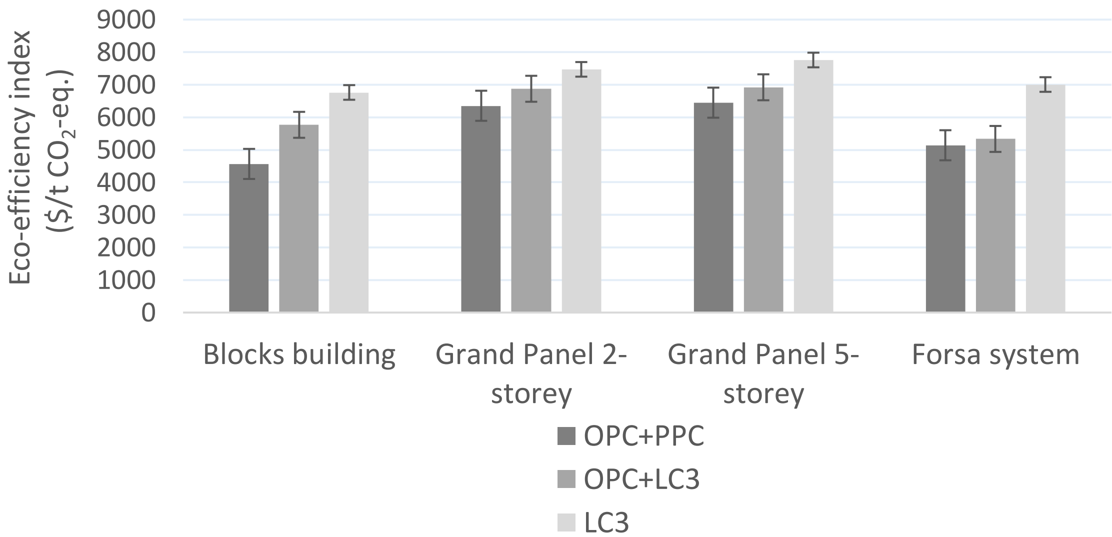

Fig. 2. Eco-efficiency index comparison for the case studies being assessed

- Grand panel seems to be the most eco-efficient construction technology within the case studies under examination, which represents an intermediate level of industrialisation in between the concrete block system and Forsa technology.
- By inspecting the two building sizes within Grand panel technique, some potentials for economies of scale are achieved: up to 15% cost reduction would be possible to attain, strictly coming from the building size. It also contributes reducing the land use, therefore, the ecological footprint of mankind construction activities.
- LC^3 would be more effectively used in RMC-intensive choices from a sustainability viewpoint, but it always must be seen in light of raw materials transport distances.

Ceteris paribus the cement type used for construction, the cost of transporting raw materials needs for attention, particularly for those economies like Cuba where the productive efficiency depends upon the transportation parameters. Material selection in construction sector is crucial because of the enormous volume and mass needed to be transported. That is why the nearness of raw materials deposits constitutes a core piece of the cost analysis.

The figure 3 describes an estimated transport cost function for raw materials, according to those case-studies under assessment. Detailed calculations can be found in [4].

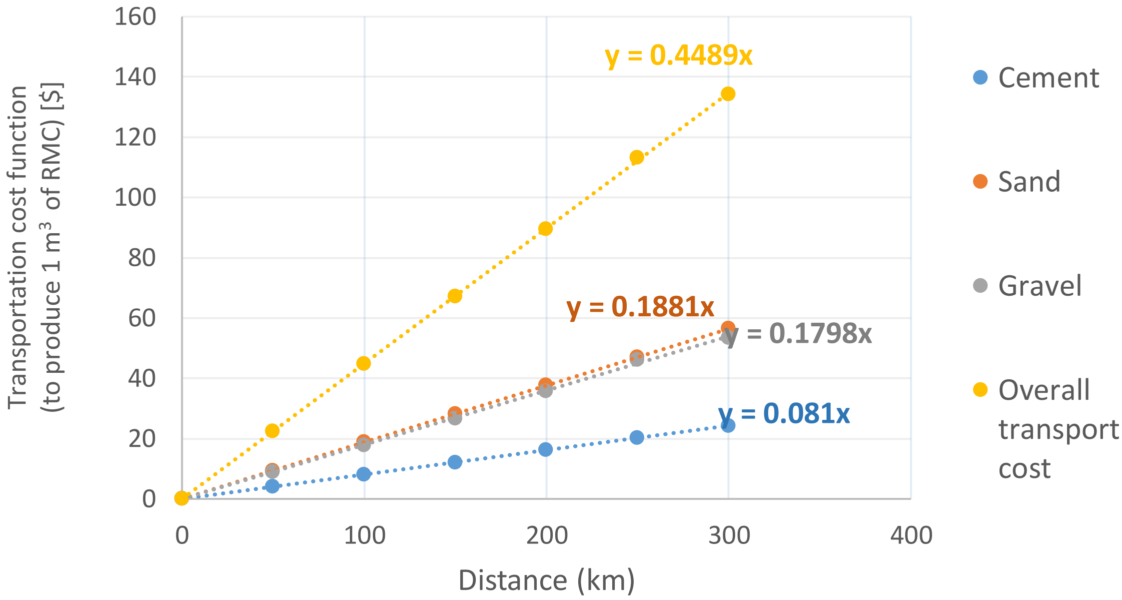

Fig. 3. Transportation cost function at the level of raw material

In a second step, using (i) functional data from formulas shown on Fig. 3, (ii) quantities from data inventory reported in table 1, and (iii) transport distances between source of materials and construction sites, authors developed the Overall Transport Cost Function at the level of buildings (Fig. 4). Afterwards, the distance breakeven point was calculated for each case study, taking as a relevant input, a maximum cost limit determined by the cost savings between LC3 and conventional cements. The economic distance threshold was anticipated around 50 km in the Forsa system, 141 km in the blocks building and 345 km for Grand panel. It means that beyond such a threshold the construction activities would become economically unfeasible, if transport parameters are taken into consideration.

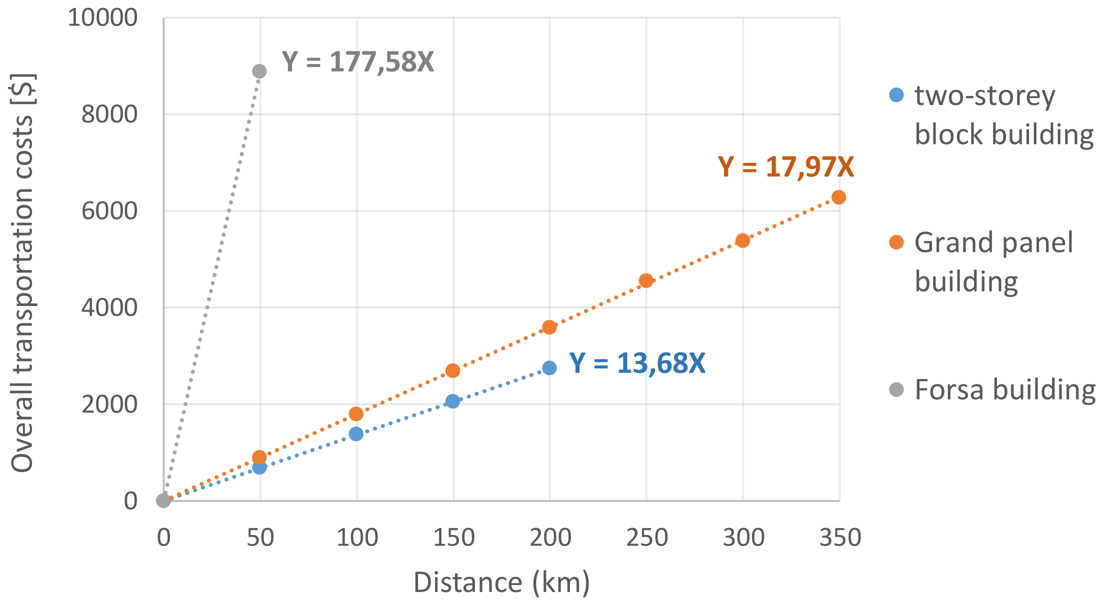

Fig. 4. Transportation cost function at the level of building

However, it appears to be clear that both material selection and the construction technology choice have to be thought in the light of case-to-case building design/location, because depending on the distance from construction site to quarries —particularly the deposits of aggregates due to the enormous amount per concrete volume— the construction method might be subject to adaptations and rethinking.

4. Conclusions

According to the case studies taken from Villa Clara province (Cuba), the future implementation of LC3 within the construction sector would attain better eco-efficiency parameters if those building methods characterised by medium-to-high level of industrialisation are prioritised. Least industrial intensive choices —such as concrete blocks— seems to be highly correlated to cement consumption, in turn, meaning high energy consumption, carbon emissions and production costs. Transportation parameters also would strongly influence the material selection and eventually the construction technology choice. None of the construction techniques is, in principle, superior per se; a proper combination of them based on a multiple-criteria approach, let decision makers better stick to the suitable benchmark combination of techniques through the lens of sustainability.

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Optimizing the economic, environmental and technical performance of concrete mixes with fly ash and recycled concrete aggregates

Kurda R, Silvestre J D, Brito J

CERIS, Department of Civil Engineering, Architecture and Georesources, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001, Lisboa, Portugal

rawaz.kurda@tecnico.ulisboa.pt

Abstract. This study answers an important question that may arise when selecting a sustainable concrete, namely "concrete mixes containing low cement and recycled aggregates are a sustainable solution?" To answer this question, this study shows how to optimize concrete mixes in terms of technical performance, and economic and environmental life cycle. Firstly, the weight to be considered for each of these dimensions of performance depends on the concrete application (e.g. residential house and high-rise building) and on the consumer's requirements (e.g. business as usual, green, strength, service life and cost scenarios). In this study, concrete mixes containing recycled concrete aggregates (RCA) and/or fly ash (FA) are optimized to be used in sustainable residential houses. For that purpose, the CONCRE***Top*** methodology (developed by the same authors of this study) was applied to these concrete mixes by considering a "green scenario". The results show that, for sustainable residential houses, the concrete mixes made with high incorporation ratios of FA and RCA are considered the best option.

1. Introduction

Concrete has a serious influence on environmental impacts (EI) due to the fact that it is the most consumed product by Man after water. Thus, many alternative ways were suggested to decrease its influence on EI, specifically by using cementitious [1-7] and recycled materials [8-20]. For that purpose, there were many attempts to study the effect of non-conventional materials on the cost, quality (e.g. durability and mechanical characteristics) and EI (energy consumption and greenhouse gas emissions) of concrete. Since most of the studies focused on only one of the mentioned dimensions of performance (quality, cost and EI), and there is no direct relationship between them, a critical gap occurs concerning the assessment of sustainable concrete. Even though, there are many alternative materials which use in concrete is a sustainable solution because their EI are lower than that of the conventional materials. However, the advantage of these non-traditional materials may not be obvious when the service life of the concrete mixes made with them compares with that of conventional concrete.

To analyse these issues, this study optimized concrete mixes containing various incorporation ratios of fly ash (FA) and recycled aggregates (RA), with and without superplasticizer (SP). But it is not easy to compare the performance of concrete mixes considering simultaneously several dimensions of performance. Thus, the authors of this study had already proposed a novel method (CONCRE***Top*** - A multi-criteria decision method for concrete optimization - [21]) to optimize conventional and nonconventional concrete mixes in the mentioned dimensions. For that purpose, the CONCRE***Top*** methodology was applied to these concrete mixes by considering a "green scenario". This study is an example of CONCRE***Top***'s application and also contributes to its validation.

2. Materials and methods

This study followed the steps that are described in the CONCRE***Top*** method [21] to optimize concrete mixes. As mentioned before, the concrete mixes can be optimized only when their quality, EI and cost are known. It is known that the environmental and cost life cycle assessment data of different concrete mixes cannot be directly compared. Accordingly, the CONCRE***Top*** method used a non-parametric linear technique to optimize the concrete mixes. In addition, the aim of the *CONCRE**Top*** method is to simply compare the options without any complex analyses (e.g. Holomorphic function, disk algebra and power series) in order to be used by any Engineer in the construction industry. According to the CONCRE***Top*** method, seven actions are required to reach a final decision (Figure 1).

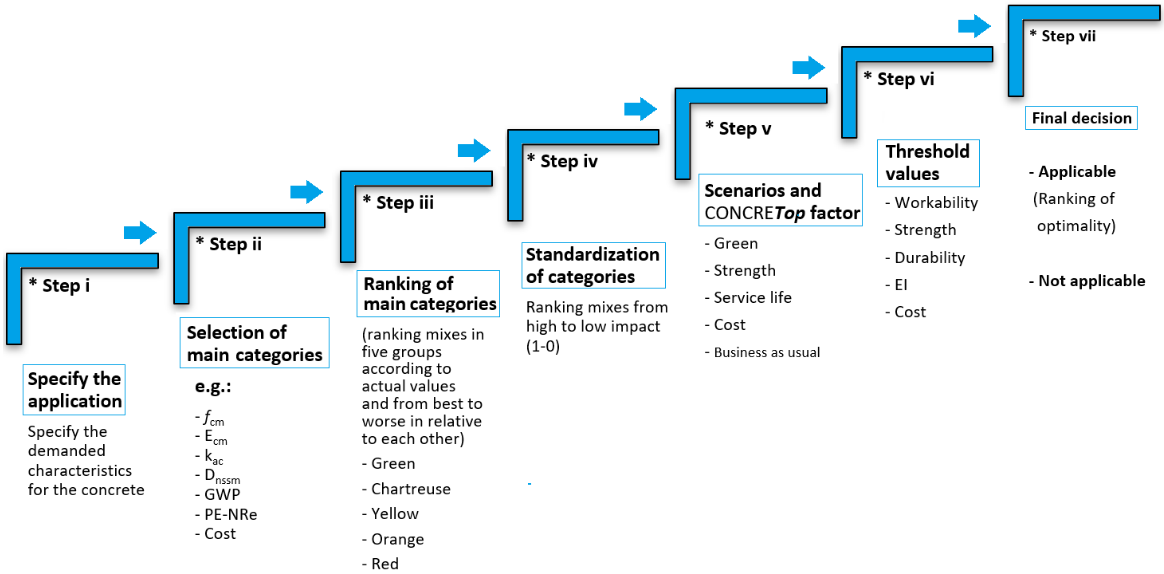

Figure 1 - Profile of the CONCRE***Top***. Each step is described in study [21]

Cement and FA used as binders were type "CEM I 42.5 R" and "F", respectively. The fine and coarse RA are made from the same source concrete without any contamination (100% concrete). The fine and coarse natural aggregates (NA) are "natural silica sand" and "crushed limestone", respectively. In this study, 20 concrete mixes (Table 1) are considered to be optimized. They were made with various incorporation ratio of FA (0%, 30% and 60%), fine RA (0%, 50 and 100%), coarse RA (0% and 100%) and SP (0% and 1%). All the information related to the characteristics of the materials (e.g. size of aggregates, density, and water absorption) and mix composition (e.g. mixing procedure, quantity of materials) is described in another study by the same authors [22].

To consider the requirements needed to optimize concrete mixes, the following standards were considered to determine the compressive strength [23], modulus of elasticity [24], carbonation [25], chloride ion penetration [26, 27], cost, and global warming potential and non-renewable primary energy consumption (based on Life Cycle Assessment (LCA) methodology [28, 29]) of the concrete mixes. Regarding LCA, the EI of the concrete mixes were found by considering the most probable case scenario in the centre of Portugal (Lisbon region). Further details regarding the mentioned characteristics (e.g. curing procedure, size of samples, number of samples and case scenario) are described in previous studies of the same authors [5, 7, 30, 31].

3. Application of CONCRE*Top* to the concrete mixes

3.1 Specification of the application (step i)

As detailed in the CONCRE***Top*** methodology, the optimization process of concrete mainly depends on its application. In this study, the concrete mixes are optimized to be used in a "sustainable residential houses". According to this methodology, "sustainable residential houses" will be categorized according to a "green" scenario. Thus, the threshold values that are specified for the green scenario were applied to the concrete mixes.

Table 1 - Mixes composition

Mixes [a]	Fine RA (%)	Coarse RA (%)	FA (%)
M1; M1-SP	0	0	0
M2; M2-SP	100	0	0
M3; M3-SP	50	0	30
M4; M4-SP	0	0	60
M5; M5-SP	100	0	60
M6; M6-SP	0	100	0
M7; M7-SP	100	100	0
M8; M8-SP	50	100	30
M9; M9-SP	0	100	60
M10; M10-SP	100	100	60

[a] M and M-SP are concrete mixes without and with SP (1% of binder's weight)

3.2 Selection of the main categories (step ii)

There are many characteristics that can be considered to optimize concrete. The CONCRE***Top*** method specifies the most relevant ones for this purpose, but unlimited characteristics can be considered using this method. According to this method, the following characteristics are relevant for the green scenario: workability, compressive strength (f_{cm}), modulus of elasticity (E_{cm}), carbonation resistance, chloride ion penetration resistance (D_{nssm}), global warming potential (GWP) and non-renewable energy consumption (PE-NRe).

3.3 Ranking of the main categories (step iii)

Before optimizing the concrete mixes based on the next steps (§3.4-§3.5), namely by considering the weight of each category, mathematical rules and threshold values, the characteristics of the concrete mixes were compared to each other in order to provide a general idea about their performance. However, the aim of the CONCRE***Top*** method is to find an optimal mixes instead of the best one in each category. According to this methodology, the results of the concrete mixes were compared (Table 2), namely by two main colours (green for the best performance and red for the worst performance). According to this step, mixes M3, M3-SP, M4-SP, M6-SP and M8-SP were identified as optimal for "sustainable residential houses", because most of their characteristics are not in the red category.

3.4 Standardization of categories (step iv)

The characteristic values of concrete mixes are standardized based on step iv from Kurda *et al.* [21]. It is known that the results of different properties cannot be compared if their measuring unit are not the same. Therefore, the actual values of all characteristic were standardized (normalised or homogenised) from 0 to 1. Then, the mixes were ranked according to the standardized values from the best to the worst performance (Table 3).

*3.5 Scenarios and CONCRE**Top** factor (step v)*

This step is one of the most important of the optimization process because the mixes were ranked based on the CONCRE***Top*** factor. This factor can be determined by the equation proposed in this method [21]. In addition, for the selected scenario (green), the weight of each category (characteristic of concrete) for the CONCRE***Top*** factor is defined in the same method according with their order of importance. For the selected application and scenario, the weight of the strength, durability, LCA and cost are 10%, 20%, 50% and 20%, respectively (based on 20 years of experience of one of the authors of this manuscript as a structural designer.). According to the CONCRE***Top*** method, the weights can be changed, depending on the client's perspective. However, this method was prepared for engineers with basic knowledge regarding the construction sector in order to choose the weights. But this method also include threshold values to overcome this issue. Even if the weights are not always considered properly, the threshold values will not permit inadequate choices. Figure 2 presents the result of the process of optimization of the concrete mixes based on green scenario ranked by their CONCRE***Top*** factor (1-0) without considering threshold values.

Table 2 - Ranking of concrete mixes according to their performance

Concrete mixes	Slump (cm)	$f_{cm,cube}$ (MPa)		E_{cm} (GPa)		D_{nssm} ($\times10^{-12}$ m²/s)		Carbonation "k_{ac}" (mm year$^{0.5}$)	GWP (kg CO_2 eq)	PE-NRe (MJ)	Cost (€/m³)
		28 days	365 days	28 days	365 days	28 days	365 days				
M1	7.3	55.8	61.3	43.8	47	12.6	7.9	11.3	361.6	1949.5	79.9
M1-SP	8.5	73.5	83	51.4	55.7	6.4	3.9	1.6	364	1983.2	90.1
M2	8.1	45	51.5	34.7	39	16.2	9.8	26.9	360	1936.2	76.7
M2-SP	8.8	54.1	63.7	39.9	42.6	9.4	5.5	7.8	362.5	1970.8	86.7
M3	8.3	36.4	57.2	38.3	46.3	8.9	3	37.7	267.9	1572.2	71
M3-SP	8.9	60.4	79	43.9	50.2	4.2	1.0	4.2	270.3	1605.6	81.1
M4	7.2	24	42.2	38	46.1	11.2	3.1	61.58	175.9	1209.7	65.3
M4-SP	8.1	42.4	58	40.7	47.7	5.4	1.1	59.84	178.7	1248.1	75.5
M5	8.5	21.5	40	32.3	41.4	13.2	3.3	66.4	174.2	1194.5	62.2
M5-SP	8	37.1	57	34.4	42	6.6	1.3	51.83	176.6	1228.5	72.1
M6	7.6	51.9	59.2	37.1	41.4	14	8.5	15.35	331.1	1528.6	74.6
M6-SP	8.8	63	73	43.5	47.7	7.6	4.6	1.5	331.8	1538.2	84.5
M7	8.1	42	50.2	28	31.4	18.1	10.6	30.3	330.3	1525.4	71.6
M7-SP	8.9	49	60.6	33.9	35.8	10.6	6.1	9	331	1534.9	81.2
M8	8.8	33	56.6	32.5	40	9.3	3.2	42.3	237.6	1153.9	65.8
M8-SP	8.7	53.8	74	38.3	44	4.6	1.1	12.2	238.3	1163.4	75.5
M9	8.6	23	41	33	41.1	11.9	3.2	59.8	145	783.1	59.9
M9-SP	8.8	38	59	38.3	43.6	5.9	1.2	57.1	145.7	792.6	69.8
M10	7.3	21	38	26.9	35.3	14.2	3.6	66.3	144.2	779.1	57
M10-SP	8.9	32.3	54	30.1	35.5	7.3	1.4	44	144.8	788.7	66.6

Table 3 - Ranking and standardization of the concrete mixes

f_{cm} (28 days)		f_{cm} (365 days)		E_{cm} (28 days)		E_{cm} (365 days)		D_{nssm} (28 days)		D_{nssm} (365 days)		Carbonation		GWP		PE-NRe		Cost	
M1-SP	1.00	M1-SP	1.00	M1-SP	1.00	M1-SP	1.00	M3-SP	1.00	M3-SP	1.00	M6-SP	1.00	M10	1.00	M10	1.00	M10	1.00
M6-SP	0.80	M3-SP	0.91	M3-SP	0.69	M3-SP	0.77	M8-SP	0.97	M4-SP	0.99	M1-SP	1.00	M10-SP	1.00	M9	1.00	M9	0.91
M3-SP	0.75	M8-SP	0.80	M1	0.69	M4-SP	0.67	M4-SP	0.91	M8-SP	0.99	M3-SP	0.96	M9	1.00	M10-SP	0.99	M5	0.84
M1	0.66	M6-SP	0.78	M6-SP	0.68	M6-SP	0.67	M9-SP	0.88	M9-SP	0.98	M2-SP	0.90	M9-SP	0.99	M9-SP	0.99	M4	0.75
M2-SP	0.63	M2-SP	0.57	M4-SP	0.56	M1	0.64	M1-SP	0.84	M5-SP	0.97	M7-SP	0.88	M5	0.86	M8	0.69	M8	0.73
M8-SP	0.62	M1	0.52	M2-SP	0.53	M3	0.61	M5-SP	0.83	M10-SP	0.96	M1	0.85	M4	0.86	M8-SP	0.68	M10-SP	0.71
M6	0.59	M7-SP	0.50	M3	0.47	M4	0.60	M10-SP	0.78	M3	0.79	M8-SP	0.84	M5-SP	0.85	M5	0.66	M9-SP	0.61
M7-SP	0.53	M6	0.47	M8-SP	0.47	M8-SP	0.52	M6-SP	0.76	M4	0.78	M6	0.79	M4-SP	0.84	M4	0.64	M3	0.58
M2	0.46	M9-SP	0.47	M9-SP	0.47	M9-SP	0.50	M3	0.66	M8	0.77	M2	0.61	M8	0.58	M5-SP	0.63	M7	0.56
M4-SP	0.41	M4-SP	0.44	M4	0.45	M2-SP	0.46	M8	0.63	M9	0.77	M7	0.56	M8-SP	0.57	M4-SP	0.61	M5-SP	0.54
M7	0.40	M3	0.43	M6	0.42	M5-SP	0.44	M2-SP	0.63	M5	0.76	M3	0.44	M3	0.44	M7	0.38	M6	0.47
M9-SP	0.32	M5-SP	0.42	M2	0.32	M5	0.41	M7-SP	0.54	M10	0.73	M8	0.37	M3-SP	0.43	M6	0.38	M4-SP	0.44
M5-SP	0.31	M8	0.41	M5-SP	0.31	M6	0.41	M4	0.50	M1-SP	0.70	M10-SP	0.35	M7	0.15	M7-SP	0.37	M8-SP	0.44
M3	0.29	M10-SP	0.36	M7-SP	0.29	M9	0.40	M9	0.45	M6-SP	0.63	M5-SP	0.22	M7-SP	0.15	M6-SP	0.37	M2	0.40
M8	0.23	M2	0.30	M9	0.25	M8	0.35	M1	0.40	M2-SP	0.53	M9-SP	0.14	M6	0.15	M3	0.34	M1	0.31
M10-SP	0.22	M7	0.27	M8	0.23	M2	0.31	M5	0.35	M7-SP	0.47	M9	0.10	M6-SP	0.15	M3-SP	0.31	M3-SP	0.27
M4	0.06	M4	0.09	M5	0.22	M7-SP	0.18	M6	0.29	M1	0.28	M4-SP	0.10	M2	0.02	M2	0.04	M7-SP	0.27
M9	0.04	M9	0.07	M10-SP	0.13	M10-SP	0.17	M10	0.28	M6	0.22	M4	0.07	M1	0.01	M1	0.03	M6-SP	0.17
M5	0.01	M5	0.04	M7	0.04	M10	0.16	M2	0.14	M2	0.08	M10	0.00	M2-SP	0.01	M2-SP	0.01	M2-SP	0.10
M10	0.00	M10	0.00	M10	0.00	M7	0.00	M7	0.00	M7	0.00	M5	0.00	M1-SP	0.00	M1-SP	0.00	M1-SP	0.00

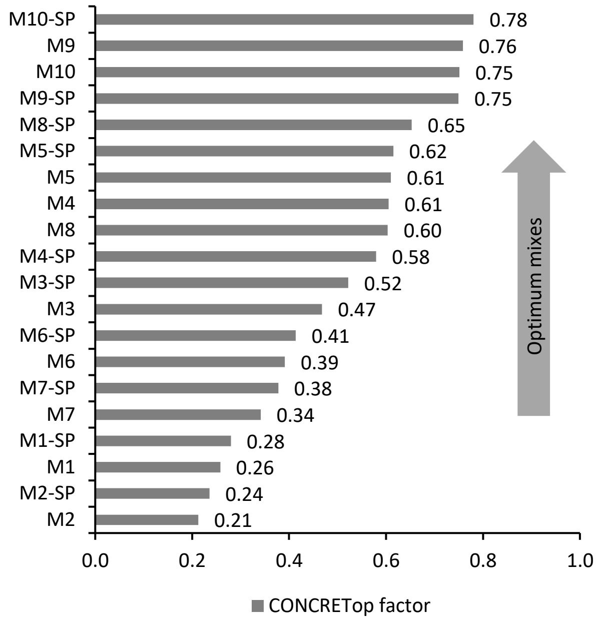

Figure 2 -Optimization of the concrete mixes according to green scenarios without considering threshold values

3.6 Threshold values (step vi)

As mentioned before, the considered weight may not be reliable or correct. Therefore, this step works as another sort of screen to optimize the concrete mixes. The boundaries (threshold values) for all the selected parameters (f_{cm}, E_{cm}, carbonation, D_{nssm}, GWP and PE-NRe) for this step are identified in the study of Kurda *et al.* [21]. According to this method, the threshold value depends on the case study. Thus, in this step, green scenario and its threshold value were chosen out of all scenarios (business as usual, strength, cost and service life) due to the fact that the concrete mixes are optimized for sustainable residential houses. Thus, the concrete mixes were ordered based on the values shown in Figure 2, and then the results were compared with the threshold values set by the mentioned study (Table 4). The concrete mixes that comply with the threshold values are not presented in Table 4. The results show that, along with the fact that the values of the CONCRE***Top*** factor of the traditional concrete (M1 and M1-SP) and of mixes containing 100% of fine RA (M2 and M2-SP), with and without SP, are relatively low, their characteristics also do not comply with the boundaries given by CONCRE***Top*** method.

3.7 Final decision (step viii)

One of the advantages of the CONCRE***Top*** method is that the consumer can easily choose the optimal mix for the selected application. According to the optimization process, mix M10-SP is the optimal one (highest CONCRE***Top*** factor) and the worst one is mix M7 (lowest CONCRE***Top*** factor). Based on the mentioned factor, all the mixes made with 100% coarse RA and 60% FA (M10-SP, M9, M10 and M9-SP) can be considered as optimal choices for sustainable residential houses (their CONCRETop factor is relatively similar). Thus, it is advisable to use high volume of coarse RA and FA to build sustainable residential houses. Furthermore, the method shows that the EI of the fine RA concrete made with ordinary Portland cement (OPC; M7 and M7-SP) is lower than that of conventional concrete, but it is still considered one of the worst choices because it significantly affects the service life of concrete.

The above conclusions show that consumers need to consider other dimensions of performance (e.g. quality and cost of concrete) to select the optimal/sustainable concrete, even if they only demand EI's minimization. In addition, the optimal mixes cannot be easily anticipated by simply looking at the individual results in each dimension (§3.3). Furthermore, in some cases, the high-strength concrete mixes are not considered as an optimum [21] solution due to their cost (their cost are very high) or EI (due to high cement content which is the major contributor to the high EI values of concrete).

Table 4 - Optimizing concrete mixes for sustainable residential house in the "GREEN" scenario

Ranked mixes	CONCRE***Top*** factor	Threshold	Applicable [21]	Reasons
M6-SP F 0% C 100% FA 0% SP 1%	0.41	Strength = 45/55 - 36 Carbonation R. = Very good Chloride R. = Very high GWP = Low PE-NRe = Low Cost = Very high	NO	The cost is very high.
M1-SP	0.28	Strength = 55/67 - 38 Carbonation R. = Very good Chloride R. = Very high GWP = Medium PE-NRe = Low Cost = Very high	NO	The cost is very high. For the green scenario, the GWP is expected to be lower than medium.
M1	0.26	Strength = 40/50 - 35 Carbonation R. = Good Chloride R. = Very high GWP = Medium PE-NRe = Low Cost = High	NO	For the green scenario, the GWP is expected to be lower than medium.
M2-SP	0.24	Strength = 35/45 - 34 Carbonation R. = Very good Chloride R. = High GWP = medium PE-NRe = Low Cost = Very high	NO	The cost is very high. For the green scenario, the GWP is expected to be lower than medium.
M2	0.21	Strength = 30/37 - 33 Carbonation R. = Good Chloride R. = Moderate GWP = Medium PE-NRe = Low Cost = High	NO	For the green scenario, the GWP is expected to be lower than medium.

Table 5 - Applicable concrete mixes for the sustainable residential house according to the "Green" scenario

Mixes	M10-SP	M9	M10	M9-SP	M8-SP	M5-SP	M5	M4	M8	M4-SP	M3-SP	M3	M6	M7-SP	M7
Fine RA (%)	100	0	100	0	50	100	100	0	50	0	50	50	0	100	100
Coarse RA (%)	100	100	100	100	100	0	0	0	100	0	0	0	100	100	100
FA (%)	60	60	60	60	30	60	60	60	30	60	30	30	0	0	0
SP (%)	1	0	0	1	1	1	0	0	0	1	1	0	0	1	0
CONCRE***Top*** factor	0.78	0.76	0.75	0.75	0.65	0.62	0.61	0.61	0.6	0.58	0.52	0.47	0.39	0.38	0.34

4. Conclusions

The results of this study show that the optimum concrete mixes may not be easily chosen by comparing the performance of concrete in each dimension (e.g. quality, cost and EI). In practical terms, for each selected application, it relies on the CONCRE***Top*** factor and threshold values. In other words, the weight of each characteristic depends on the specific concrete application. For example, mixes produced with high incorporation ratios of FA and RCA (e.g. M9 and M10 with and without SP) are not anticipated to be an optimal choice according to their individual characteristics, but their characteristics comply with the threshold values and their CONCRE***Top*** factors are the highest. In addition, the optimal mix (e.g. for sustainable house) may not necessarily be the one with the highest result in the demanded characteristic (e.g. EI). In practical terms, it is chosen by the combined performance in all the characteristics. Broadly speaking, the mixes are judged based on their performance on all characteristics, not in just one characteristic (dimension).

Finally, this study is an example of CONCRE***Top*** application and shows that concrete cannot be optimized without knowing its application and the consumer's demand. Therefore, the outcome may be different for other approaches or assumed scenarios.

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Sensitivity Analysis of Life Cycle Impacts Distribution Methods Choice Applied to Silica Fume Production

Timm J F G[1], Morales M F D[1], Passuello A[1,2]

[1]Federal University of Rio Grande do Sul, Building Innovation Research Unit, NORIE, Osvaldo Aranha avenue, 99–7th floor. Centro, Porto Alegre, RS, Brazil.
[2]Federal University of Rio Grande do Sul, Interdisciplinary Department, Campus Litoral Norte. RS 030 KM 92, 11700, Tramandaí, Rio Grande do Sul, Brazil.

ana.passuello@ufrgs.br

Abstract. The construction sector is known as an important consumer of natural resources. The use of by-products from different production chains in the sector is encouraged, promoting a reduction in the extraction of natural resources, reducing the need for residues disposal and enhancing circularity. Silica fume is a by-product from the smelting process in the silicon and ferrosilicon industry, commonly used as concrete supplementary cementitious material, which provides chemical and physical effects on concrete microstructure. When LCA evaluation is conducted, different impact distribution models may be applied to assess the potential impact of the by-productss. Although their benefits are recognized, some studies still report them as burden free, having no allocated impacts . Thereby, the aim of this paper is to evaluate the differences in silica fume life cycle impacts by analyzing three scenarios from cradle to gate, considering the modeling procedures described by ISO 14040, the Cut-off model from Ecoinvent version 3.3 and the impact assessment method CML v.4.4, according to the CEN EN 15804 recommended categories. Results enhance the understanding regarding model selection and demonstrate that the selection of the proper distribution model is key, considering that this may lead to important differences in the results.

1. Introduction

The construction sector is recognized by producing numerous environmental impacts due to the high consumption of natural resources, high energy consumption for extraction of the raw material and for the large production of waste. These characteristics set up unsustainable patterns of development and consumption that could potentially lead to resource depletion and the inability to manage the amount of waste produced. Different studies and initiatives make efforts to mitigate this problem by improving materials, constructive techniques and developing new products. In addition, the production chain of the construction industry has enormous potential to increase the volume of materials it recycles, due to the large amount of materials consumed [1]. The use of construction and demolition waste, as well as the waste from other industries in the substitution of natural raw materials, is a sustainable way of handling by-products that would be otherwise disposed of.

There are environmental benefits related to the use of by-products in the construction industry. However, it is essential to quantify such benefits to provide clear information on the advantages or disadvantages related to their use. In this way, Life Cycle Assessment (LCA) is a methodology which allows for the assessment of potential environmental impacts of the use of such materials by calculating and evaluating resource consumption and emissions [2]. It is a recognized methodology that provides a structure to develop an environmental assessment of products [3].

LCA models the life cycle of a product through a system product, which is composed of activities that transform inputs to outputs (called 'processes') [3]. Processes that have more than one product as output, are known as multifunctional process [4]. In LCA studies involving multifunctional process(es), ISO 14044:2006 standard recommends firstly, the elementary process division or system expansion. Secondly, it recommends allocation using physical relationships and, thirdly, when a physical relationship cannot be applied, entries should be allocated by functions in a way that reflects other relationships between them such as economic value [5].

Tillman (2000) discussed the relevance of these different methodological choices in an LCA paper of a multifunctional process and its relationship between their goals and applications [6]. This paper distinguished a retrospective LCA, which are commonly known as attributional LCA and a prospective LCA, known as consequential LCA. The paper differentiates between the attributional approach, applied to learn about existing impacts, used to identify improvement possibilities or to make market claims; with the consequential approach, used to investigate the consequences of the changes in product or process design [6]. The ILCD handbook (2010) defines attributional modelling as involving the current or forecasted specific or average supply-chain [4].

Both approaches can be found being applied in LCA of the multifunctional process. Considering the attributional one, Chen et al. (2010) state that the mass allocation procedure has the advantage of being constant with time since the mass proportion between the product and the by-product is not very variable unless there are changes in its production process [7]. Despite being a consolidated method, there are different ways to conduct it. Choices related to the Life Cycle Inventory (LCI) modeling process, such as the different sets of rules that can be applied in the studies, may lead to different results [8]. On the other hand, Saade, Silva and Gomes (2015) mentioned that the conceptual limitations of allocation methods are that they do not look beyond partitioning impacts, and awkward ratios between physical characteristics and market value may distort the results [9]. These authors cited the system expansion approach (which encompasses the whole-system level, redefining the system boundaries to include the function related to the by-product) as their preference due to its capacity to precisely model the studied processes, following a complete and conceptually consistent description which also allows for the consideration of potential improvements at whole-system level. However, they recognize that system expansion application requires alternative data, which can be hard for certain processes [9].

In this regard, different modeling approaches are considered in the Ecoinvent v.3.3 database, giving consistency to studies related to diverse human activities. This database provides the choice among three system models. Two of them are based on the attributional system model - Allocation and Cut-off by classification (Cut-off) and Allocation at the point of substitution (APOS) and the last one is based on the consequential system model and named as Consequential, long-term [10]. It is important to mention that, whenever different alternatives of allocation procedures seem applicable, a sensitivity analysis should be conducted to explain the consequences of replacing the selected approach [5].

The environmental evaluation of the by-products used in the construction sector has been much discussed recently. Some of these studies are related to concrete production, one of the most produced materials in the world and with great potential for incorporating wastes/by-products [11]. In the concrete mix, pozzolanic materials have been used to improve properties related to mechanical strength and durability. Silica fume (SF) is one of these by-products, commonly applied due to its pozzolanic characteristics, extreme fineness and high amorphous silicon dioxide content. It is recognized as a pozzolanic admixture that is effective in enhancing concrete mechanical properties [12].

In the environmental assessment context, some SF studies have been developed assessing its environmental impacts as a supplementary cementitious material (SCM). Van Den Heede et al. (2014) compared a cement based concrete slab with a concrete slab with high cement replacement level [13]. By evaluating the impacts adopting an attributional approach, using economic allocation, the authors found a reduction when the SF is applied as SCM. Habert et al. (2011) assessing a concrete environmental impact, also applied an attributional approach, finding substantial differences coming from the three SF allocation procedures chosen (no allocation, mass allocation and economic allocation), with mass allocation showing the highest impact [14].

Although, some studies have been developed, the literature still has a lack of studies demonstrating in a clear way the influence of choice of multifuncional modeling procedure on the environmental impacts results. Considering that, and the common use of SF in construction products, the objective of this research is to enhance the understanding of differences in silica fume life cycle impacts by analyzing three scenarios from cradle to gate, considering the multifunctional modeling procedures by ISO 14040, the three distribution Cut-off models from Ecoinvent version 3.3 and the impact assessment method CML v.4.4-2001, according to the CEN EN 15804 recommended categories.

2. Methodological approach

2.1. Goal, scope and inventory analysis

The objective of this LCA is to understand the impacts of choosing a modeling procedure to deal with multifunctionality, as described by ISO 14040, in the LCA of the by-product SF. SF is produced during the silicon metallurgical production process, being collected in very large filters in the baghouse and then made available for use in concrete without further treatment (Figure 1). SF is also produced by the ferrosilicon productive process, but the silicon metallurgical is selected to this evaluation, since it produces higher amounts of proper SF for concrete production [1].

The scope of this LCA considers the production system from cradle to gate. In this way, the impacts related to the material extraction, material production stage, and transportation to the silicon metallurgical factory are evaluated. The use, maintenance phase and end-of-life (recycling and disposal, including transport) are not considered. The functional unit is defined as 1 kg of Silica Fume, produced in Brazil.

The Ecoinvent database version 3.3 presents the inventory data in three modeling methods to distribute environmental loads [8]. The Cut-off and APOS models are based on attributional approaches and they differ in the approach towards the allocation of recycling and waste treatment products. In the Cut-off model, the product system does not have any previous flows of by-products, waste treatment or recyclable materials since they are burden-free [8]. The APOS model measures all the benefits and impacts of any by-products by means of performing an expansion of the system, and allocation at the point of substitution. It is broader than the Cut-off because it includes all necessary secondary processes, such as treatment, to allow the material to be used as a by-product. Finally, the Consequential model is the broadest system, including the market and the consequences (avoided burden) of the replacement of the raw material by the by-product. And it differs considerably from the attributional system models, depending on the difference of perspective and the modeling principles [8].

Since this paper focuses on the multifunctional modeling procedures, the inventory data used is silicon production, metallurgical grade, location Rest of World (RoW) [15]. Complete data inventory is available on Ecoinvent v.3.3 documentation [15]. The location selected is due to the economic data applied, which are from Brazil. Despite the Ecoinvent v.3.3 having a SF dataset available (in the three models), it is not connected to the silicon production chain and it is reported as material for treatment or recyclable product. Even without this connections, SF is considered as a by-product in this study, and a system expansion and allocation are developed.

The Cut-off system model is selected. The simple cut-off method is the easiest to apply but it does not reflect the full consequences of the outflows and inflows [16]. The cut-off system and APOS system are similar since both models differ mainly in the treatment of recycling materials and wastes [17]. The conflicting criteria are probably part of the explanation as to why it is difficult for the international LCA community to agree on what allocation procedure is the best [16]. Figure 2 shows a silicon production scheme considering the three system models in evaluation.

LCA methodology is complex and demands a considerable amount of data because it is based on the life cycle perspective and demands data collection of different flows of energy and materials (input and output). The primary data collection cannot usually be gathered within each specific LCA due to high costs and time limitations [18]. When the primary data is not available, background data may be used as a supplement. The background LCI databases can be considered the backbone of any LCA because they provide the process building structure and the disaggregated unit data [8].

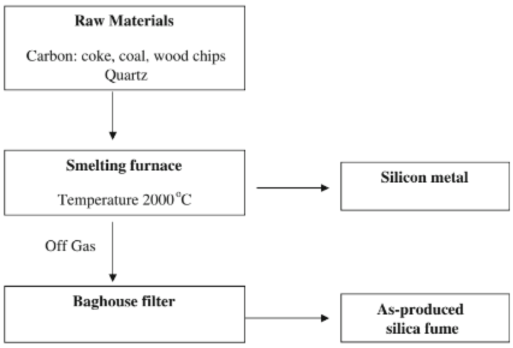

Figure 1. Schematic diagram of silica fume as produced [12].

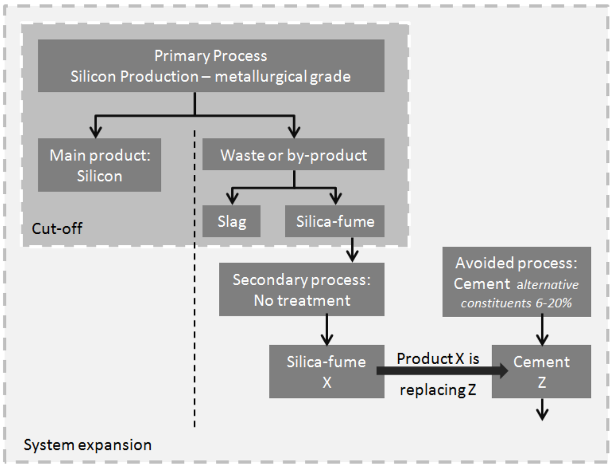

Figure 2. Silicon and silica fume production representation with the available multifunctional modeling procedures. No treatment needed to SF [1].

2.2. Scenarios description of sensitivity analysis

Three different scenarios are proposed resulting from the choice of the product system models: (i) Scenario 1- System expansion model; (ii) Scenario 2- System model Cut-off with allocation by physical relationship (mass); (iii) Scenario 3- System model Cut-off with allocation by economic value. The three scenarios are proposed in seeking to expand the discussion about by-product allocation in attributional LCA studies.

Scenario 1 is based on standard ISO 14044:2006 recommendation to divide the elementary process into two or more subprocesses or make a system expansion. In this scenario, a modelling adjustment is needed, because the silicon metallurgical production dataset does not have an output of SF, as a by-product or waste. In this study, the avoided burden of the SF as a cement replacer is considered [19]. The documents of Ecoinvent 3.3 of silica fume mention it as a replacer of different cement types [20]. The cement production, alternative constituents 6-20% - RoW (CEM II/A) is considered to calculate the avoided burden. This cement type is cited as the greater participation in the market [21].

Scenario 2 is calculated according to Chen et al., (2010) [7] and considers the percentage production as published by Fidjestol (2008) [22]. Scenario 3 is recommended in cases where the by-product represents more than 1% of the economic value of the product (SF accounts for 6.19% of the total economic value) and added to a share in relation to the total revenue considered low (less than 25%) [23]. The production percentages of SF (SiO_2 %) from silicon metallurgical production data were provided by a manufacturer [22], given as 40-50% (in mass) of SF. In this paper, a midpoint of 45% is used. Table 1 presents the values used in the allocation of SF.

2.3. Impact assessment

The support platform used for performing the LCA was OpenLCA 1.6.3, and the potential environmental impact evaluation is based only on the impact categories mentioned in CEN EN 15804 (2013): (i) Climate change – GWP-100 – kg de CO_2-Eq. (100a); (ii) Acidification potential – AP – kg

SO2-Eq. (average Europe); (iii) Eutrophication – generic EP – kg PO4-Eq. (generic); (iv) Photochemical oxidation -POCP – kg etileno-Eq. (high Nox); (v) Ozone layer depletion – ODP – kg CFC-11-Eq. (steady state); (vi) Depletion of abiotic resources – not fossil – ADPN – kg antimônio-Eq. (ultimate reserves); (vii) Depletion of abiotic resources – fossil – ADPF – MJ-Eq. (fossil fuels),; all from CML v. 4.4 baseline (2015) [24].

Table 1. Silica fume allocation percentages by mass and by economic value [7].

	Production (tons)	Market price (1 ton)	Allocation by mass	Allocation by economic value
Silicon	1,00 t	US$ 3145 [a,b]	-	-
Silica fume	0, 45 t	US$ 354 [a,b]	4,8%	31,0%

[a] Morales et al. (2016).
[b] Considering that US$ 1,00= R$ 3,82 (price of the currency in march/2019).

3. Results and discussion

Table 2 presents the impacts of the three available multifunctional modeling procedures by ISO 14040. Comparing the results, Scenario 2 (allocation by mass) shows higher numbers than the others followed by Scenario 3 (allocation by economic value).

Table 2. LCA impacts of 1kg of SF considering three available multifunctional modeling procedures by ISO 14040. Values (in %) represent the comparison between SF and the avoided product impacts.

	System model Cut-off 1kg de SF					**Avoided product[a]**	
Impacts	Scenario 1 - System expansion	Scenario 2 - Allocation by mass	%	Scenario 3 - Allocation by economic value	%	Cement CEM II/A	%
GWP-100	-8,56E-01	9,38E+00	1095%	1,46E+00	170%	8,56E-01	100
AP	-1,78E-03	4,81E-02	2697%	7,46E-03	419%	1,78E-03	100
EP	-4,32E-04	1,46E-02	3384%	2,27E-03	525%	4,32E-04	100
POCP	-6,98E-05	3,30E-03	4724%	5,12E-04	733%	6,98E-05	100
ODP	-2,13E-08	4,31E-07	2023%	6,69E-08	314%	2,13E-08	100
ADPN	-3,00E-07	2,40E-06	800%	3,73E-07	124%	3,00E-07	100
ADPF	-3,13E+00	8,07E+01	2577%	1,25E+01	400%	3,13E+00	100

[a] Silica fume is cement replacement.
GWP-100 - Climate change (kg de CO2-Eq. 100a); AP – Acidification potential (kg SO2-Eq.); EP - Eutrophication Potential (kg PO4-Eq.) ; POCP – Photochemical oxidation (kg etileno-Eq.); ODP – Ozone layer depletion (kg CFC-11-Eq.); ADPN - Depletion of abiotic resources – non fossil (kg antimônio-Eq.); ADPF - Depletion of abiotic resources – fossil (MJ-Eq.).

The Scenario 1 system expansion approach assume that 1 kg of SF could be applied in concrete production as an equivalent replacement of 1 kg cement CMII/A show negative results related to the avoided burden. This result is coherent since it is related to other markets. However, special attention should be given to issues regarding the availability of the by-product, because when we replace the main product (cement) with the by-product (SF), we assume "infinite" availability of the by-product, which does not occur because it belongs to a restricted production market. The worldwide generation of SF is estimated at 1.5 million tons, but today some of these materials are still not captured [22]. In an optimistic scenario assuming the capture of 70% of the generated SF (currently does not occur), the SF production would be 1.05 million tons [22]. This production represents approximately 0.13% of the world's cement production, which reached 818 million tons in 2016 [25]. This fact demonstrates that the market for SF production is restricted, and that it is therefore not appropriate to consider high cement replacement rates for this material because of its low availability in comparison to the large size of the cement market. Besides this, SF efficiency in concrete is not constant at all percentages of replacement [12].

The system boundaries of the LCA of multifunctional processes can be relevant in the results. In Scenario 2, allocation by mass value, the amount of by-product generated increases the percentage of impacts related to SF. These results prove the importance of the allocation method selection. In Scenario 3, allocation by economic value, the low sales value of SF in the generation point results in lower shareholdings (Table 1). The different allocation approaches can lead to significant result variability when economic parameters are applied. In contrast, mass relationships are controlled by the production process, which is tied to the main product's production process [7]. It is therefore quite straightforward and the mass ratios are mainly constant in time [9]. However, it is important to consider that allocation by mass induces large impacts on by-products that are used in the cement industry [7]. Hence, it could increase the impacts, influencing the interest to apply by-products as replacement. In this sense, the choice of system boundaries is closely related to the objective, including the activities relevant to the purpose of the study [26].

The use of pozzolanic material as SF in SCM has been consolidated. However, special attention should be given when the system expansion multifunctional modeling procedures are applied, because the avoided product functions can be equivalent to it but not equal. According to ASTM C 618 (1978) and NBR 12653 (ABNT, 1992), pozzolanic material is defined as a siliceous or silico-aluminous material which by itself has little or no cementitious property but when finely divided and in the presence of moisture, reacts with the calcium hydroxide at room temperature to form compounds with cementitious properties [1]. In this sense, SF may only partially substitute cement, in specific rates.

Despite the concern to reduce the environmental impact by replacing raw materials with by-products or residues, it is fundamental to guarantee the quality of the new product produced without causing losses in the durability and resistance [1]. In this way, the addition of SF to concrete protects the embedded steel from corrosion and improves the durability of concrete through reduction in the permeability and refined pore structure. This leads to a reduction in the diffusion of harmful ions and reduces calcium hydroxide content which results in a higher resistance to sulfate attack [12].

The lack of data affects the quality of the LCA application and emphasizes the importance of the quality of the available data of the unitary processes provided by the database, as well as its relation between the different productive chains.

4. Final remarks

The results enhance that the selection and understanding of the proper distribution model is key, due to their great influence on the results obtained. In addition, the evaluation of modeling choices and allocation systems is decisive, since they may influence the decision-making process. When the by-product allocation is not considered, an increase in fluxes in the main product is observed. In the system expansion, the avoided burden of by-product (in this case SF) replacing a virgin raw material, (in this case cement) with a by-product (in this case the SF) contains the assumption that the by-product is available for the entire world market. This inference may not be real, in this particular case, as the demand for clinker is considerably greater than the SF production, it seems like the system expansion is not suitable.

Finally, the importance of the modelling choice and its understanding must be highlighted, especially in product systems that deal with multifunctionality, to promote results that properly represent the evaluated products.

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Variability of environmental impact of ready-mix concrete: a case study for Brazil

Silva F B[1,2], Oliveira L A[1], Yoshida O S[1], John V M[2]

[1] Institute for Technological Research, Av. Prof. Almeida Prado, 532, São Paulo, SP, 05508-901, Brazil
[2] Polytechnic School, University of São Paulo, Av. Prof. Almeida Prado, Trav. 2, n; 87, São Paulo, SP, 05508-900, Brazil

fbsilva@ipt.br

Abstract. Life Cycle Assessment is a powerful tool towards sustainable construction, but it often relies on average impact results, failing to identify the dispersion of environmental impact among construction product manufacturers. This work presents cradle-to-gate impact results for ready-mix concrete production, based on primary data provided by several plants in Brazil, and the associated variability among plants and in the upstream processes of cement and sand production. Four compressive strength classes are considered. Concrete, cement and aggregates inventories are modeled with Brazilian information and other upstream processes are based on ecoinvent. EN 15804 impact categories are assessed. The ranges between minimum and maximum impact values can be as large as 7.2 times the average impact result of the analyzed sample, which shows that the variability among manufacturers is high and decisions based on average impacts may be highly misleading. For some impact categories, the differences among concrete plants (mix design, cement type and operational conditions) represent the highest contribution for variability, while for others the dominant variation comes from upstream processes, especially clinker production. These results indicate a high potential for process improvement and that manufacturer selection based on environmental performance can be an effective strategy for sustainable construction.

1. Introduction

Concrete is the most consumed manufactured substance on the planet [1]. It is a vital construction material, but also a key driver of many environmental impacts in the construction sector, including global warming potential [1], fossil fuels depletion [2], mineral resources depletion [3], water consumption [4], among others. Since concrete cannot be substituted by other construction materials on a large scale, it is essential to improve its environmental performance, which requires assessment methods capable of measuring the environmental impacts of concrete production and tracking the results of these improvement initiatives [5].

Life Cycle Assessment (LCA) suits well this purpose, due to its quantitative and comprehensive approach [6]. Many LCA studies on concrete have been conducted [2,7], with Life Cycle Inventories (LCIs) and Environmental Product Declarations (EPDs) for concrete and concrete products published in databases [8–13]. Most studies only disclose average impact values and therefore do not consider the variability of impact results among concrete producers or among suppliers of its raw materials

[2,7] and “average EPDs” are even accepted by standards [14–16]. Moreover, these averages are not necessarily calculated based on a statistically representative sample of the population.

However, studies show that the variability among construction material producers should not be disregarded. For concrete, differences in CO_2 emissions for the same strength class can easily reach 100 kg CO_2/m^3 [17] and be as high as 400 kg CO_2/m^3 of concrete, which is larger than the magnitude of the average emissions [18]. Different cement types and binder intensity explain these variations [19]. Furthermore, LCA studies on cement production show high variability among manufacturers [20,21]. Sand and gravel production also vary considerably in energy consumption and corresponding environmental impacts [22]. By adding the variability of the concrete production and of its upstream processes, impact values can significantly deviate from the average. In this scenario, selecting the optimum concrete source bears significant mitigation potential.

The aim of this work is to present and discuss cradle-to-gate impact results for ready-mix concrete production in Brazil and the associated variability due to differences between concrete plants, as well as variations in upstream processes, based on primary industry data.

2. Method

This study covers four concrete strength classes (characteristic compressive strength of 25 MPa, 30 MPa, 35 MPa and 40 MPa), made with two Brazilian cement types according to ABNT NBR 11578 [23][1]: CP-II-E (with addition of 6% to 34% of ground granulated blast furnace slag and up to 10% limestone filler) and CP-II-F (with addition of 6% to 10% limestone filler), with a 100 mm slump value.

Data about the concrete production process were collected via questionnaires responded by the managers of 34 ready-mix concrete plants, located in 10 different states of Brazil (predominantly in the state of São Paulo), on a voluntary contribution, under a confidentiality agreement. Each plant provided information about concrete mix design; consumption of water for the mixing and other purposes (such as mixer truck cleaning), electricity and diesel for internal equipment (such as loaders; the fuel used for mixer trucks is not included); consumption of other process inputs (lubricating oil, steel parts and rubber parts for replacing worn industrial equipment parts) and total concrete production for the year of 2017. These flows were informed based on plant controls per month, in order to avoid mistakes in the calculation of unit flows, which were done by the authors of this study. Validation of data was carried out by comparing the resulting inventories to literature data and existing datasets, and clear outliers were excluded.

Except for mix design and diesel consumption, some flows have not been reported by all plants. Electricity consumption, for example, was informed by only 79% of the plants. In such cases, the average of the reported flows was adopted for the plants that did not provide data for it. Although required, origins of raw materials to assess their transportation distances to the concrete plant were not informed, so they were approximated by the average distance informed by Brazilian concrete block manufacturers from their respective aggregate suppliers [22]. Despite covering multiple plants and regions, the data that were collected correspond to less than 10% of the national ready-mix concrete production volume for these strength classes [24] and this sample probably represents an optimistic estimate of the environmental performance of ready-mix concrete in Brazil, since it is composed of plants that agreed to deliver their data.

This data collection was part of a broader initiative to develop life cycle inventories for construction products in Brazil. Therefore, it was also possible to model the production of some raw materials based on primary data from the Brazilian industry, namely cement, including the production of clinker and the granulation and grinding of blast furnace slag, sand and gravel. For cement, data were collected from six Brazilian manufacturers, which represent about 70% of the national production volume, with plants distributed over the Brazilian territory, which allowed to assess the dispersion of impact results among cement manufacturers and plants. For natural sand, extraction from

[1] Superseded version, valid at the time of the data collection.

open pit and from riverbed sources were inventoried; however, each process was modelled using data from only one quarry, located in the South and Southeastern regions of Brazil. It was not possible to obtain variability information for gravel, since it was modeled using data from only one Brazilian manufacturer and one quarry.

Other upstream processes, such as the production of admixtures, provision of water, production of diesel, electricity and auxiliary inputs (lubricating oil, steel and rubber parts), were modeled using the ecoinvent database version 3.4, with the allocation system “cut-off by classification” and the geographical scope “Rest of the World” – except for electricity, since the Brazilian electrical mix is available in this database. The use of this database to provide part of the inventories, due to the lack of local data, has the drawback of underestimating the actual variation between companies, as discussed later. The variability of upstream processes modeled with the ecoinvent database was not taken into account, because uncertainty information cannot be considered representative for Brazil.

Cradle-to-gate life cycle impact assessment (LCIA) was carried out using the “CML baseline” method, considering the impact categories requested by EN 15804 [15]: abiotic depletion potential of elements (ADP-e), abiotic depletion potential of fossil fuels (ADP-f), global warming potential (GWP), ozone layer depletion potential (ODP), photochemical oxidation potential (POCP), acidification potential (AP) and eutrophication potential (EP); using the Simapro software version 8.5, excluding infrastructure processes.

Impact results were calculated for each mix design to assess the variability among concrete producers within a specific strength class, irrespective of the cement type, since in Brazil ready-mix concrete is usually requested by the strength class specified in the structural design and the cement type is chosen by the concrete producer (e.g. based on local availability). In this first step, upstream processes were modeled considering only their average values. Average, minimum and maximum concrete impact results were calculated from the sample, for each strength class.

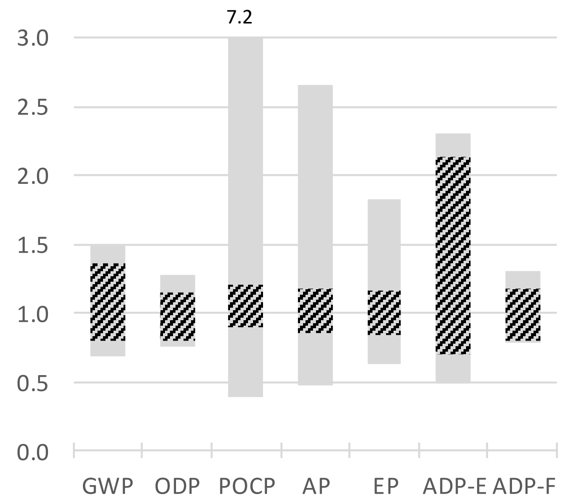
A second step was carried out, considering the minimum and the maximum values of the embodied impact of cement (dispersion among manufacturers) and sand (variation between two production routes), in order to assess the effect of upstream variability on the variability of concrete impact results. Overall minimum and maximum concrete impact results for each strength class were extracted from this second step of analysis. Variability propagation was done using a simplified approach, in which ranges were compiled by combining all minimum and all maximum values for the impact results [25]. This approach assumes that all cement and sand manufacturers may supply all concrete plants with equal probability, which is a rather conservative estimate.

3. Results

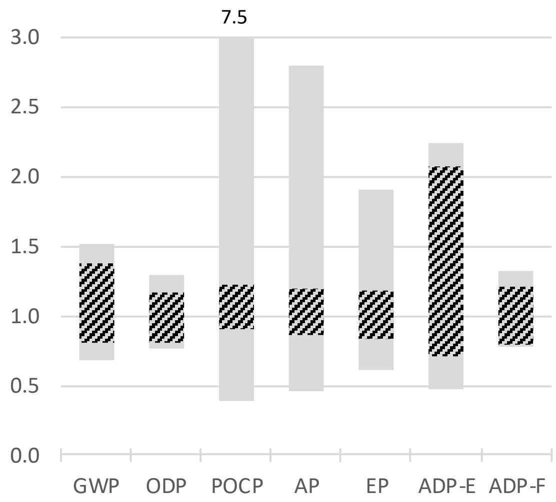
Table 1 shows an overview of the average impact results for 1 m³ of ready-mix concrete, by strength class. Figure 1 shows the ranges between minimum and maximum impact values, expressed as relative numbers to the average impact (which is considered equal to 1.0), including the range only among ready-mix concrete plants (hatched bars) and the range considering upstream variability (grey bars). Table 2 shows the variations in concrete mix, with the minimum and maximum content of each material considering the sample of concrete plants, by strength class; no distinction was made between cement types because the ranges of material contents of both cement types overlap.

Table 1. Sample average impact results for 1 m³ of ready-mix concrete, by strength class.

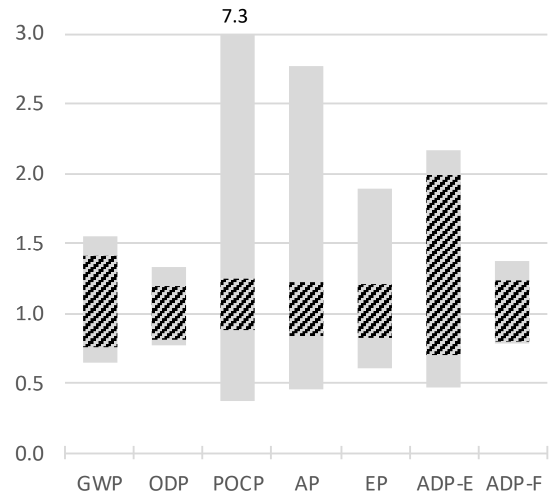
Impact category	25 MPa	30 MPa	35 MPa	40 MPa
GWP (kg CO_2 eq.)	196	220	248	295
ODP (10^{-6} kg CFC-11 eq.)	7.3	7.8	8.4	9.2
POCP (kg C_2H_4 eq.)	0.031	0.034	0.038	0.044
AP (kg SO_2 eq.)	0.74	0.80	0.87	0.98
EP (kg PO_4^{3-} eq.)	0.14	0.15	0.16	0.17
ADP-e (10^{-5} kg Sb eq.)	1.3	1.3	1.4	1.5
ADP-f (MJ eq.)	707	761	825	911



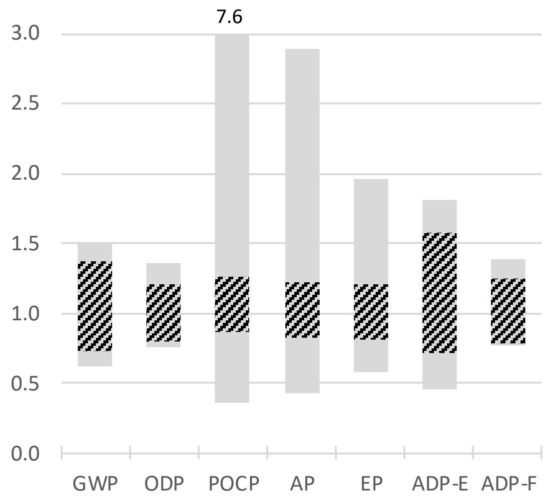
(a)



(b)



(c)



(d)

Figure 1. Impact result ranges relative to the average = 1.0; hatched bars: variation caused by differences among concrete plants; grey bars: variation caused by differences among concrete plants plus upstream variation (a) 25 MPa; (b) 30 MPa; (c) 35 MPa; (d) 40 MPa.

Table 2. Minimum and maximum content of materials in 1 m³ ready-mix concrete, by strength class.

Material	25 MPa		30 MPa		35 MPa		40 MPa	
	min.	max.	min.	max.	min.	max.	min.	max.
Cement (kg/m³)	216	304	251	350	268	408	307	476
Natural sand (kg/m³)	268	859	260	833	252	804	251	772
Artificial sand (kg/m³) [a]	0	651	0	633	0	613	0	540
Gravel (kg/m³)	1004	1193	1008	1201	1008	1176	1008	1232
Water (mix) (kg/m³)	167	209	167	209	170	209	165	209
Admixture (kg/m³) [b]	1.2	2.6	1.4	3.0	1.6	3.5	1.9	4.0

[a] Very finely ground gravel, inventory modelled as gravel.
[b] Plasticizer and polyfunctional admixtures.

Global warming (GWP) shows a considerable variation among ready-mix concrete plants, with minimum impact values up to 28% lower than the average and maximum impact values up to 41% higher than the average. The use of two different cement types, with different clinker content, along with variations in mix design (cement content) among producers (Table 2) explain the differences in the impact results. This variation corresponds to an impact range between 157 and 267 kg CO_2 eq./m³ for the 25 MPa strength class, i.e., a difference of 110 kg CO_2 eq./m³. This difference increases for higher strength classes, reaching 192 kg CO_2 eq./m³ for 40 MPa (between 213 and 405 kg CO_2 eq./m³).

For the impact categories ozone depletion (ODP), photochemical oxidation (POCP), acidification (AP), eutrophication (EP) and depletion of fossil resources (ADP-f), the ranges between minimum and maximum impact results are generally within the limits of ± 20% relative to the average impact. These variations can be attributed mainly to differences in the mix design, especially cement consumption (which varies between -10% and +26% relative to the average consumption) and gravel consumption (which varies between -21% and +27% relative to the average consumption), since these inputs significantly influence these impact categories in concrete production.

The impact category with the highest variability among concrete plants is abiotic depletion of elements (ADP-e), with ranges from 0.70 to 2.14 times the average impact result, because this category has a significant contribution from the steel parts' consumption for factory maintenance and this flow cannot be estimated with a good accuracy level by manufacturers.

By considering the variations in upstream processes, the total variability of concrete impact results increases, but in different proportions according to the impact category. For GWP, ODP and ADP-F, the increase in the coefficient of variation is rather small. For GWP for example, there is an increase of up to 71 kg CO_2 eq./m³ between those limits compared to the fluctuation among ready-mix plants (for the 40 MPa strength class). Direct CO_2 emission from the clinker production process is the major cause for GWP and this flow shows low variability among cement manufacturers (coefficient of variation of 3%). Fossil fuel consumption is also similar among cement producers, which explains the low upstream variability for ODP and ADP-F. For ADP-e, the increase in the impact range is not significant and the variability among concrete plants is still predominant.

For POCP, AP and EP, the contribution of upstream processes to total variability is much larger than the variation among concrete plants. For EP, the range increases from approximately 0.4 times the average to 1.3 times the average. This increase can be attributed to variations in NO_x emissions among clinker manufacturers (coefficient of variation of 65%), since NO_x emissions cause 85% of clinker EP impact and the clinker contributes for 91% (CP-II-E) and 94% (CP-II-F) of cement EP impact (on average). Variations in NO_x emissions during clinker production are also a major variability source for AP (NO_x corresponds on average to 46% of clinker impact), together with variations in SO_2 emissions in the same process (coefficient of variation of 128% among manufacturers, contribution of 44% for the clinker impact result, contribution of clinker of 94% for CP-II-E and of 97% for CP-II-F impact results). Maximum values for the AP impact category can be almost 3 times higher than the average. The extremely high maximum impact values considering upstream variability observed for POCP (up to 7.6 times the average) occur because some cement manufacturers use charcoal as fuel for clinker production and the charcoal production process has a high POCP impact; if those manufacturers were excluded from the sample, the variability level would be similar to the AP impact category.

Impact results per cubic meter of concrete increase with the increase in strength, due to the corresponding increase in cement consumption. However, if the reference unit is changed from 1 m³ to 1 m³ x 1 MPa, by dividing impact results by the declared characteristic compressive strength (which defines the strength class), impact results generally decrease for the higher strength classes, as presented in Table 3. It can also be observed that the level of variation of impact results is similar for the different concrete strength classes. This reference unit (1 m³ x 1 MPa) is closer to the functional unit concept of LCA, since it includes the strength provided by the concrete [18].

Table 3. Sample average impact results for 1m³ x 1 MPa of ready-mix concrete, by strength class.

Impact category	25 MPa	30 MPa	35 MPa	40 MPa
GWP (kg CO_2 eq.)	7.9	7.3	7.1	7.4
ODP (10^{-7} kg CFC-11 eq.)	2.9	2.6	2.4	2.3
POCP (10^{-3} kg C_2H_4 eq.)	1.2	1.1	1.1	1.1
AP (kg SO_2 eq.)	0.029	0.027	0.025	0.025
EP (10^{-3} kg PO_4^{3-} eq.)	5.4	4.9	4.5	4.4
ADP-e (10^{-7} kg Sb eq.)	5.1	4.4	4.0	3.7
ADP-f (MJ eq.)	28	25	24	23

4. Discussion

Absolute differences between best and worst producers are staggering. Even for impact categories with lower levels of variation, maximum impact values (worst environmental performance) can be up to 1.5 times higher than minimum impact values (best environmental performance), exclusively due to differences in mix design and operation variables of concrete plants. For GWP, the indicator that is recognized as a priority for cementitious products, the difference between minimum and maximum values can reach values from 110 to 192 kg CO_2 eq./m³, which correspond to approximately 60% of the average impact values. These ranges are comparable to the dispersion assessed by Damineli et al. [18] and by Park et al. [17] for cradle-to-gate CO_2 emissions for concrete. They are also of the same magnitude of the ranges assessed by Oliveira et al. [22] for cradle-to-gate CO_2 emissions among concrete block producers in Brazil.

The results demonstrate the large mitigation potential of selecting the best ready-mix concrete producers. Although the technology adopted by ready-mix concrete producers is quite similar (dry batching trucks), there is large room for process improvements aiming to minimize the environmental impact of ready-mix concrete, such as optimization of mix design. Even though it might not be possible for all manufacturers to reach minimum impact values (for instance, due to local aggregates' characteristics), it is likely that some reduction can be achieved with existing technology and management measures.

Another important aspect is the propagation of variability of upstream processes to final variability. This study considered only the variations for the production of cement and sand, for which primary data were available, although for sand variation reflects only the differences between two production routes. The contribution of the variability of cement impact to the variability of concrete impact is relevant, especially for those impact categories affected by NO_x and SO_2 emissions, for which high variation has also been reported in literature about cement production [7,20,26]. Because sand contributes with a maximum of 9% to the total impact of concrete, the variation between production routes did not have a significant effect on the variability of concrete impact results.

Gravel constitutes most of concrete's mass and contributes with up to 66% of concrete's impact results. If variability in gravel production had been considered [22], total upstream variability would be certainly higher, as well as the variations in transportation distances for the raw materials to the concrete plants. Despite the underestimation caused by lack of data for upstream processes, the contribution of upstream variability to the total variability detected is still significant. These findings regarding upstream processes offer an additional evidence of the potential of mitigation given by the selection of suppliers of construction products.

Furthermore, these results show that decisions based on "average" or "typical" impact values can be highly misleading. Nevertheless, assuming that these single values are representative of a technology is, unfortunately, a common practice in LCA [2]. In our case study, the minimum error of using average values can be of 10% (disregarding upstream variability) or 21% (considering upstream variability), while in the worst case, these deviations can reach values up to 114% (no upstream variability) and 658% (with upstream variability). For GWP, for instance, the difference in impact results considering upstream variability ranges from 158 to 263 kg CO_2 eq./m³ (the higher being 1.7 times the lower) which is a considerable level since it is almost of the same magnitude of the average impact. The variations observed are significantly above the level of variation recommended by ISO 21930 [14] for considering an “average EPD” valid, which is of ±10% of the environmental impact indicators, raising questions about the usability of those average assessments. By comparing technology options without considering variability between producers, one may select a product that looks better according to “average” values, but end up buying from a local producer that is actually much worse than its alternative.

Regarding uncertainty propagation, this work adopted a simplified approach of compiling ranges of extreme values, while there are more sophisticated techniques, e.g., Monte Carlo sampling. Although the probability of occurrence of extreme values is low (e.g., maximum cement content combined with maximum clinker content in cement and maximum emissions in clinker manufacturing), it is still possible since data were provided by existing suppliers. Therefore, the ranges presented here reflect the possible variations in ready-mix concrete impact results.

5. Conclusion

This works shows the high level of variation of life cycle impact results among some ready-mix concrete producers in Brazil, including both variations among concrete plants due to differences in mix design and among raw material suppliers. For GWP, the indicator most assessed for cement-based products, maximum impact values can be more than 2 times higher than minimum impact values. Depending on the impact category, total variability can be dominated by differences between concrete plants or by differences in the upstream processes.

It may be concluded that supplier selection based on environmental performance is a key strategy for reducing the overall environmental impacts in the construction sector, since bad performers will be forced by market conditions to improve their indicators, while good performers would be rewarded for their lower impact results. For decisions made when construction material suppliers are not yet defined, such as in early-design stages, the impact ranges must be considered when comparing technological alternatives and generic life cycle inventory databases must allow users to do so. This would allow LCA to effectively work as a sustainability promotion tool in the construction sector.

Acknowledgments

We would like to acknowledge the *Sustainable Recycling Industries* Program, the ecoinvent database and the Swiss Secretariat for Economic Affairs (SECO) for funding the data collection initiative for the development of life cycle inventories for construction products in Brazil, as well as the institutions involved in this project: IPT, USP, Unicamp, UFES, UFRGS and Quantis.

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Ecological performance and recycling options of primary structures

Fadai A, Stephan D
Vienna University of Technology, Department of Structural Design and Timber Engineering, Karlsplatz 13 / 259-2, A-1040 Vienna, Austria

fadai@iti.tuwien.ac.at

Abstract. A sustainably and optimally building material is defined consequently in a well-balanced relation between ecological aspects and structural engineering requirements and should be selected depending on external conditions. By choosing environmentally friendly building materials and joining techniques, at least resource-efficient and sustainable construction can be achieved. As a contribution to the discussion about which building materials offer the most optimal and environmentally friendly properties for the construction industry, this paper gives an overview of sustainable construction. It illustrates the advantages and disadvantages of certain building materials and structural components by comparing their mechanical properties and ecological aspects using various types of life-cycle assessment (LCA). As far as construction materials are concerned, e.g. wood-based materials have the greatest potential in terms of renewable primary energy demand compared to all other constructions materials. Furthermore, due to the high recycling potential, wood has the lowest share of non-renewable primary energy demand, whereas the highest non-renewable primary energy demand is caused by mineral building materials. This paper illustrates how the natural resources can be used both optimally and sustainably. It presents a conceptual framework for scenario development of the LCA of primary structures, their effect on the design and decision-making process.

1 Introduction

2017 greenhouse gas (GHG) emissions in Austria have risen for the third time in succession (cf. **Figure 1-1**). With 51.7 million tons CO_2-equivalent (not including any emission allowances from the European Union Emissions Trading System) the national goal was initially exceeded. In total, emissions rose to 82.3 million tons, which equates to a 3.3 % increase compared to 2016. This is due to the increased usage of fossil fuels in the energy and industry sector (plus 5.4 %) as well as the increased demand for the transportation of goods. Also the emissions attributed to the transportation and building sector have noticeably risen. On the contrary, the waste management industry and agricultural sector recorded falling emissions compared to 2016 [1].

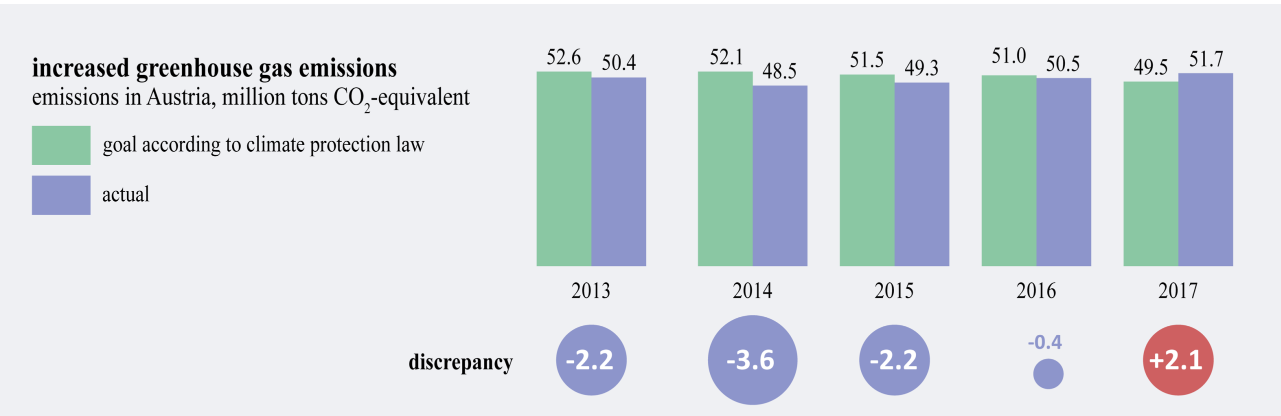

Figure 1-1 Greenhouse emissions in Austria from 2013 to 2017 [1]

1.1 State of the Art
An integral part of the European energy strategy is the increase of power efficiency. On one hand, the European council demands a 20% reduction of greenhouse emissions by the year 2020, compared to 1990 and a 20% share of renewable energy of the final energy consumption throughout the European Union. On the other hand, an increase of power efficiency is being demanded, so that the initial value for 2020 is undercut by 20% [2].

Particularly in the building sector, the focus lies on residential building. As a whole, residential buildings hold a high proportion of energy usage in this sector. But, thanks to the stricter requirements on new constructions in the past two decades and the reinforced funding conditions, the emissions induced by heating the buildings stayed relatively constant from 1990 to 2003 [2].

Nowadays the required energy standard of buildings according to building regulation is at the level of a low-energy house. By introducing the "Energy Performance of Buildings Directive", the European council established the basis for uniform valuation. These guidelines indicate that a building has to be sustainable, the used construction materials and components have to be recyclable and the use of environmentally friendly resources and secondary materials is welcome [2].

1.2 Deconstruction and recyclability
Recycling means employing the materials used for the construction and operation of a building after the initial use for a new purpose [3]. Waste products turn into secondary raw material. Easier dismantlability of an object into its components means that this object shows a better deconstruction [4]. Already in the planning stage of construction projects (cf. **Table 1-1**), recyclability of the materials has to be considered. Preferably, recyclable components or already recycled components should be used. In **Table 1-1** the life cycle phases of a building are classified.

Table 1-1 Life cycle phases of a building. [5]

Life cycle phases of a building																Additional information outside of the life cycle
A1-3 Product stage			A4-5 Construc-tion stage		B1-7 Use stage							C1-4 end of life cycle				*D* *advantages and liabilities outside of the system boundaries*
A1 Raw material supply	A2 Transport	A3 Manufacturing	A4 Transport to construction site	A5 Installation at construction site	B1 Use	B2 Maintenance	B3 Repair	B4 Replacement	B5 Refurbishment	B6 Operational energy use	B7 Operational water use	C1 De-construction and demolition	C2 Transport	C3 Waste processing	C4 Disposal	*Potential of reuse. Recycling and energy recovery*

The following factors concerning the recyclability should be considered [4]:

- Homogeneity
  Used building materials should be as homogenous as possible. The less different the materials are, the less differentiated the waste management is [3].
- Separability
  Material compounds which are easily separable, are ecologically valuable. Easily detachable materials increase the probability of a pure division and the recirculation into the substance flow [3].

- <u>Absence of pollutants</u>
  The use of building materials, that are harmful for the environment and the people, is being significantly reduced in sustainable construction. Moreover, the diligent use of unpolluted recyclable building materials optimizes the economic efficiency of the materials cycle and prolongs the material's lifespan [3].

The lifecycle of the construction alternatives is being analyzed according to EN 15978 "Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method". [6]

2 Life cycle assessment indicators

For the life cycle assessment of building materials, the following indicators are being calculated based on the German Sustainable Building Council (DGNB) [7]:

- Primary energy content PEI_{ne}, PEI_e [MJ]
- Global warming potential GWP [kg CO_2 – eq] calculated over a time horizon of 100 years
- Acidification potential AP [kg SO_2 – eq]

3 Systematic analysis of the environmental impact of building materials

The ecological attributes of the compared building materials originate from "IBU-EPD" [8], a standardized database for ecological evaluations by the Federal Ministry of Interior, Building and Community in Germany. Most of the available data refers to the life cycle phase A1-3 "production phase" (cf. **Table 1-1**).

Figure 3-1 shows the environmental impact of wood (oriented strand board, solid structural timber, medium density fiberboard) compared to bricks (insulating and non-insulating) and concrete (different classes of compression strength). The data indicates the environmental impact per m³.

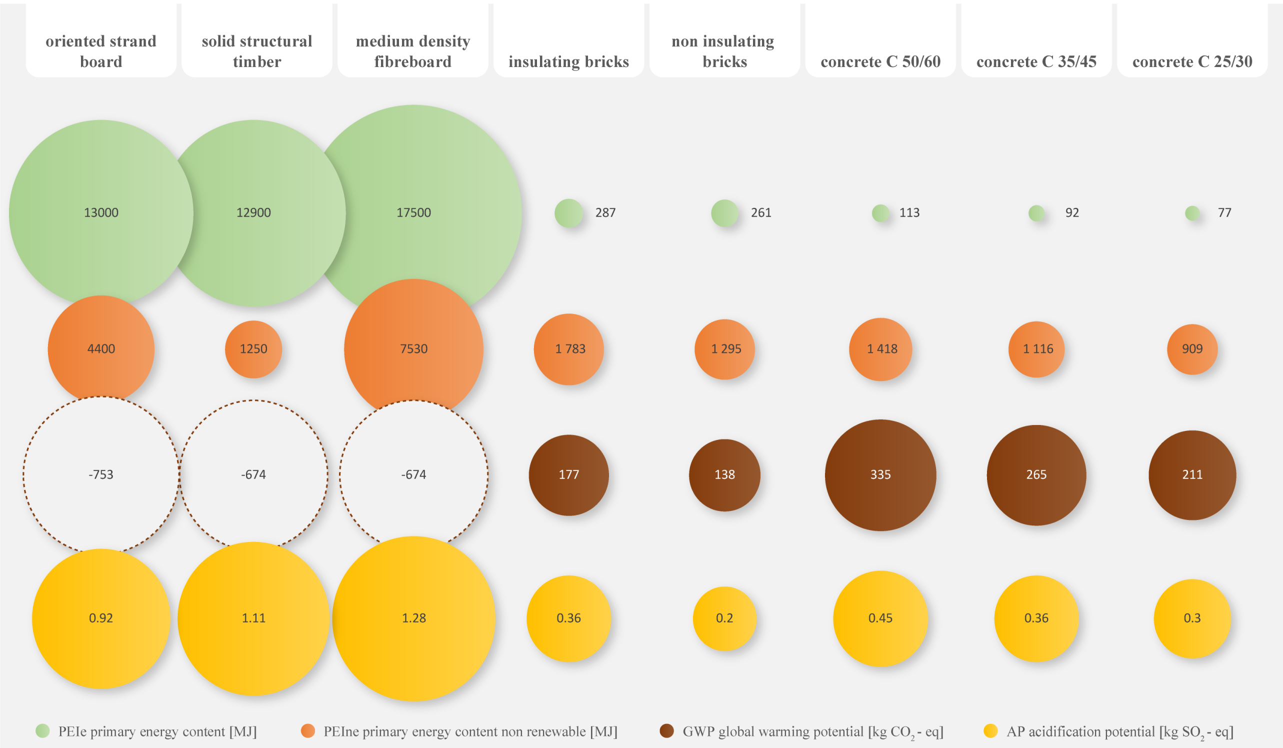

Figure 3-1 LCA indicators of building materials per m³ for the "production phase" A1-3.

Generally speaking, wood has relatively high primary energy content values in the production phases A1-3 (c.f. **Figure 3-1**). Nevertheless, compared to the other building materials most of the primary energy content is renewable. Bricks with a density of 740 kg/m³ have better environmental effects than those filled with pearlite (density 800 kg/m³). However, with the non-insulating bricks, an insulation layer with relatively high environmental impacts will most probably be needed later on. The environmental impacts of concrete increase with the compression strength. Concrete C25/30 therefore causes the least environmental effects whereas concrete C50/60 causes the most.

4 Structural elements

The ecological values of the compared structural elements also originate from "IBU-EPD" [8]. To ensure comparability all values are referenced to 1 m² of the component. The period of observation is 100 years and all life cycle phases, including phase D „*advantages and liabilities outside of the system boundaries*" are considered (c.f. **Table 1-1**). Furthermore, the structural elements were calculated referring to the location of Vienna.

4.1 Intermediate floors

Comparing the different versions of intermediate floor structures (c.f. **Figure 4-1**), it is noticeable that concrete structures have the lowest renewable primary energy consumption but nevertheless the highest non-renewable primary energy consumption. In contrast, timber floors have the highest potential in renewable primary energy consumption, while in most cases having negative non renewable primary energy consumption values, which counts as a credit for the rest of its life cycle.

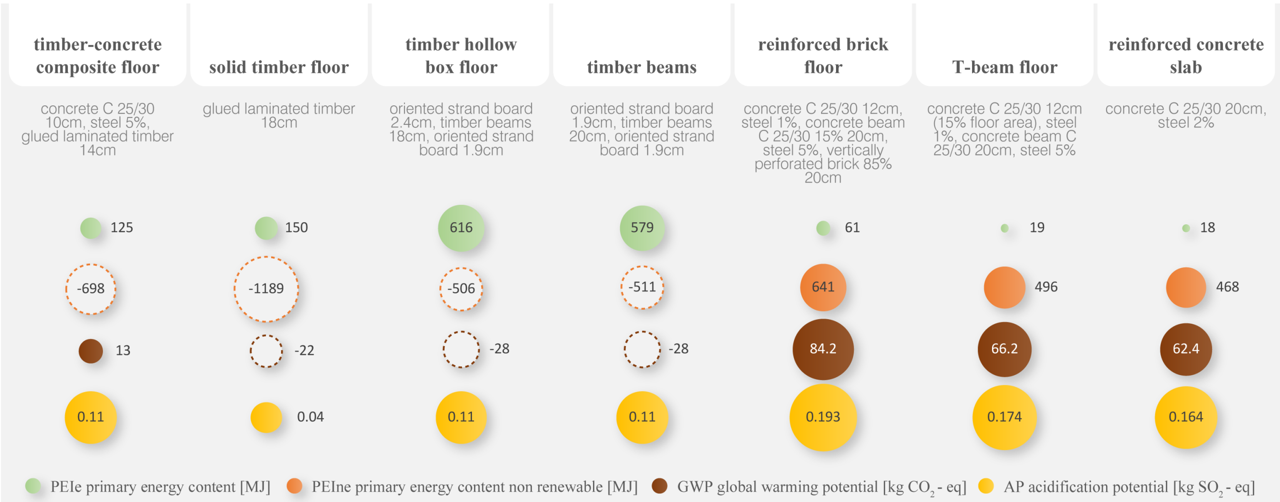

Figure 4-1 LCA indicators of intermediate floors (only constructions) per m² for the life cycle phases A-D.

4.2 Intermediate floors including floor assemblies

Concrete structures have a relatively low primary energy demand, but have the highest non-renewable primary energy demand (c.f. **Figure 4-2**). Especially, the T-Beam floor with cement screed and laminate hast outstandingly high values. By comparison, wooden floor structures have the highest potential for renewable primary energy demand and, in most cases, have negative values for non-renewable primary energy demand, which can be counted as a credit for the further life cycle. An example for this is the solid timber floor with cement screed and stoneware tiles.

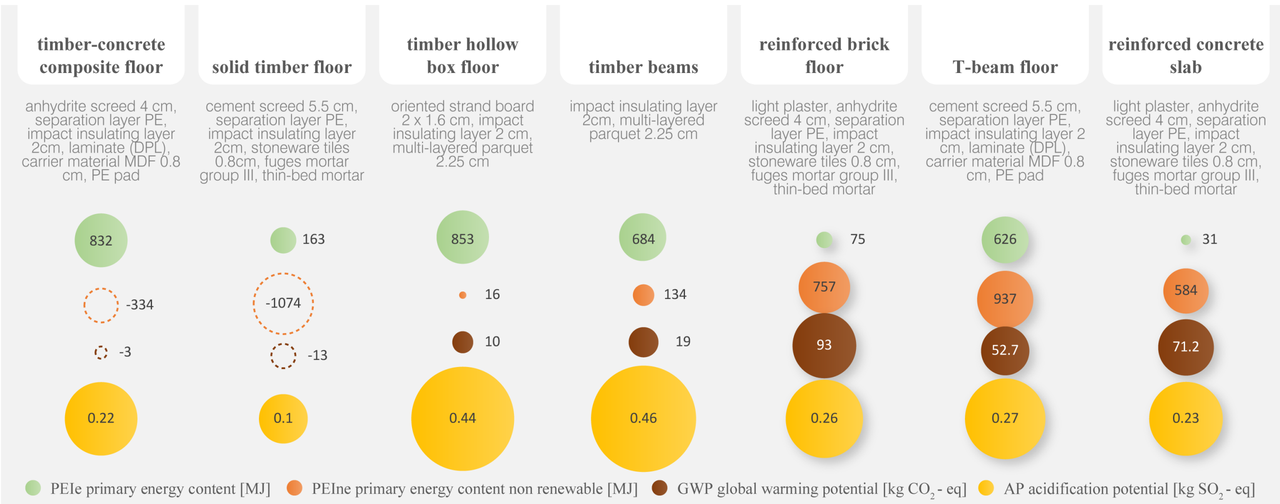

Figure 4-2 LCA indicators of intermediate floors incl. floor assembly per m² for the life cycle phases A-D.

4.3 Flat roof structures

Comparing the entire flat roof structures (c.f. **Figure 4-3**), it is noticeable, that the classic inverted roof has the highest ecological values in every aspect. The conventional warm roof performs the best. Merely the renewable primary energy consumption values are the same for all three roofs.

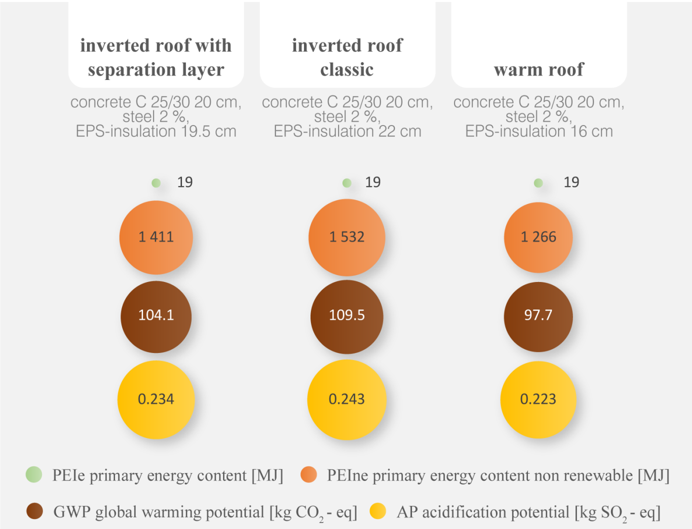

Figure 4-3 LCA indicators of flat roof structures (only construction) per m² for the life cycle phases A-D.

4.4 Flat roof structures including finished components

As shown in **Figure 4-4**, the classic inverted roof has the highest environmental impact in every aspect. A standard warm roof has the lowest values in all categories. Only in the case of the values for the renewable primary energy demand, the flat roof structures hardly differ. However, with regard to the roof construction it is noticeable, that the values of the individual roofs have become more similar.

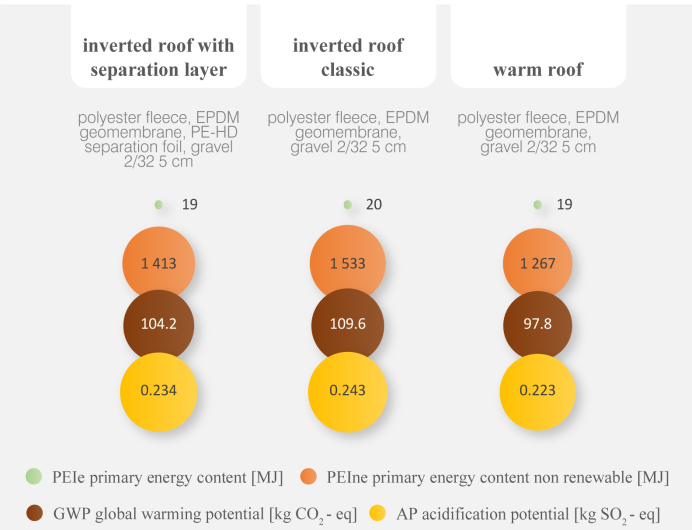

Figure 4-4 LCA indicators of flat roofs including finished components per m² for the life cycle phases A-D.

4.5 Opaque external walls

As shown in **Figure 4-5**, the renewable primary energy consumption values for brick and concrete walls in opaque external walls are the lowest, while their non-renewable primary energy consumption values are the highest. Timber constructions on the other hand perform better.

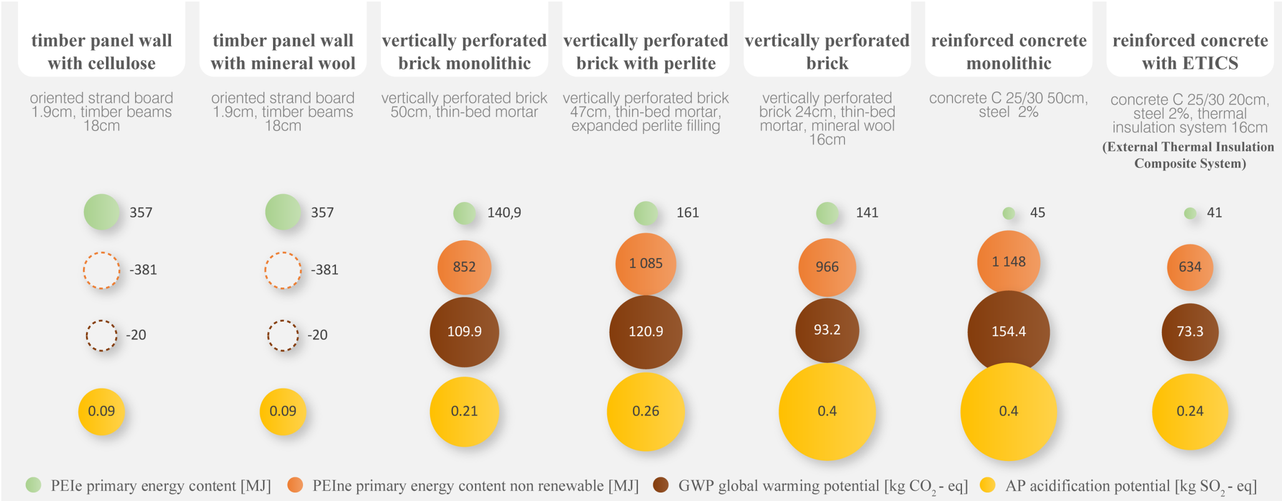

Figure 4-5 LCA indicators of opaque external walls (only construction) per m² for the life cycle phases A-D.

4.6 Opaque external walls including wall assemblies

Brick and concrete structures have the lowest values for the renewable primary energy demand, but the highest values for non-renewable primary energy demand. (c.f. **Figure 4-6**) Particularly, the reinforced concrete monolithic wall has a significantly higher primary energy demand than the other mineral wall structures. Timber constructions on the other hand perform better in this respect. Similar to intermediate floors, timber constructions consume a significantly lower amount of non-renewable primary energy.

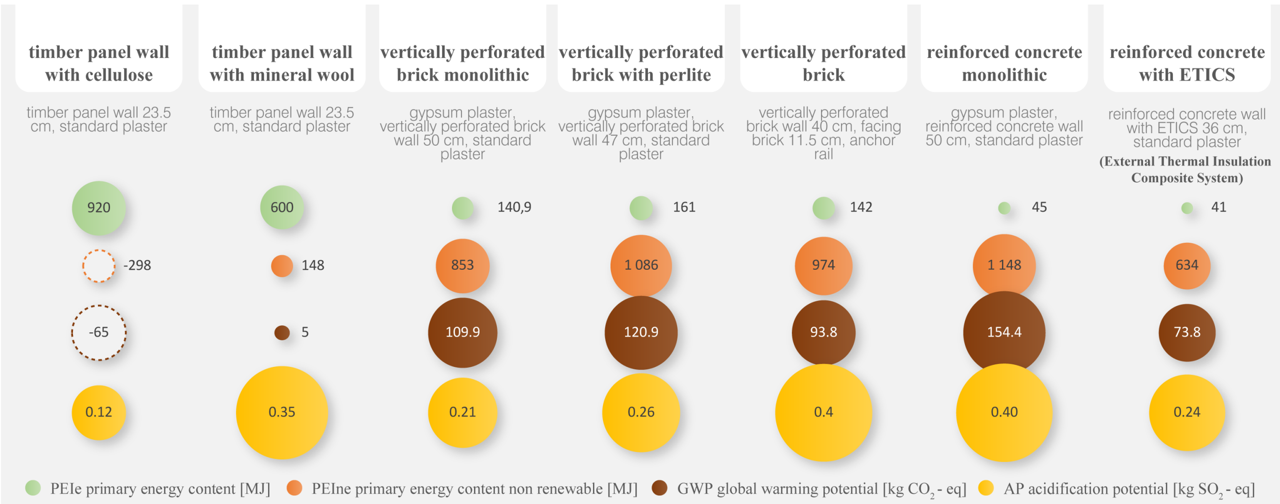

Figure 4-6 LCA indicators of opaque external walls including assemblies per m² for the life cycle phases A-D.

5 Case study

The case study consists of following components: the building site is in the yard of the main building of the Vienna University of Technology at the 4th municipal District of Vienna, Austria. The floor area of the building is 24 x 24m and is planned with two upper floors and a punctuated façade. The number of floors was chosen to give the investigation the best possible conditions. The total height of the building is 9.55 m, the floor height is 3.10 m and the clear room height is 2.70 m. The room has a floor area of 9 x 5.5m, is strained on one side and has a span width of 5.5m. The exterior design of the building (**Figure 5-1**) is a punctuated façade, which is plastered depending on the building type (bricks, ETICS = external thermal insulation composite systems) or on sight (exposed concrete).

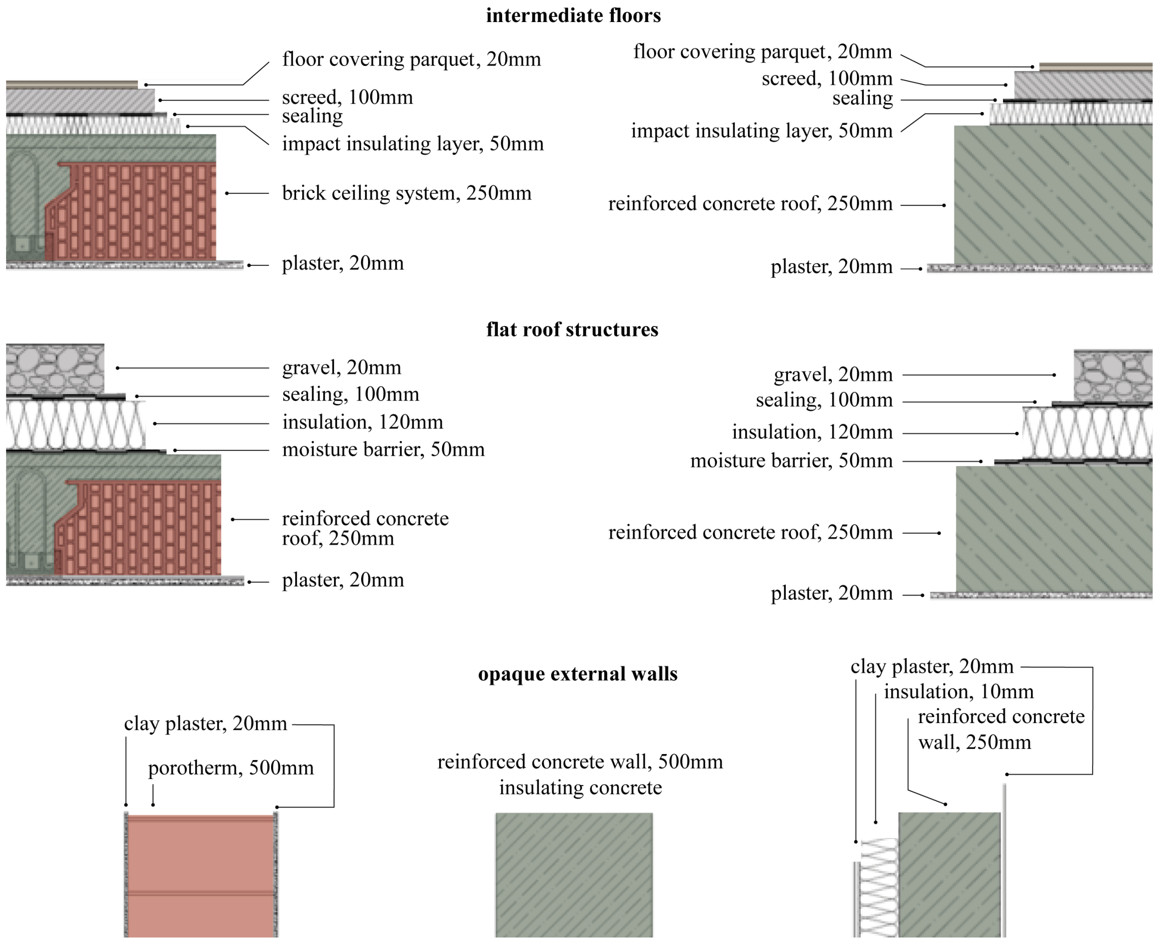

Figure 5-1 Detailed view of the chosen components

5.1 Optimization of material usage in the construction process

Both sustainability and ecological ideas should be understood as a process. To give an overview of the optimization measures in this process, individual planning strategies and processes are assigned to the generally valid planning phases: preliminary study, competition / preliminary planning, conceptual design / approval planning, tendering and contracting / implementation planning, execution / completion, handover / operation [9].

In the life cycle of materials, attention is paid to the use of resource-saving and environmental friendly building materials, whereas the focus in the building life cycle is on the adaptation of the intended use. In the material life cycle this means: use of permanently available resources, use of building materials with low primary energy consumption, use of pollutant-free and low-emission products, exchange of primary raw materials through recycling material, design optimization of the used components, preparation for reuse [9].

When optimizing use in the building life cycle, the following principles must be observed: adaptation to intended use, adaptation to durability and integration of efficiency enhancing designs, use of recoverable constructions, integration for possible conversion [9].

5.2 Component optimization of the construction model

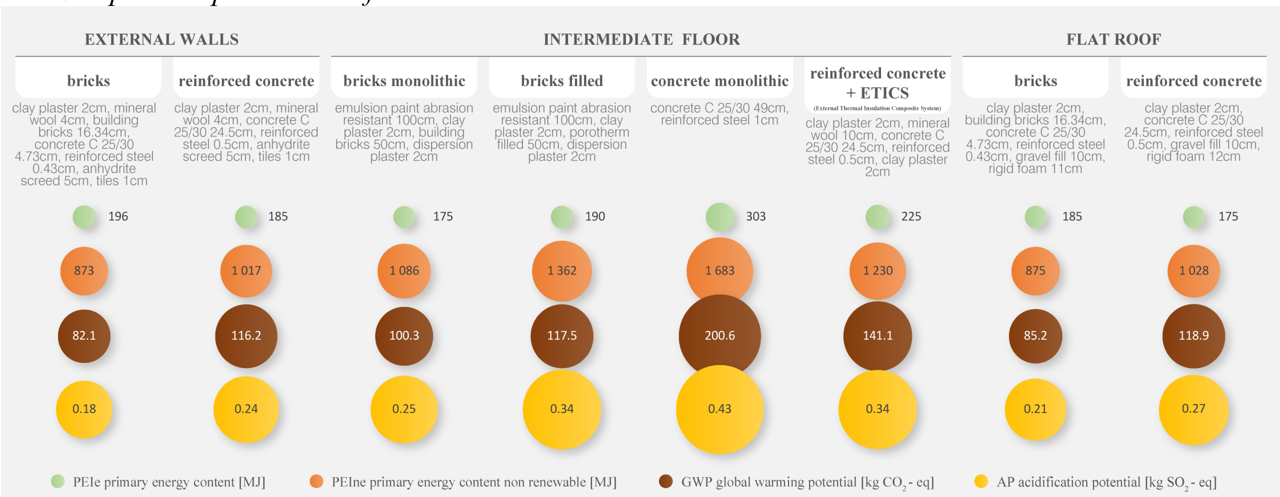

Figure 5-2 Life cycle assessment indicators of the construction model per m² for the life cycle phases A-D.

Based on necessary component optimization, the monolithic construction, both in concrete and in bricks, need more measures to achieve the summer suitability according to ÖNORM B 8110-3 [10] than constructions with a thermal insulation composite system. The concrete performs better within the particular construction. However, the best protection against summer overheating, regardless of building material, is nocturnal ventilation to get the indoor heat out of the room. It can be observed, that with an optimized design, the orientation of the room has little effect on the course of the operative room temperature.

The LCA in **Figure 5-2** shows that, among the selected parameters, the non-renewable primary energy consumption has the largest environmental impact. Within the chosen system boundaries concrete constructions tend to produce more environmental effects than brick constructions. For concrete, the monolithic variant has significantly higher environmental impacts than the insulated component, whereas for brick components the insulated brick components cause more environmental effects than the monolithic counterpart.

Overall, the calculations for the external wall reveal significantly greater differences in the component variants than would be the case with intermediate floors or flat roofs.

6 Conclusion

A sustainably and optimally building material is defined consequently in a well-balanced relation between ecological aspects and structural engineering requirements and should be selected depending on external conditions. By choosing environmentally friendly building materials and joining techniques, at least resource-efficient and sustainable construction can be achieved.

In the context of the building there are many aspects to be considered. Building materials are in a functional relationship with each other and with the construction structure. When assessing the overall situation, aspects such as location, climatic conditions, availability of renewable energy sources, user behavior or special need of the client play such an important role that they have to be taken into account when choosing the building materials.

The ecological performance and recycling options of the components are influenced to a great extent by both the choice of construction material and the insulating material, details and the type of construction in general as well as the methods of reusing and recycling them.

By selecting environmentally friendly building materials and joining techniques, at least resource-saving and sustainable construction can be achieved. Legal requirements and minimum standards will make the need to incorporate sustainable criteria into the planning process more relevant in the future. Nevertheless, it can be seen that today the results vary greatly due to different data bases. Each database and rating system is based on different criteria and objectives. Therefore it is advisable to deal with this early in the planning process and to adapt the objectives of the construction planning. Sustainable building planning requires holistic and flexible planning. Long-term thinking and matching the lifespan of building materials with utilization flexibility is essential for ecological construction.

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Overview of recycled concrete research through development years (2004-2018)

Xiao J[1], Singh A D[1], Duan Z[1], Pan Y[2], Qin J[3]

1. College of Civil Engineering, Tongji University, Shanghai 200092, China
2. China Construction Eighth Bureau Second Construction Co. LTD, Jinan, 250033, China
3. Linyi Lantai Environmental Protection Technology Co. LTD, Linyi, 276000, China

jzx@tongji.edu.cn

Abstract. Along with the urbanization process, large amount of construction and demolition (C&D) waste during the construction, reconstruction, expansion or demolition of buildings is generated. Meanwhile, the impact on environment due to natural aggregate mining has become increasingly significant. These factors have driven the building industry to look for environmentally friendly materials and focusing on sustainable construction. Through nearly a decade of research, recycled concrete (RC) made with recycled aggregates manufactured from construction and demolition (C&D) waste has shown a competitive performance compared to natural materials and has already achieved industrial application. Researches on sustainably recycled concrete have become an essential part of sustainable development and continue to play a vital role for future research.
This paper engages in the discussion and the overview of research done by the Research Group for Recycled Concrete Structures and Construction at Tongji University, Shanghai. The first part discusses the necessary mechanical and durability properties of recycled concrete with recycled aggregate as well as recycled powder focusing on workability, strength, Poisson's ratio, stress-strain behaviour along with carbonation, chloride penetration shrinkage and creep. The second part throws light on the elements and structures made with recycled aggregate concrete (RAC), discussing the behaviours of RAC components and structures.

1. Introduction

In recent years, large upscale of the construction sector and increasing requirement of advance and new habitats, caused by population growth and migration from rural to urban, have exploited a large number of construction materials. Environmental regulations and depletion of high-quality aggregates along with urgent need make natural aggregate the last option for the construction industry. Moreover, increase the cost of haulage from one place to another adds up to the increased cost of final construction materials along with explosive urbanization and increase modernization for alternate materials for construction. To reduce the impact on the environment and reduce the landfill space, it is of the dire need of finding an alternative for the construction materials in a friendlier and economical way. Moreover, to have a sustainable concrete industry, the attention should be paid to the conserve energy, resources, and environment protection.

In last decade, China has witnessed the significant degradation of natural resources. There has been a massive generation of C&D waste, which accounts for the 500 million tons of waste generated annually [1,2] as shown in Figure 1. Recycled aggregate concrete (RAC) being a sustainable material on one side, also helpful in saving the ecology by reducing the use of natural aggregates (NA). Literature suggests that the mechanical properties of recycled aggregate (RA) may be lower than those of normal concrete (NC) generally, but can be utilized in practical application for the structural purpose [3–5]. Studies prove that there are differences between the properties of recycled coarse aggregate (RCA) and natural coarse aggregate (NCA), due to some physical properties like rough and porous surface, reduced bulk and apparent density, increased porosity and adhered mortar on aggregates. These properties impact on the crushing value, soundness, and water absorption of aggregates, which are bases for the strength indexes of any concrete [5–9]. At present, implementing RAC is still at a demonstration phase, but our group has focused the research from 2004 onwards on RAC studies, thru micro-, meso- and full-scale structure.

2. RAC materials

2.1. Strength indexes

The compressive strength is one of the most essential mechanical property, which is the basis for the differentiation of RAC as compared to natural aggregate concrete (NAC). Due to difference in the physical properties between RCA and NCA compressive strength is the most important mechanical property. Based on the overall analysis of the results at early stage the compressive strength of RAC follows a similar pattern with NAC when undergoing curing.

For the evaluation of factors influencing the strength indexes and research has been carried out a test on more and 635 cube specimens in the concrete materials research laboratory, Tongji University, China. During the research phase of concrete with RA, various mixes were made using the different replacement ratio. This paper represents the review of the work done by the research team in Tongji University. Mixes with the different water-cement ratio (w/c) and the obtained results are shown in Figure 2, which shows the relative cube compressive strength at 28 days concrete strength of RAC which was cured in fog room (20±2 °C, 95% relative humidity). Figure 2 shows that the development of compressive strength coefficient before 28 days curing of RAC is higher than that of NAC. Whereas, the strength development coefficient after 28 days of curing of RAC is less than that of NAC. The reason being that additional water absorption of RA tends to provide additional internal curing in RAC than NAC. Another factor influencing the compressive strength is the weak bonding between the recycled concrete aggregate (RCA) and the new and old mortar. At the same time, higher w/c ratio leads to excess water in the pores of RCA [1,10].

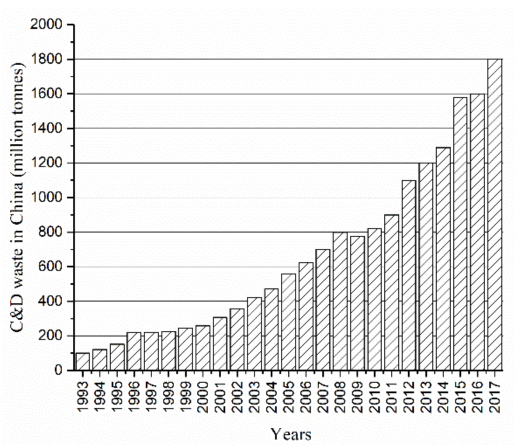


Figure 1: C&D waste generation in China [1,2]

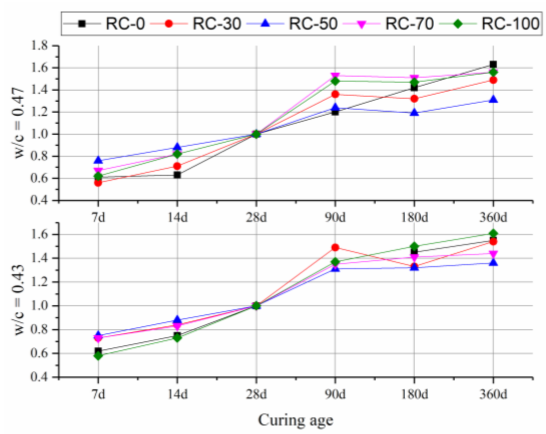


Figure 2: Relative cube compressive strength at 28 days

The results were analysed using a statistical approach to compare the outcome of RAC with NAC, which followed a normal distribution. The analysis showed that the coefficient of variance (COV) of compressive strength is not very large as compared to NAC, proving that the RCA replacement does not influence the RAC's compressive strength variation coefficient. Furthermore, to check the feasibility of a normal distribution model, Monte Carlo simulation was used for evaluation of strength distribution of RAC and probability density function (π(σ)) for concrete compressive strength of RAC was obtained:

$$\pi(\sigma) = \frac{1}{\sqrt{2\pi}\sigma_\sigma} e^{-\frac{(\sigma-\mu_\sigma)^2}{2\sigma_\sigma^2}} \qquad \text{Eq. 1}$$

Where, the average value of the standard deviation of compressive strength μ_σ =4.31 MPa, and the standard deviation σ_σ =1.1141 MPa. Furthermore, the Bayes estimation was used to get the SD for the various strength grade as shown in Table 1, but considering the situation the mixing plants, SD of RAC30 was kept at 5.0 MPa, which is closely identical to that of NAC but only applicable to the RCA from a single source which can control the quality of RCA.

Table 1: The Bayes estimation results of the standard deviation for RAC C30 compressive strength

***r* (%)**	0	30	50	100
σ (MPa)	4.31	4.5	3.95	3.2

On further analysis, after the comparison between the experimental and simulation data, the following relationships between the splitting tensile strength and the compressive strength, flexural strength and the compressive strength of the RAC are shown in Eq. 2 and Eq. 3 respectively [11].

$$f_{sp} = 0.24 f_{cu}^{0.65} \qquad \text{Eq. 2}$$

$$f_f = 0.75\sqrt{f_{cu}} \qquad \text{Eq. 3}$$

Where, f_{cu} is the compressive strength in MPa, f_{sp} is splitting tensile strength in MPa and f_f is the flexural strength in MPa.

2.2 Constitutive relationship

For the constitutive relationship between various parameters of concrete, with an investigation on a stress-strain curve with/without confinements [12], axial loading [13], shear loading [14] and impact loading [15] along with shear transfer behavior and compressive behavior of RAC under high strain rate. During testing, strain rate of the test specimens was kept constant to 44×10^{-6}/s and Eq. 4 [16] was used to represent the axial loading constitutive model for the linear analysis of the RAC structure and members:

$$y = \begin{cases} ax + (3-2a)x^2 + (a-2)x^3 & 0 \le x < 1 \\ \dfrac{x}{b(x-1)^2 + x} & x \ge 1 \end{cases} \qquad \text{Eq. 4}$$

The values attained a and b using the statistical data are:

$$a = 2.2(0.748r^2 - 1.231r + 0.975)$$

$$b = 0.8(7.6483r + 1.142)$$

1.

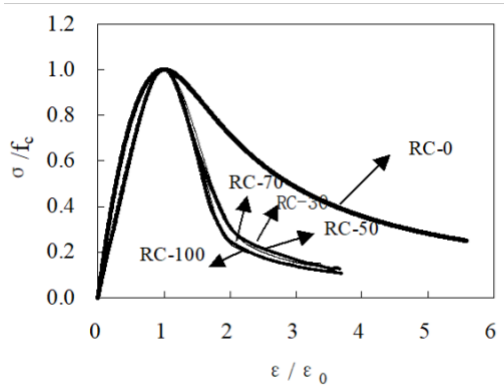


Figure 3: Normalized stress-strain curve for recycled aggregate

Where, $x = \varepsilon / \varepsilon_0, y = \sigma / f_c$ from a normalized recycled concrete stress-strain curves as shown in Figure 3, a is the initial gradient line non-dimensional curve, it reflects RAC's initial modulus of elasticity, b the value is related to the non-dimensional dropping stage of the curve area, representing the ductility of concrete and r is the replacement ratio of RCA.

2.3 Long term properties

In real conditions, the materials are usually exposed to prolong loading or cyclic loading during the design life of a structure. The first and far most important long-term property is shrinkage and creep. Test were carried out as per GB/T 50090-2002 [17]. The shrinkage and creep of RAC with four different replacements ratio of 33, 66 and 100% are 2.6, 15.4 and 26.9% and 28.7, 75 and 103% higher than that of NAC respectively, whereas environment has no drastic impact on the shrinkage and creep of RAC [18]. Mineral admixtures, water-reducing agents, bulking agents, etc. can reduce shrinkage deformation, whereas old adhering mortar cannot be ignored when calculating the creep of RAC because creep characteristics of RAC are influenced significantly by the content, elastic modulus, and creep behaviour of the old adhering mortar.

Evaluation of carbonation and chloride diffusivity are by Chinese codes GB/T50082-2009 [19] which are the second most long-term property. The porosity and attached mortar, which is higher in RCA than natural aggregate along with the same w/c ratio, can improve the carbonation resistance. Based on ghe esisting formula from *fib* carboantion model [20], Chinese code's model [21], Zhang and Jiang's model [22], Xiao and Lei [23] represented two modified carbonation models, namely Xiao and Lei Model 'a' (Eq. 5) and Xiao and Lei Model 'b' (Eq. 6). These models are based on the factor, replacement percentage, which is an important factor in prediciton of carbonation depth.

$$x_c(t) = K_{CO_2} \cdot K_{k1} \cdot K_{ks} \cdot T^{0.25} \cdot RH^{1.5} \cdot (1 - RH) \cdot \left(\frac{230}{f_{cu}^{RC}} + 2.5 \right) \cdot \sqrt{t} \quad \text{Eq. 5}$$

$$x_c(t) = 839 \cdot g_{RC} (1 - RH)^{1.1} \sqrt{\frac{W / \gamma_c C - 0.34}{\gamma_{HD} \gamma_c C} n_0} \cdot \sqrt{t} \quad \text{Eq. 6}$$

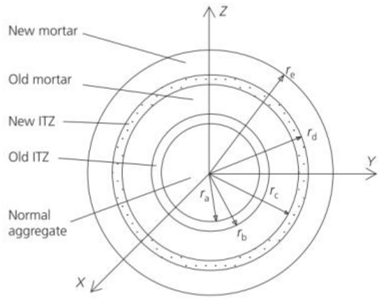


Figure 4: Five-phase composite model of RA

where $x_c(t)$ is the carbonation depth of concrete at time t, in mm; W is the water content (kg/m^3); C is the cement content (kg/m^3); γ_c is the coefficient for cement type (1.0 for Portland cement); γ_{HD} is the coefficient of the degree of hydration (0.85 for 28 days' curing, 1.0 for 90 days' curing); and n_0 is the CO_2 concentration by volume (%); K_{CO2} is the factor of CO_2 concentration, $K_{CO_2} = \sqrt{\frac{n_0}{0.02}}$; K_{k1} is the location factor, 1.4 for corner and 1.0 for another place; K_{ks} is the stress factor, 1.0 for compression and 1.1 for tension; T is the temperature (°C); RH is the relative humidity; f_{cu}^{RC} is mean value of RAC compressive strength; and g_{RC} equals to 1.0, while for RAC with a 100% replacement percentage of RCA, g_{RC} equals to 1.5. On the other hand, for chloride diffusivity, the experimental and theoretical data are generally in agreement with Fick's second law similar having a deviation from NAC. Moreover, Xiao et al. [24] proposed a model that considered RAC as a five-phase composite model (Figure 4) [25] in order to describe the chloride diffusion coefficient (D_{eff}) in RAC (Eq. 7 and Eq. 8). Based on the residual mortars, which is the critical factor, the RAC will become NAC when the attached mortar value is less than the threshold value of 0.5.

$$D_{eff} = \frac{x^2}{4\left[erfc^{-1}\left(\frac{C_{mean}}{C_s}\right)\right]^2 t} \quad \text{Eq. 7}$$

$$C_T = \int_{-5mm}^{+5mm} C(5,y)dy \quad \text{Eq. 8}$$

where C_s is the boundary conditions of chloride concentration (x10^{-1} mg/mm^3), and erfc^{-1}() is the inverse complementary error function, C_{mean} is the mean value of C_T at the position of x and the mean value of chloride amount along the boundary X = 5 mm is calculated by Cmean = CT ÷10 mm.

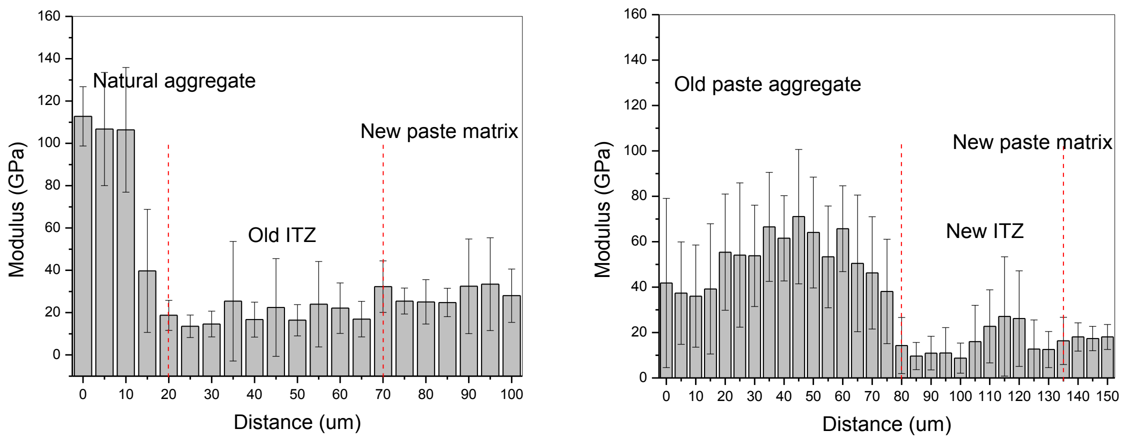
Theoretical equation, finite element method (FEM) and simulation on modeled RAC (MRAC) [26] showed that D_{eff} decreases with the rise in RCA volume fraction, but increases with the adhesive rate of the old mortar adhering and the thickness of the ITZ.

3 New types of RAC

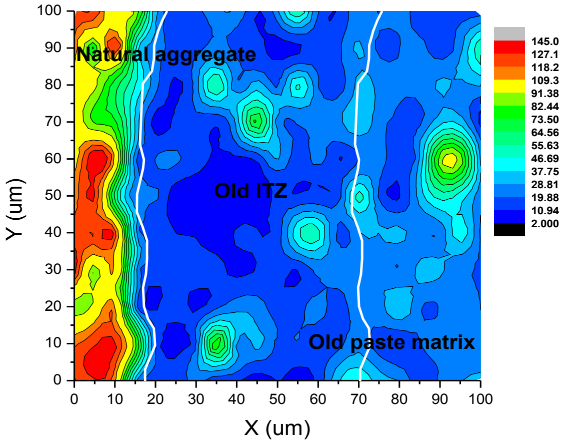
3.1 Modification of conventional RAC

Compared to traditional concrete, it is hard to predict the properties of RAC on a direct basis. Investigators have found that a two-stage mixing approach (TSMA) have improved the mechanical properties and durability of RAC [27]. Nano-indentation was used to evaluate the microstructural and nanomechanical properties of ITZs in RAC prepared with different mixing approaches. The contour variation of indentation modulus histogram is seen in old ITZ and new ITZ with TSMA (Figure 5). The result proves that TSMA can effectively reduce the size and effect of water layers, reducing the amount of porosity enhancing hydration. TSMA also produce a stronger and denser ITZ due to the calcium carbonate crystals covering the RCA surface [28].
Moreover, it should be noted that modulus distribution with age of old and new ITZ is different. The properties of old ITZ in RAC do not change with the hydration age, while the indentation modulus of new ITZ and new paste matrix increases with the curing age

Nano-SiO_2 and nano-TiO_2 particles were also used to enhance the properties of RAC. Due to the large specific surface area and high activity [29], nano-particles helped in refining the pore structure of RAC. The pore structure increases and then decreases up to an extent with increasing content. Results proved that 2% addition of nano-TiO_2 is slightly better than nano-SiO_2 [30]. Moreover, hydrated cement in old ITZ between gravel and cement paste (OITZ), the calcium silicate hydrate (CSH) having a short rapid growth and decline rapidly, whereas in new ITZ between new and old cement paste (NITZ) the rapid growth is close to zero and begin with a relatively high generation of CSH gel.



(a) (b)



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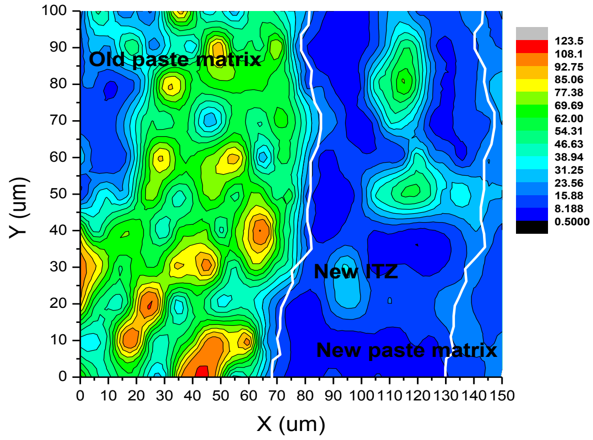

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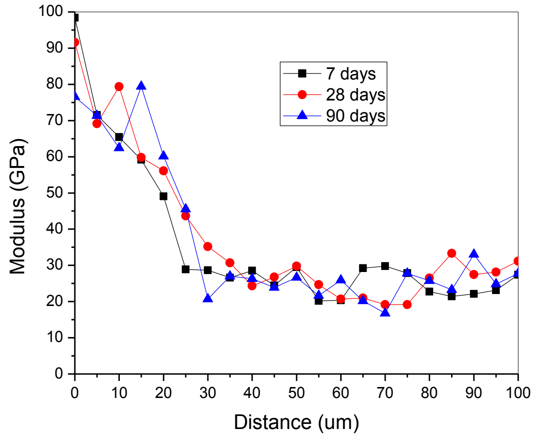

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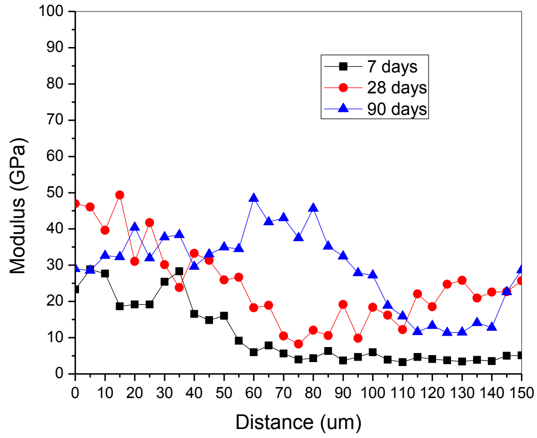

(f)

Figure 5: Modulus distribution across (a) old ITZ (b) new ITZ with TSMA, Contour map of indentation modulus across (c) old ITZ and (d) new ITZ with TSMA, Modulus distribution across (a) old ITZ (b) new ITZ with TSMA at different hydration ages

3.2 Sea-water and Sea-sand RAC

Based on the previous studies and sustainability issues, the combination of seawater, sea-sand, and RCA was investigated. The focus is on the demolition of the structures from coastal and the marine regions, which suffer the corrosion from chemicals like chloride, and hard to separate the harmful chemicals from the waste. So, this kind of concrete can be used to deal with resource exhaustion and the disposal of waste concrete [31]. Two additional types of sea-sand with seawater is used for mixing of concrete. Various concrete mixes were cast and tested for the mechanical properties of properties were examined. The concrete produced with sea-sand, seawater, and RAC showed good cohesion, required workability, increased behavior of early strength is noted but delayed in the underlying strength. Moreover, an increase in 8%-16% of elastic modulus is observed in the concrete made with sea-sand, seawater, and RAC, following the models for strain and strain by previous researchers and specifications [10,32]. Figure 6 and Figure 7 represent the compressive strength, split tensile and variation between split tensile and axial compressive strength of concrete made with sea-sand, seawater, and RCA.

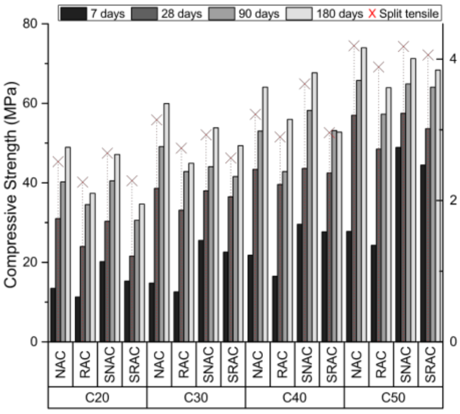

Figure 6: Variation between the strength of different strength grade

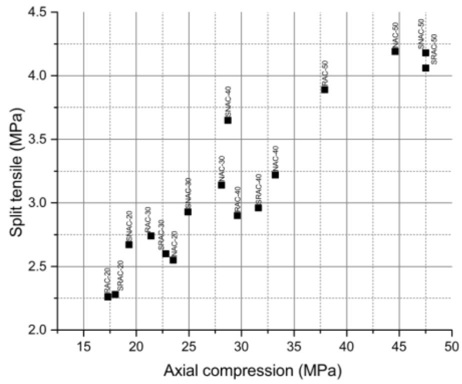

Figure 7: Variation between axial and split tensile strength

4 RAC structures

4.1 Flexural and shear properties

Properties may differ due to different mix proportions and different replacement percentage of RA. Based on these, semi-precast elements are better in quality as compared to precast hybrid-components. Flexural and shear specimens were cast with U-shape and C-shape precast beams, regular and eccentric columns and slabs for shear. Based on the assumptions of “plan cross-section” and the results, plane section assumptions remain valid in applications for semi-precast beams made of RAC and follows the Chinese code DG/TJ08-2018-2007 [33]. Based on the reliability analysis, beams showed that the reliability was lowest and highest when 100% permanent and 100% live load was applied respectively [34]. In bending behavior of RAC beam, diagonal cross-sectional area cracking load is smaller than NAC. Also, the cracking pattern, deflections, and bearing capacity of U-, C-shaped beams are similar to that of NAC beams with no adverse effects on flexural performance. Along with RAC columns under axial and eccentric compressions, the RAC column showed failure by axial compression, small eccentricity compression failure, limit failure, and large eccentric compression failure, and the increase in the RCA replacement percentage did not cause any change.

4.2 Seismic performance

Based on the test on the precast elements, under cyclic loading, the characteristics of the RAC elements are the same as that of NAC. The ductility coefficient of fully cast-in-situ is more than that of semi-cast columns, along with better ductility of external elements than internal. These results conclude on the full-scale test on the elements with a generation of hysteresis loops. In this study, understanding of structural behaviour of frames under low-frequency cyclic lateral load with constant vertical actions. Based on these the failure pattern, the hysteresis curves, the skeleton curves, the energy dissipation capacity, and the stiffness degradation laws of frame structures with RAC were examined. The failure of the frames is characterized in a manner of “strongest joints, stronger columns and weaker beams” because the ductility coefficient was about 4.0 implying the fine ductility of the structural frames [35]. Whereas, RCA has no remarkable effect on the energy dissipation capacity of frames and is good enough to resist earthquake according to Chinese standard GB 50011-2001 [36].

5 Life cycle assessment

Apart from the specifications, and technical objectives, the drive toward sustainable development leads to the methodological framework and the life cycle assessment (LCA). From the time of introduction from 1994, International Standard Organization (ISO) played an essential role in the area of multi-criteria optimization for NAC and RAC, based on their local life cycle inventory (LCI) [37–41]. The research was focused on the feasibility of aggregate delivery and production and is based on ISO 1404

(2016) and ISO 14044 (2006) [37,39]. In this study, the data for regional LCI for NAC and RAC collected and comparative study was made between both with 50% and 100% replacement ratio to have a rational understanding of LCA [42]. To be more precise the cradle-to-grave theory was adopted to change it to cradle-to-cradle (Figure 8) shows the methodologies. Another method for the LCA based on the CO_2 absorption model is evaluated. Effect of NAC replacement with RAC on the carbon footprint of a tall structure having 12 floors and area of 15000 m^2 were investigated. The system boundary used in this study, as shown in Figure 9. In this whole study, the pre-wetting RCA were used to provide the required additional water.

It should be noted that utilizing non-local LCI data for estimation of carbon emissions. The assumption was made on the choice of NAC or RAC as the new building material, which has been the determining factor which affects the choice of waste processing strategy, recycling vs. landfilling, for the container terminal. Based on these, the end-of-life phase of the demolished project was considered. The RAC and NAC structures emitted on average 2.152×10^6 (i.e., 143.47 kgC_e/m^2 or 366.64 kgC_e/m^3 of concrete) and 2.302 $\times10^6$ kgC_e (i.e., 153.47 kgC_e/m^2 or 392.20 kgC_e/m^3 of concrete), respectively. Furthermore, these two towers led, on average, to 8.345×10^6 MJ (i.e., 556.32 MJ/m^2 or 1421.71 MJ/m^3) and 8.907×10^6 MJ (i.e., 593.78MJ/m^2 or 1517.45MJ/m^3 of concrete) embodied energy, respectively. Based on the RAC's environmental benefits and reduced embodied carbon, energy consumption, need of natural resource and C&D wastes processing and its competitive structural performance, the result highlights RAC as a sustainable alternative to NAC. The carbon emission implications of RAC were found to be highly dependent on landfill and transportation phases.

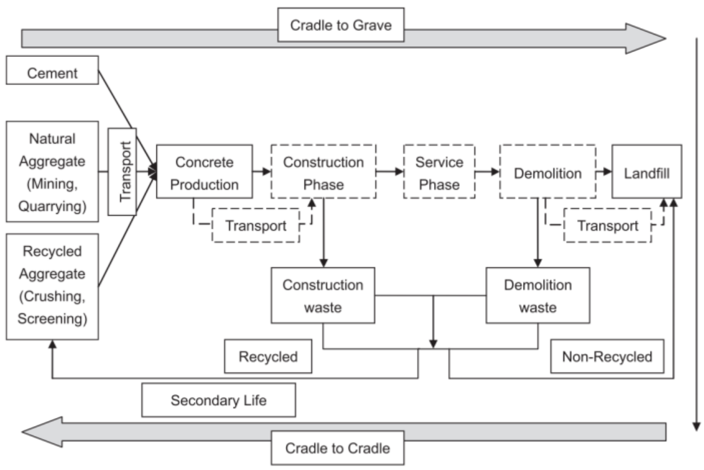

Figure 8: Methodologies from cradle-to-grave and cradle-to-cradle

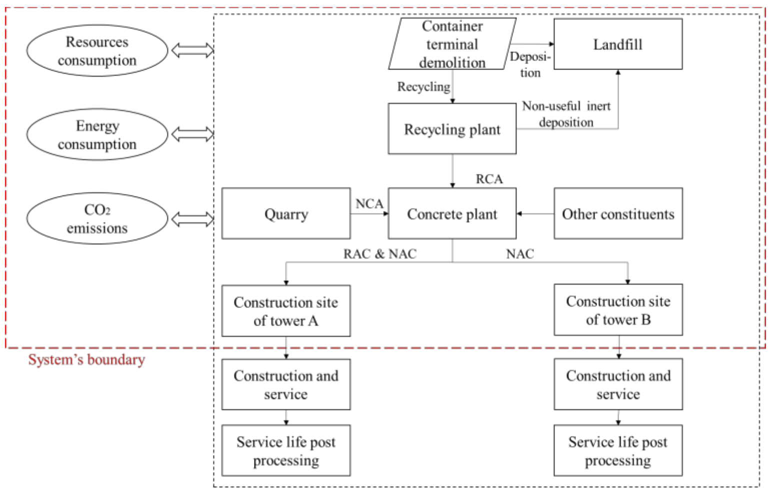

Figure 9: System's boundary and LCI analysis based procedures

6 Conclusions

Based on the experimental results and analysis, the main findings can be summarized as follows:

The structural behaviour of RAC elements/members has inferior properties as compared to members or structures made with NAC. Tensile and shear strengths of RAC are generally lower than those of conventional concrete, modulus of elasticity for RAC generally reduces as the RCA content increases; however, the strain at peak stress is larger than that of conventional concrete. Additional modification parameters such addition of nano-SiO_2 and nano-TiO_2 helps in enhancing the durability, chloride diffusion resistivity. Whereas, the modification with carbonation proves to be beneficial for enhancing the interfacial properties of RAC. Sea-sand and seawater minimum affect the workability and accelerate the strength development at an early age due to higher chloride content. Addition of three components (sea-sand, seawater, and RCA) is expected to enhance the sustainability of concrete structures at a greater level.

Further investigation on LCI and LCA showed that carbon emission implications of RAC were found to be highly dependent on the transportation phase. Also, with the continuing expansion of cities and the resulting increase in distance to remote quarries and landfills, the carbon reduction benefits of RAC, compared to NAC, is expected to increase.

However, taking in the account of the situation where we can use the recycled aggregates instead of natural aggregates to supplement the need the environment protection, would definitely leads to the solution to the sustainability of concrete structures. This concept can lead to a 'zero' waste encouraging researchers and construction industry to provide green solution for a sustainable future.

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A comparative study on nonlinear damping behaviors of precast and cast-in-situ recycled aggregate concrete frames

Xiao J[1,2], **Wang C**[1], **Wang C**[1], **Ding T**[1], **Singh A**[1]

[1] Department of Structural Engineering, Tongji University, Shanghai 200092, China

[2] State Key Lab. For Disaster Reduction in Civil Eng., Tongji University, Shanghai 200092, China

jzx@tongji.edu.cn

Abstract. It has been well accepted that applying recycled aggregate concrete (RAC) into structural engineering is a sustainable method to solve the problem of construction and building waste (CDW) accumulation meanwhile to save natural resources exploitation. Precast RAC members in factories is beneficial to improve their qualities and will extend the RAC application. This study presents nonlinear damping behaviors of precast and cast-in-situ RAC frames after simulated earthquakes, as a reference of quality control of precast RAC members, and of damage detection under ambient vibration. The nonlinear damping of precast RAC slabs with different damage degrees was studied to validate the feasibility of applying the quadratic damping coefficient as a sensitive damage factor without any requirement of undamaged baseline. Meanwhile a comparative study on nonlinear damping behaviors of a precast and a cast-in-situ RAC frames was conducted. Results highlight a change of nonlinear damping mechanism for both precast and cast-in-situ RAC frames from a viscous damping into a nonlinear damping. The precast RAC frame had a comparatively larger quadratic damping coefficient before and after earthquake hitting, indicating it had more severe initial damage and damage developed more significantly compared with the cast-in-situ frame. A unified damage classification was proposed for both precast and cast-in-situ RAC frames based on quadratic damping coefficient and observation.

1. Introduction

The use of construction and demolition (C&D) wastes as building materials has been gradually common in recent decades. Both the growing scarcity of raw materials and the gradual accumulated C&D wastes encourage the application of recycled materials in new built structures. Concrete recycling, crushing waste concrete into recycled concrete aggregates (RCAs), is considered as one of the most widely adopted strategies around the world, mostly due to its ease of implementation and the availability of market for the recycled products, such as recycled aggregate concrete (RAC). For extending the application of RAC to consume more C&D wastes, many reliable researches have been reported in terms of mechanical properties, durability, workability and seismicity of RAC structures [1-4]. It is generally accepted that the durability of RAC is inferior to that of natural aggregate concrete (NAC), which significantly limit the application of RAC in engineering, especially those exposed in corrosive environment [5]. Precast RAC members in factories might be a solution to this problem, considering its superior qualities of concrete members to the cast-in-situ ones [6].

Furthermore, prefabrication in factories has the benefits of higher opportunity for standardization of concrete structures, processing large waste concrete for on-site activities, and saving cost and construction time [7].

For proving the feasibility of precast RAC structures, the authors carried on the first shaking table test of a precast RAC frame model [6]. The result demonstrated that the precast RAC frame had a comparable seismic performance under minor earthquakes to the corresponding cast-in-site one; the displacement ductility of the precast RAC frame was adequate to resist moderate earthquakes; however, a more significant damage occurred in the joint area of the precast RAC frame lead to an inferior stiffness deterioration and energy dissipation performance under stronger earthquakes.

Though the advantages of combining the RAC and the prefabrication technique, there are still challenges faced by researchers and engineers. One of them is how to control their qualities of the prefabricated RAC members, and to detect the damage within the RAC structures after extreme events, for example, strong earthquakes. In this study, the nonlinear damping mechanism was identified of precast RAC slabs and frames based on their vibration responses, as a reference of quality control of precast RAC members, and of damage detection under ambient vibration as well.

2. Nonlinear damping and damage detection method

Normally, the linear damping mechanism was generally applied in dynamic calculation for the sake of simplification and adequate accuracy when the structural members were undamaged. However, it has been clearly expressed by Franchetti and Modena [8] that the damaged concrete members generally behaved nonlinearly, not only considering the stiffness softening behavior, but also a nonlinear damping behavior. Researchers have proposed manifolds of models to describe the nonlinearity of damping under damage [8-11]. Among these, the viscous-quadratic combined damping model firstly proposed by Franchetti and Modena [8] could properly estimate the nonlinearity of damping with comparatively small vibration amplitudes. This model assumed that the undamaged concrete behaved following a viscous damping mechanism, while the damaged part in concrete members behaved nonlinearly. The pure viscous damping was combined with a polynomial damping, as illustrated in Eq.(1) [8]:

$$F_D = c\dot{x} + d\dot{x}|\dot{x}| \# (1)$$

where F_D represents the damping force; $c\dot{x}$ represents the viscous damping force; and $d\dot{x}|\dot{x}|$ represents a quadratic damping force, in which d was a constant coefficient.

The equation of motion of a free oscillation with small vibration amplitudes for a quadratic and viscous combined system became:

$$m\ddot{x} + c\dot{x} + d\dot{x}|\dot{x}| + kx = 0 \# (2)$$

Through energy balance, the envelope curve of a free oscillation could be presented as Eq.(3):

$$a(t) = \frac{(a_0 c_1)e^{-c_1 t}}{c_1 + a_0 c_2 (1 - e^{-c_1 t})} \# (3)$$

where

$$c_1 = \xi\omega \# (4)$$

$$c_2 = \frac{4}{3\pi}\delta\omega \# (5)$$

$$\delta = \frac{d}{m} \# (6)$$

By fitting the envelope curve of the free decay vibration, the viscous damping factor ξ and the quadratic damping factor δ could be estimated and give information about the percentage of the total energy dissipated by each damping mechanism. δ=0 means that no nonlinear damping acted on the system, therefore no damage occurred. On the contrary, a positive value of δ means a nonlinear dissipation acted on the concrete member. Therefore, the quadratic damping factor δ could be directly correlated to the presence of damage in the considered concrete structure. This damage detection method has the benefit of baseline free, which is especially suitable for application in detection initial imperfections in precast members in factories, as well as structures survived after earthquakes. For RAC members and structures, this benefit was even more valuable due to the fact that the essential difference between RAC and NAC was the initial imperfections introduced by pores and weak interfacial transition zones (ITZs) and damage development during extreme events.

3. Nonlinear damping behaviors of the precast NAC and RAC slabs

Two precast slabs, one made with NAC and the other with RAC whose aggregates were 100% replaced by RCA, were damaged to different levels by static loads and subjected to impact loads by a hammer, to extract the damage information in the free delay vibration signal of acceleration through the aforementioned damage detection method. The NAC and the RAC slabs shared the same geomatic sizes and reinforcements, as shown in Figure 1.

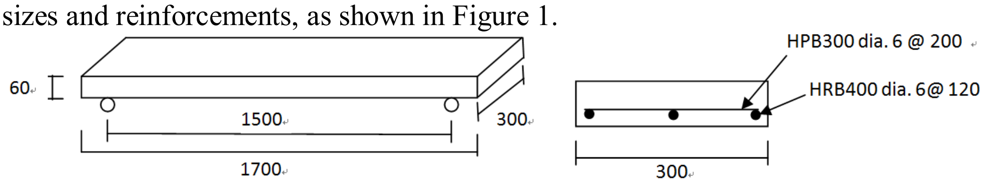


Figure 1. Geomatic sizes of precast NAC and RAC slabs.

5 damage phases were subjected by static loads on slabs, i.e. undamaged, cracked, yielding, peak bearing capacity and failure, judged by strains on the surface of concrete and reinforcement, and deflections of the slabs as well. Then, impact loads were subjected by a hammer after each phase and the free delay vibration responses were recorded by the acceleration gauges. A typical acceleration record is shown in Figure 2. And a comparison between fitting results by the combined damping model and the viscous damping model is shown in Figure 3. It is easily to find that the acceleration responses showed significant features of nonlinearity that the combined damping model achieved a better fitting result compared to the viscous damping model.

Development of damping coefficients, namely, viscous damping coefficient ξ and quadratic damping coefficient δ for the combined damping model, and the equivalent viscous damping ratio for the viscous damping model, correspondingly, are demonstrated in Figure 4. For the sake of convenient discussion, only relative values to the initial corresponding damping coefficient of the NAC slab was presented. A comparatively high value of equivalent viscous damping ratio of the RAC slab was observed at different damage stages in Figure 4, which agreed well with the other reliable experimental observations [12]. However, the viscous constituent of the dissipated energy somehow decreased with the increasing damage, for both NAC and RAC slabs. The viscous damping coefficient ξ decreased to 0.246 and 0.115 at failure stage correspondingly for the NAC slab and the RAC slab compared to the undamaged conditions. While the higher quadratic damping coefficient of the RAC slab than that of the NAC slab accounted for the higher equivalent damping ratio of the RAC member caused by the more energy dissipated by the nonlinear channel. The initial quadratic damping coefficient of the RAC slab was slightly higher than that of the NAC slab, demonstrating a severer initial damage within the RAC slab. The differences between the quadratic damping coefficients of the RAC slab and the NAC slab increased at first, then tend to decrease when the slabs suffered severe damages. However, the quadratic damping coefficient had an increasing trend along with the damage accumulation for both RAC and NAC, which increased to 6.885 and 7.087 times higher at failure stage than beginning for the NAC and RAC slabs correspondingly. The decrease of the viscous damping coefficient and the increase of the quadratic damping coefficient illustrate a shift of the energy dissipation mechanism. It is generally accepted that the nature of the viscous damping mechanism was molecular forces within materials, while the nonlinear damping mechanism might be caused by the friction between imperfections and cracks [13]. This phenomenon confirmed the fact that the undamaged precast RAC slab contained more imperfections, i.e. pores or weak ITZs compared to the NAC slab, besides a more significant damage development. Meanwhile, the increasing trend of the quadratic damping coefficient δ with cumulative damage highlighted the feasibility of using as a unified baseline free reference of damage detection for both precast RAC and NAC members and structures.

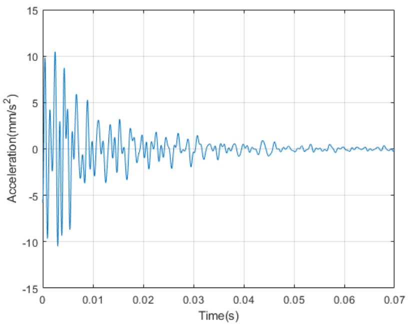


Figure 2. A free decay acceleration response.

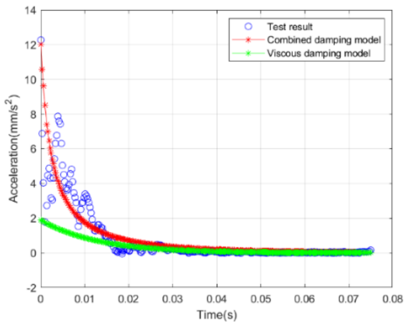


Figure 3. Comparison between fitting results by combined damping model and viscous damping model.

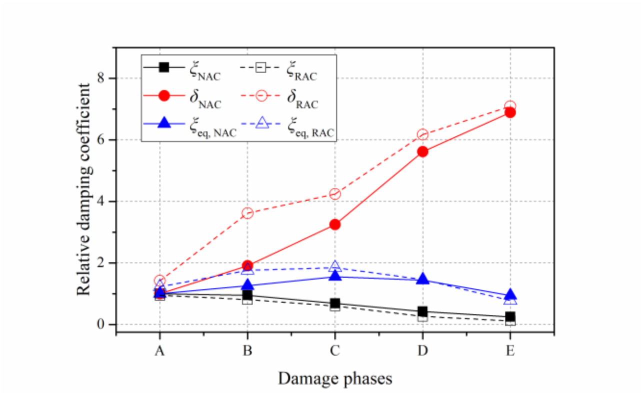
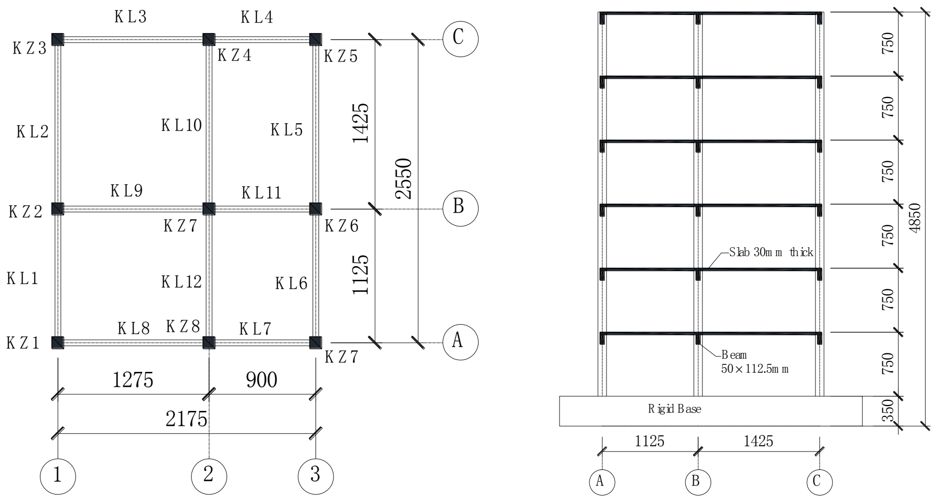


Figure 4. Development of relative damping coefficients with damage.

4. Nonlinear damping behavior of precast and cast-in-situ RAC frames

4.1. Description of the RAC frames

Two 6-floor, 2-span, 2-bay RAC frame structures, one was prefabricated and one was cast in-site, were constructed to conduct the shaking table test. These two frames had totally same configuration, as shown in Figure 5, as well as the reinforcement distributions. These two frames utilized the identical target strength RAC, whose replacement percentages of RCA were 100%. For the sake of convenient discussion, the precast RAC frame was represented as RAC-PRE, well the cast-in-site RAC frame was represented as RAC-CIS.



(a) Layout plan (b) Elevation

Figure 5. Configuration of the precast and cast-in-situ frames.

The process of constructing the precast RAC frame included three steps: (1) fabricated beams and columns in a factory, and (2) transported the members to the lab and (3) constructed the frame. 9 columns and 12 beams were erected on each floor level. The beams were seated on the head of columns. For assuring rigid beam-column connections between beams and columns, the longitudinal reinforcements were welded within the joint, as shown in Figure 6. Following that the molds were erected and RAC in joints and slabs was casted, as shown in Figure 7.

Figure 6. Erecting columns and beams.

Figure 7. Casting joints and slabs.

4.2. Shaking table tests

The Wenchuan wave (WCW), El Centro wave (ELW) and the artificial Shanghai wave (SHW) as a group with increasing peak ground accelerations (PGAs) of 0.066g, 0.130g, 0.185g, 0.264g, 0.370g, 0.415g, 0.550g and 0.750g were inputted into the frame from the rigid ground of the shaking table. Before and after each group of earthquakes, low-intensity white noise waves (WNW) were inputted to extract dynamic characteristics and to detect damage.

The displacement and acceleration responses were recorded by the displacement linear variable differential transducers (LVDTs) and acceleration gauges, respectively, on the rigid table and each floor of the frames. Meanwhile, strain gauges were fixed on the surface of concrete and reinforcement to analyze the failure procedures of these two RAC frames under earthquakes.

4.3. Nonlinear damping behaviors and damage detection

The aforementioned method of damage detection was proposed for the members or structures behaved harmonically without any load. However, in this study, the structures were excited by the earthquake waves and WNWs, and the nonlinear fitting method could not be applied directly. The random decrement technique (RDT) [14] was applied to extend the application of this damage detection method from free decay vibration into vibration excited by WNWs. WNW is the most accessible vibration that can be easily acquired from a real structure in the ambient environment, since the measurement requires neither the structure being taken out of service, nor expensive exogenous excitations. The RDT enables the resulting signature from the ensemble averaging of segments of the response to extract damping characteristics from free vibration signature.

The detailed comparison of failure pattern and seismic performances of these two models was elaborately discussed in reference [15]. It could be found in this comparative study that the precast RAC frame suffered a more significant damage under the same dynamic loads than the cast-in-situ one. The relatively severe damage level of a post-cast joint was the main reason for the overall inferior seismic performance of the precast structure, during an earthquake of high-level intensity. Compared to the cast-in-situ RAC frame, it was observed that the precast frame suffered more serious damage under the shear action of the earthquakes.

The quadratic damping coefficient δ and viscous damping coefficient ξ by nonlinear fitting with the combined damping model are shown in Figure 8. It is worth to mentioning that these coefficients were extracted from the acceleration responses recorded by the acceleration gauges fixed on the roofs of both precast and cast-in-situ RAC frames. In Figure 8, it could be observed that the viscous damping coefficients increased at first and then decreased, while the quadratic damping coefficient increased with the cumulative damage for both precast and cast-in-situ RAC frames. Based on the assumptions of the combined damping model that the undamaged part of structure behaved viscously, while the damaged part behaved nonlinearly, the energy dissipation mechanism changed from the viscous damping mechanism into a viscous-nonlinear damping mechanism, demonstrating a damage development process with the increasing PGA. It could be deduced that the friction and sliding between the two sides of cracks absorbed the inputted energy and accounted for the nonlinear damping mechanism.

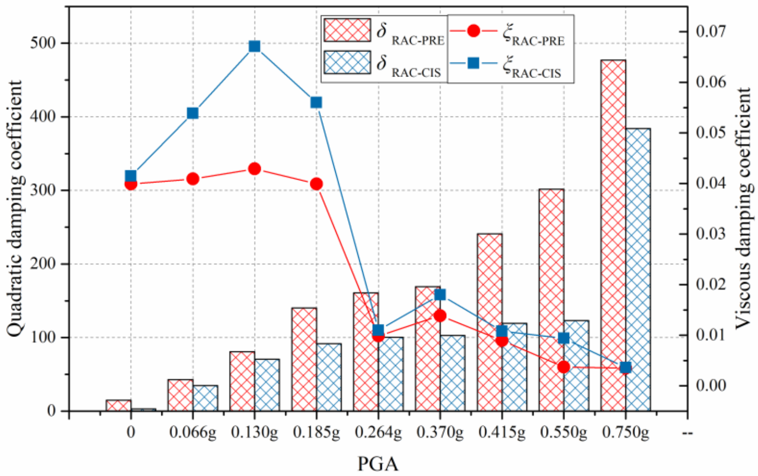


Figure 8. Variations of quadratic and viscous damping coefficient with the increasing PGA.

Furthermore, due to the advantage of baseline free feature, the initial damage within the precast and the cast-in-situ RAC frames were detected. Before excited by earthquakes, the precast RAC frame presented a much higher quadratic damping coefficient than that of the cast-in-situ one. This fact might be caused by the initial cracks between the precast members and the post-cast joints. This difference kept constant after suffered the earthquakes with 0.066g and 0.130g PGA, demonstrating that under low-intensity earthquakes, the precast RAC frame presented a similar seismic resistance compared to the cast-in-situ frame. However, the difference between the quadratic damping coefficients of these two frames became significant under 0.185g PGA earthquakes. It demonstrated the inferior seismic performance of the precast RAC frame to the cast-in-situ one.

Combining the description of the failure procedures and the quadratic damping coefficients for these two frames, it can be concluded that the precast RAC frame suffered a severe damage under 0.185g with a δ of 140.1, and was completely damaged under 0.550g with a δ of 307.7; while the cast-in-situ RAC frame suffered a severe damage under 0.415g with a δ of 123.3, and was completely damaged under 0.750g with a δ of 384.1. This result highlighted a better seismic performance of the cast-in-situ RAC frame under strong earthquakes. And the quadratic damping coefficient could be used as a reference to guide the retrofit of precast and cast-in-situ RAC structures after earthquakes.

5. Conclusions

In this study, nonlinear damping behaviors of precast and cast-in-situ RAC frames after simulated earthquakes were analyzed, aiming to provide a reference of quality control of precast RAC members, as well as of damage detection under ambient vibration. The nonlinear damping of both the precast NAC and RAC slabs with different damage degrees was studied to validate the feasibility of applying the quadratic damping coefficient as a sensitive damage factor without any requirement of undamaged baseline. By analyzing the experimental results, a shift of the damping mechanism was confirmed from a viscous damping mechanism into a viscous-quadratic combined damping mechanism. Meanwhile a comparative study on nonlinear damping behaviors of a precast and a cast-in-situ RAC frames was conducted. The precast RAC frame had a comparatively larger quadratic damping coefficient before and after earthquake hitting, indicating it had more severe initial damage and more significant damage developed compared to the cast-in-situ frame. The friction and sliding between cracks were deduced to explain the increase of quadratic damping coefficient. A unified damage classification was proposed for both precast and cast-in-situ RAC frames based on quadratic damping coefficient and experimental observation.

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Modification on Recycled Aggregates and its Influence on Recycled Concrete

Huang K[1], Ding T[2], Xiao J[3], Singh A[4]

[1] Ph.D. Student, Tongji University, Shanghai 200092, China.

[2] Ph. D, Tongji University, Shanghai 200092, China.

[3] Professor, Tongji University, Shanghai 200092, China.

[4] Ph.D. Student, Tongji University, Shanghai 200092, China.

1410217@tongji.edu.cn

Abstract. Recycled aggregates produced from waste concrete are widely accepted as green building material. However, demolition processes will bring recycled aggregates with a lower apparent density, bulk density whereas a higher porosity, silt content, water absorption, crushing index value when compared with natural aggregates. So the strengthening and modification of recycled aggregates have become a prominent technological issue in the producing process.
This paper introduces current modification methods on the recycled aggregates, which mainly include: (1) physical technology, its basic idea is to remove the waste cement paste adhered to recycled aggregates, such processions as rubbing, heating, particle shaping, and micro-heating; (2) chemical technology, carried out by immersing recycled aggregates in different kinds of chemical grout, which can be mixed with additive Kim powder, silica fume, fly ash, and any other fine mineral powder or slag; (3) carbonation technology, when newly collected crushed aggregates are put into atmosphere with high CO2 concentration, the adhesive cement paste can react with CO2 and produce CaCO3 that will precipitate in the capillary pores or cracks, which will improve properties of recycled aggregates; (4) nano technology, the use of nanomaterials can promote the hydration reaction, react with cement based materials, fill pores and control the process of crystallization. Conclusions are put forward and several problems concerning modification need to be considered for further research and application are proposed and discussed. Compared with natural concrete, RAC is superior to environmental value in the reduction of CO2 emission in Life Cycle Assessment.

1. Introduction

The demolition of buildings will produce more than 200 million tons of solid wastes in China every year, and 80% are waste concrete, however, there are still no effective disposal measures. The building wastes need to be buried or piled up after demolition thus will occupy more arable lands or even bring about pollution to the lands. Therefore, it’s urgent to develop the recirculation and reutilization of building resources. Among them, recycled concrete aggregates are available impetus[1]. This improves efficiency of recycling of concrete and provides a topic linked to sustainability of cement based materials.

Researchers all over the world have conducted majority experiments on modification of recycled aggregates, these modifications can be summarized as physical technology, chemical technology, carbonation technology and nano technology.

2. Physical Technology

2.1. Abrasive Grinding Method

For grinding the preliminary crushed concrete blocks (diameter 5~40mm), the use of ball mill or rod mill to remove effectively the adhesive hardened cement pastes can produce high quality recycled aggregates, this idea can be described as abrasive grinding method[2]. The ball mill usually has dry treatment or wet treatment, while the rod mill is usually designed for wet treatment. Take the example of ball mill, its working principle is shown in Figure 1. This device is provided with several partitions, between the partitions there is a lot of steel balls. The interactive collisions between steel balls and recycled aggregates or interactive collisions simply between recycled aggregates will remove the adhesive cement paste and thus improve the properties of recycled aggregates. However, the abrasive grinding equipment will always lead to higher energy consumption and lower efficiency, besides, the device and grinding blocks will suffer a lot from serious wear and tear.

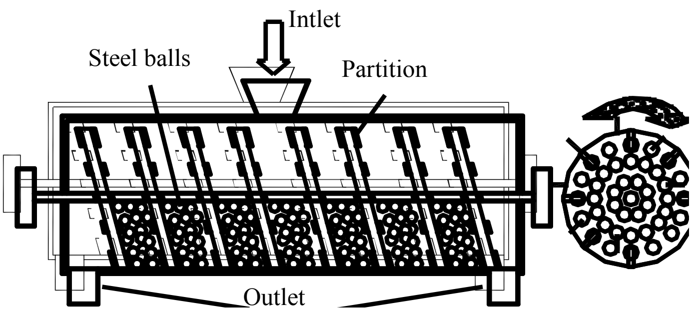

Figure 1. Ball milling equipment of abrasive grinding method

2.2. Particle Shaping Method

The configuration and structural principle of the particle shaping equipment are shown in Figure 2. This equipment consists of host system, dust removal system, electric control system, lubricating system and pressure sealing system. The host system is provided with a vertical totary impeller (the aggregates projection disk). Recycled aggregates that need to be modified are introduced into the machine from the upper inlet and then are divided into two streams; one part falls into the impeller cavity and is projected with high speed (the maximum can be 100m/s) due to the centrifugal effect; another falls along the aggregates distribution system of the host and its aggregates then collide with the ones projected from the impeller. After several times' collisions the recycled aggregates will be crushed and modified. In this process, the equipment consumes less energy and has a longer service life because the high-speed recycled aggregates rarely contact with the machine wall, it's also convenient to install, operate and repair the equipment. After the process, the recycled aggregates will have smooth surface, good particle shape, and the bulk density will be improved with higher purity[3].

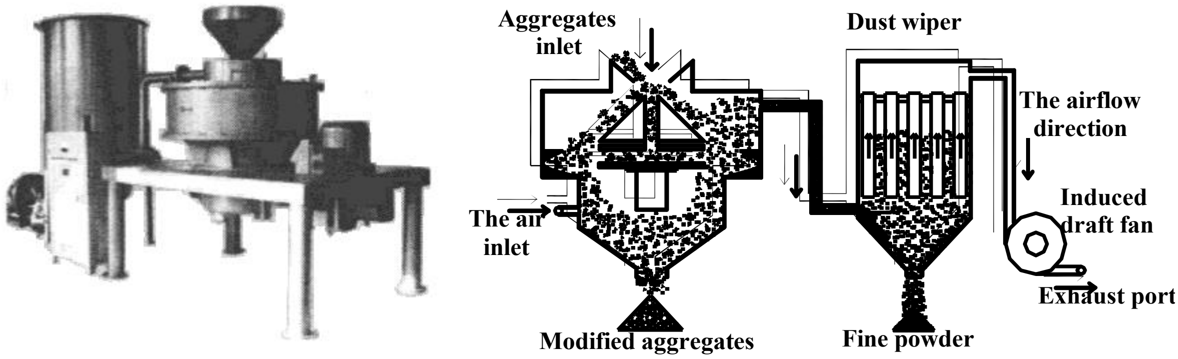

Figure 2. The configuration and structural diagram of the particle shaping equipment

2.3. Microwave-Assisted Method

A novel microwave-assisted method may be effectively used to partially remove the adhering cement paste by developing high temperature gradients and high thermal stresses within the mortar, especially at the interfacial zone with the gravels. Furthermore, recycled aggregates exposed to microwaves can significantly increase other properties. The Pilot microwave heating system is shown in Figure 3. Unlike conventional heating method, microwave-assisted method needs lower temperature, less energy and shorter duration which would eliminate degradation of recycled aggregates during processing as well as the potential durability concerns. According to experimental studies[4], concrete prepared with microwave-treated recycled aggregates can significantly enhance the mechanical properties such as the compressive and flexural strengths and modulus of elasticity.

Figure 3. Pilot microwave heating system used for experimental program

3. Chemical Technology

Chemical technology is mainly about recycled aggregates' treatment of immersing (soaking) and drying by using specific chemical grout which will cohere or fill the micro-cracks or micro-pores in recycled aggregates, this technology achieves the purpose of modification by changing the chemical composition of recycled aggregates' surface and makes them denser or improves their strength[5].

The available chemical grout can be listed as follows:

3.1. Polymer Emulsion

Polymer emulsion solution can be used to improve the properties of recycled aggregates, especially recycled fine aggregates. The tests of mortar blocks made of recycled fine aggregates after the modification of polymer emulsion solution showed that: the flexural strength improved obviously, while the compressive strength has little improvement[6].

Yang studied the strengthening of recycled aggregates by using cement grout with different kinds of high activated superfine mineral additives[7], the result is listed in Table 1. Compare the results of physical properties before and after strengthening, so were the mechanical results of recycled concrete made of modified recycled aggregates. Although the amounts of additives, mix proportions, and any other environmental conditions in these two experiments have some variations, they can still imply the strengthening degrees of the mixed grout.

Table 1. Experimental results of different polymer emulsion

Chemical grouts	Physical properties of RA				Mechanical properties of recycled concrete	
	Water content /%	Water absorption rates /%	Apparent density /(kg/m^3)	Crushing index value /%	28d compressive strength (MPa)	Growth rate of strength /%
untreated	2.58	6.77	2470	16.73	30.78	0
Neat cement grout	3.37	6.93	2580	13.24	31.10	1.04
Cement grout with additive slag	3.78	7.51	2570	13.12	33.08	7.47
Cement grout with additive diatomite	2.71	7.13	2523	12.11	36.39	18.23
Cement grout with additive silica fume	2.79	7.43	2534	12.80	35.72	16.05
Polymer emulsion solution	2.63	6.34	2500	11.80	37.58	22.09

3.2. Polymer emulsion and cementitious grouts

For modification of recycled aggregates, activators have similar function and mechanism to mixed cement grout. Immersing the recycled aggregates with inorganic composite alkaline activator and organic compound acid ester activator respectively, the test results are shown in Table 5[8].

Table 2. Experimental results of different activator

Aggregates	Water absorption rates /%		Crushing index value /%	Apparent density /(kg/m^3)
	10min	1h		
Untreated	3.80	6.25	24.1	2269
Inorganic impregnating solution	2.60	5.42	18.9	2290
Organic impregnating solution	3.50	5.73	22.5	2289

When considering the water absorption rate, crushing value, apparent density and other indicators, the properties of recycled aggregates with inorganic impregnating solution are slightly better than those with organic impregnating solution. The different performance indicators of recycled aggregates, when treated with organic impregnating solution, won't increase obviously.

4. Carbonation Technology

Carbonation will contribute to volume change, normally because the precipitation of CaCO3 mainly fill empty spaces in the capillary pores and cracks, thus leading to the reduction of porosity in the cement paste. Meanwhile, both the densification and strength will be improved. This is really a theoretically feasible technology for recycled aggregates' modification. The carbonation mechanism is shown in Figure 4.

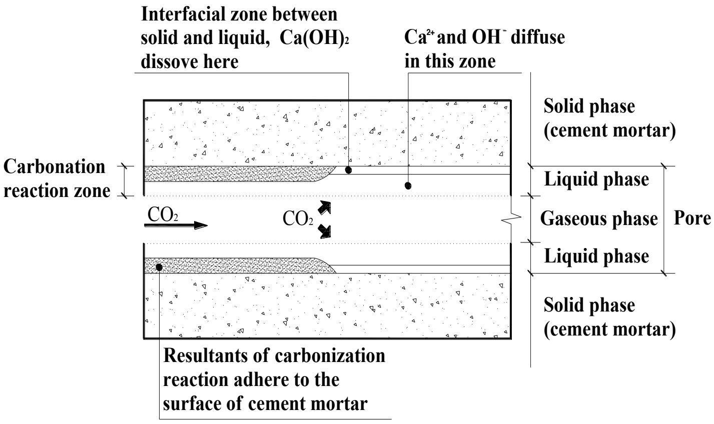

Figure 4. Schematic diagram of carbonation mechanism

Kou[9] chooses recycled mortar aggregates (RMA) to illustrate the relevant carbonation problems. RMA1 and RMA2, with sand to cement ratios of 3.0 and 2.5, and water to cement ratios of 0.55 and 0.45, respectively. And their carbonated counterparts are CI-RMA1 and CI-RMA2, respectively. Carbonation test is conducted in a steel airtight container with a CO2 concentration higher than 99%. The physical properties of aggregates are shown in Table 3 .After carbonation, each type of RMA was used to prepare recycled concrete, which will be tested for subsequent durability properties, such as compressive and tensile splitting strength, slump, drying shrinkage and chloride penetrability.

Table 3. Physical properties of aggregates

Property	Particle size (mm)	Aggregate type				
		Natural granite	RMA1	RMA2	CI-RMA1	CI-RMA2
Density (Kg/m^3)	20	2620	2326	2355	2345	2371
	10	2620	2326	2355	2351	2379
Water absorption (%)	20	0.89	11.82	9.30	7.32	4.84
	10	0.87	12.25	10.81	7.57	4.95
10% Fine value (KN)	14	156	96	116	108	134

The test results of the properties of different aggregates such as density, water absorption and 10% fine value are shown in Figure 5 , It was found that the properties of carbonated RMA improved compared with uncarbonated ones, but still lower than Natural granite's. And it also concluded that 24 h CO2 treatment was optimum.

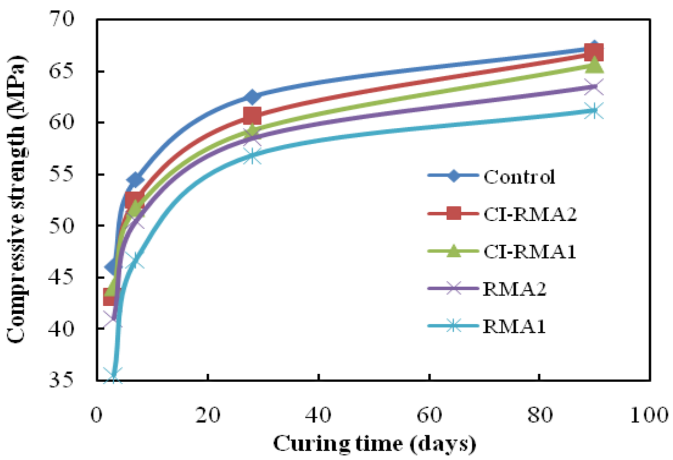

Figure 5. Development of compressive strength of concrete

The development of compressive strength of different concrete according to curing time is presented in Figure 5. Although the compressive strength of concrete prepared with RMA, carbonated or not, was still lower than that of control concrete at all tested ages, both the CI-RMA1 and CIRMA2 improved the compressive strength of the concrete significantly. At 90 days, the compressive strength of concrete made with CI-RMA2 was only 1% lower than that of control concrete. Besides, there is also an improvement in the resistance to chloride ion penetration for the concrete prepared with CI-RMA, and the drying shrinkage was decreased. Generally, carbonation is applicable for the modification of recycled aggregates.

5. Nano Technology

Just as improving the performance of concrete, nanomaterials are also being used to enhance the performance of RAC. Compared with other methods, nanomaterials have unique advantages to improve the performance of RAC.

Zhang et al.[10] apply surface treatment to recycled aggregate (RA) by two slurries containing nanomaterials. The new ITZs in RAC containing RAs surface treated by either of the two Nano slurries (the Nano-silica + nCa slurry or the Cement + Nano-silica slurry) were significantly enhanced. And the slump of fresh RAC, compressive strength and resistance to chloride diffusion was improved. The width and elastic modulus of the old ITZs in RAC did not develop as time passed, regardless of surface treatment on RA using nanomaterials, mainly because few unhydrated cement particles existed in the old ITZs and nanomaterials were not able to penetrate into the old ITZs. Maybe this phenomenon could be improved by increasing the processing time. Zhang et al.[11] discussed the modification effects of a Nano-silica slurry on microstructure, strength, and strain development of RAC applied in an enlarged structural test. Together with NAC, non-modified and modified RAC were applied in three beams in a real project. It is verified that beneficial effects of the employed nano-slurry on both the mechanical properties of MRAC material, and the deformability against shrinkage and loads of MRAC applied in reinforced beams in a real project. The nano-silica slurry employed in this study have improved the properties of MRAC's new ITZs between the old and new cement mortars, while the old ITZs between the virgin aggregate are not enhanced.

6. Conclusions

This paper has presented a critical review of existing and ongoing research on the modification of recycled aggregate. This review allows a number of significant conclusions to be drawn as follows:

1) Physical technology: with the help of the mechanical forces to remove the adhering cement pastes, then the ultimate recycled aggregates have high purity of gravels. However, this technology consumes more energy and resources, demands complicated equipments which tend to wear more serious, thus resulting in high cost. Therefore, physical technology is not suitable for long-term performance. Even so, the current recycled aggregates modification is mainly about physical technology.

2) Chemical technology: using chemical grout soaking to improve the performance of the adhering mortar in place of removing it. Although this technology has the advantage of convenient production process, considering the possible subsequent chemical reaction and the influence on the ultimate concrete strength or durability, this technology is still in the evaluation and discussion without been applied to engineering practice.

3) Carbonation technology: this technology has some commons with chemical technology based on the strengthening of cement pastes. Carbonization technology has the simple processes and environmental friendly advantages, but considering the cost of industrial carbon dioxide collection and carbonization room or conditions, there is a lot of subsequent research work to be done.

4) nano technology: nanomaterials can reduce the amount of cement content, improve the mechanical durable properties of recycled concrete especially at early age. These are based on the optimization of nanomaterials for microscopic structures and the promotion of hydration reactions. But at the same time, nanomaterials are prone to agglomerate that difficult to be stirred evenly, dispersion is not good and easy to reunite. the workability of RAC is affected largely.

For the modification of RA, we should not confine in physical and mechanical properties or any other short-term researches. When taking account of recycled concrete's long-term serviceability, it's indispensable for us to conduct deep researches on strength stability and durability. Compared with natural concrete, RAC is superior to environmental value in the reduction of CO2 emission in Life Cycle Assessment[12]. Besides, the available equipment, recycling utilization rates and costs of recycled aggregates' demolition and production should be evaluated. All these work also need to be incorporated with national conditions.

Acknowledgments
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Parametric life cycle assessment of a reusable brick veneer

Vandervaeren C[1], **Galle W**[1,2], **De Temmerman N**[1]

[1] VUB Architectural Engineering, Vrije Universiteit Brussel (VUB), Pleinlaan 2 – 1050 Brussels, Belgium;
[2] VITO Transition Platform, Flemish Institute for Technical Research (VITO), Boeretang 200 – 2400 Mol, Belgium;

camille.vandervaeren@vub.be

Abstract. A possible design strategy to improve the sustainability of building products is facilitating their future reuse. This strategy inspires some manufacturers to design innovative products, such as reusable façade products. Although these products might have a higher environmental impact for production, their reusability could lead to an environmental saving from a life cycle perspective. A possible method to evaluate their environmental performance is life cycle assessment (LCA). Nevertheless, LCA studies of reusable products are still rare. Furthermore, although the general LCA frameworks is fixed by ISO and CEN standards, some methodological choices must still be made by LCA practitioners. This paper first presents a method (as four methodological choices) for a parametric life cycle assessment of reusable building elements. Then, this method is applied to a comparative LCA of reusable and brick-and-mortar veneers. With proposed method, the reusable brick veneer is environmentally advantageous if it is reused at least once and if it is properly recycled at its end-of-life. The parametric method also indicates the relative influence of various parameters such as reuse rate, number of interventions, transport distances and waste treatment. The manufacturers can use this LCA study as a retrospective assessment to validate the relevance of design choices, but also as target-driven product management support to know hot-spots in the product' life cycle management. This study will hopefully inspire other designers and manufacturers and accelerate the transition towards a sustainable built environment.

1. Introduction

To achieve a sustainable built environment, circular economy principles advise designers to reuse construction products. However, using and reusing a product has also an environmental impact is henceforth no guarantee for environmental benefits [1,2]. These benefits can be quantified by performing a life cycle assessment (LCA). However, the link between LCA results and the design and use parameters is not always explicit, though important for designers. Therefore, governmental initiatives are developing tools, such as the Belgian TOTEM [3] or the French Elodie [4], to facilitate the use of LCA by the architectural practice. Nevertheless, these tools do not yet integrate the principles of circular economy. Further, the standards for LCA remain ambiguous when a product has more than one use cycle, for the reasons explained in Section 2. Some researchers even question whether LCA is at all suitable to evaluate so called 'circular' products [5,6]. To understand to what extend reusable products can be evaluated with LCA, we conducted a case study of a reusable brick veneer. In this paper, we present first four difficulties when evaluating reusable products with the LCA framework defined by the international (ISO) and European (CEN) standardization committees and propose a parametric LCA method to overpass them (Section 2). The proposed method uses parameters to understand the impact of decisions made at product design stage, production, or when the product is installed in a building. The method is then illustrated with the comparison of the environmental impact of reusable and conventional brick veneers (Section 3). We finally summarize our findings (Section 4) and conclusion (Section 5).

2. Parametric LCA of reusable products

When performing a life cycle assessment (LCA) of reusable or recyclable products, a recurrent difficulty is setting relevant system boundaries and allocating the environmental impact for production and waste treatment over the different products, as shown by the efforts invested in the search for an appropriate End-of-Life formula in the context of the Product Environmental Footprint calculation [7]. Often, an LCA assessor must choose to take the perspective of either the first use cycle (i.e. the 'new' reusable product), the second use cycle (i.e. the 'reused reusable' product), or the last use cycle before waste treatment (i.e. the 'reused non-reusable' product). To this difficulty is added the lack of (reliable) data about parameters influencing the life cycle inventory, such as products' lifespan, maximum amount of use cycles and necessary remanufacturing processes. The difficulties can be summarized into four methodological choices in the next paragraphs. These choices constitute the proposed parametric LCA method for reusable products and supports the case study in Section 3.

2.1. Should we take a product or building perspective?

Depending on the goal of the LCA, the assessment is performed either at building or product level. In the present case study, the goal of the LCA is to position the product on the market and the results are intended mainly as a marketing instruments. Therefore, SETAC recommends to take a product perspective, though the products must be brought into the building context in order to make a valid comparison [8]. Notably from the perspective of a reusable product, an LCA would then consider in module B, all use cycles, including the impact of relocating and reconditioning a product, until the end of its technical lifespan, which is usually longer than the building lifespan. A second reason for taking a product perspective is that approximating at once all the avoided products thanks to reuse is more abstract than defining scenarios including successive reuses. This second option implies a *system expansion*, which consequently solves the problem of allocating the impacts over multiple use cycles (i.e. multiple 'reused reusable' products). Nevertheless, the avoided products due to recycled content and product recyclability must still be accounted through an appropriate allocation procedure. Allocation procedures are not discussed in this paper.

2.2. How do we define the system boundaries in time?

Circularity means in theory endless use. If we take a product perspective, the period of analysis should not be limited to the lifespan of the assembly the product is part of, neither it can be endless. So, when to start and when to stop the inventory? We decide to define the period of analysis based on the technical lifespan of the reusable product. After all, no manufacturer guarantees that its product will last forever.

2.3. How to define use scenarios at building level that make sense for all compared products?

Use scenarios are conventionally defined at building level, by defining what creates the need for, and triggers, relocating/replacing the product. Then the product's 'response' to this need for change is evaluated. Nevertheless, the need for change at building level can be influenced by the feasibility of change at product level (i.e. rebound effect). This feasibility differs in both products. A conventional product can, in practice, be less often altered than a reusable product because of the burdens each intervention generates (which is the reason why we design reusable products). Here, because the reusable and conventional products must be comparable in terms of their 'resilience to change', we choose to test both products for identical use scenarios (i.e. the same need for change). Hence, they both have the same amount of use cycles (Figure 1).

2.4. How to (time-efficiently) evaluate many different use scenarios?

Because of the system expansion, the two products go through multiple cycles with multiple use scenarios to consider, and hence more uncertainty (e.g. different reuse rate, different transport distance, etc.). Even the amount of cycles can be unknown. To model these many scenarios efficiently modelled, parameters are introduced in the calculation of the total environmental impact (E), as in equation (1)

$$E = E_{prod} + E_{trans,c} + E_{cons} + N \times (E_N) + E_{dec} + E_{trans,w} + E_w \quad (1)$$

in which the potential environmental impact of the N[th] reuse cycle (E_N) is defined by equation (2).

$$E_N = E_{dec} + E_{cons} + E_{trans,N} \times R + \left(E_{prod} + E_{trans,c} + E_{trans,w} + E_w\right) \times (1 - R) \quad (2)$$

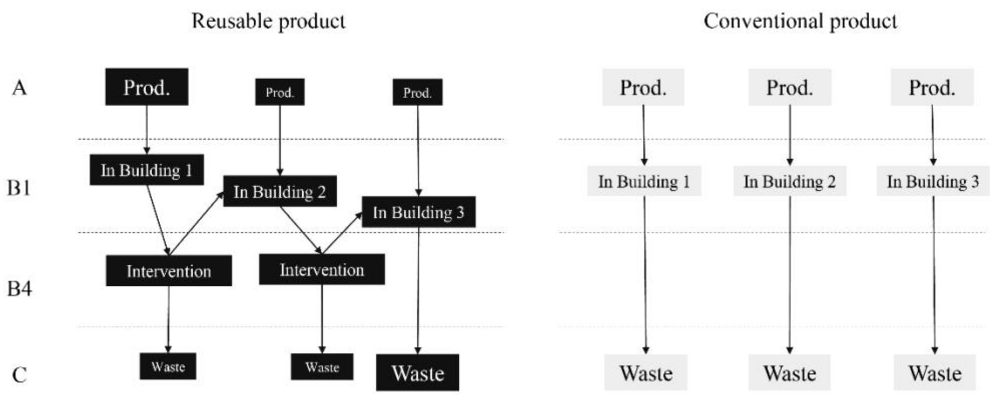

Figure 1. The reusable product is used over three cycles (with some losses), while the conventional product must be produced three times. ('Prod.' = production; 'Waste' = waste treatment)

in which,
E is the total environmental impact;
E_{prod} is the environmental impact of production;
$E_{trans,c}$ is the environmental impact of transport to construction site;
$E_{trans,w}$ is the environmental impact of transport to waste treatment;
$E_{trans,N}$ is the environmental impact of transport to next construction site;
E_{cons} is the environmental impact of assembly or construction;
E_{dec} is the environmental impact of deconstruction or demolition;
E_w is the environmental impact of waste treatment;
R is the reuse rate (i.e. the percentage in mass of the whole product that is reused in the next cycle);
N is the number of interventions, hence the number of use cycles occurring after the initial use, during the period of analysis.

The two main parameters are the reuse rate (R) and the number of interventions (N). R depends on the design but also on the use: it's not because a product is design for disassembly that it will be disassembled. By this parameter the level of 'circularity' of the system is represented. The higher the reuse rate, the more materials remain in use. A low R characterises a linear use of materials, while a high R characterises a circular use of materials. N depends on the need for functional changes (e.g. aesthetics, necessity to access and alter an internal layer, reconstruction of the whole system), and not on the need for technical changes. N is identical for both products, although in practice N might be higher for a reusable product than a non-reusable one due to rebound effect.

All the parameters and their interaction can be visualized in a process diagram (figure 2) which supports the case study presented in the next section.

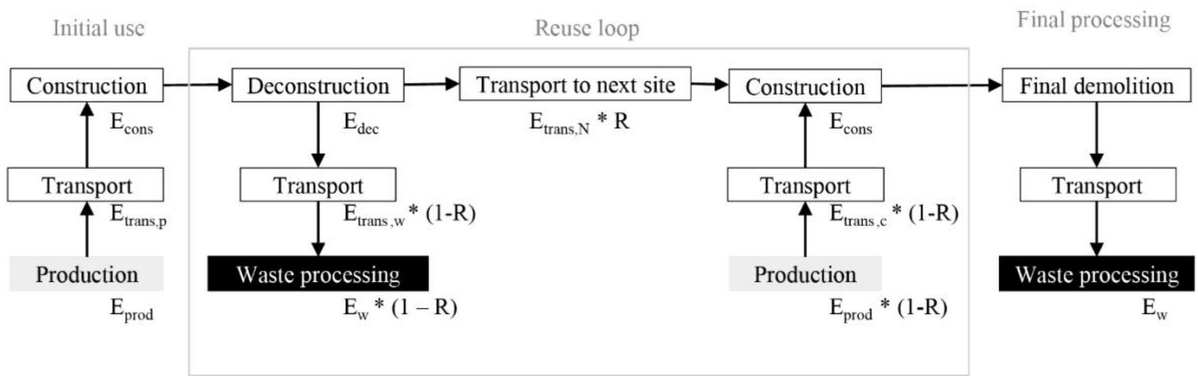

Figure 2. Process and flow model for the life cycle of product with multiple uses.

3. Case study

With the method for a parametric life cycle assessment (LCA) (Section 2), the potential environmental impact of two building products was compared. This section reports the LCA step 1 (goal and scope), step 2 (inventory) and step 3 and 4 (impact assessment and results of the attributional LCA).

3.1. Goal, functional unit and system boundary

The LCA is mandated by the manufacturer of a dry brick veneer available on the Belgian market, called '*Façadeclick*' (FC). The goal is to compare the environmental impact of FC, designed for a circular use of materials, with a '*brick-and-mortar'* (B&M) veneer, its most conventional alternative.

The functional unit (FU) is "a brick veneer, covering one square-meter of external wall with a self-bearing system, including anchors to the load-bearing structure, for 80 years". Both products have similar aesthetical, structural[1] and thermal performances[2], and both act as a rainscreen. Both products can reach a thermal transmittance (U) value of 0.24 W/m²K when combined with 0,14 m masonry wall and 0,11 m EPS insulation. The environmental consequences of a different of product's weight on the dimensioning of the foundations are not included in this illustrative case study.

As for the system boundary, the inventory of mass and energy flows is estimated from cradle to grave (from modules A1 to C4, as defined in the EN15804 norm). It includes the production of the different parts (E_{prod}), their transport between the different production and construction sites (E_{trans}), and the waste processing (E_w). Excluded from the analysis are packaging, storage, maintenance of the wall, assembly and disassembly of FC and construction and demolition of B&M.

[1] The compression resistance values are 11 N/mm² for the plastics inserts and 5 N/mm² the mortar, according to the product technical documentation.

[2] Thermal conductivity (λ) values are 0.69 W/mK for the reusable brick and 0.59 W/mK for the conventional brick, according to the product technical documentation.

3.2. Life cycle inventory

The life cycle inventory was carried on with LCA software SimaPro 8 [9], using the process data from the Ecoinvent 3.1 database [10], with default allocation[3]. The impacts of by-products are allocated following the recyclability approach (0:100) with credit for avoided virgin production, as defined by Allacker et. al. [7] who consider this approach valid for the criteria 'physical realism' at system level. Following this approach, no credit is given to recycled content (e.g. recycled plastic used in the plastic inserts), but the recyclability at End-of-Life is credited following Belgian conventional recycling rates [12]. The consumption data comes from the product manufacturers. Both FC and B&M products weight respectively 136 kg/m² and 176 kg/m². FC uses 130 kg of hollow bricks and plastic inserts to 'click' each brick on top of the other. B&M uses a similar quantity of bricks (128kg) and 48 kg of mortar. FC requires 8 steel anchors to attach to the load-bearing structure, while B&M only needs 5 anchors.

3.3. Modelling assumptions

The final environmental impact (E) score is calculated with the impact assessment method 'ReCiPe Endpoint (H) V1.12 / Europe ReCiPe H/A – single score'. The parameters value for the baseline scenario are estimated from discussion with the product manufacturers[4], with some modelling simplifications:

- The impact of production (E_{prod}) is calculated based on the inventory of materials and energy given by the product manufacturers.
- FC and B&M are both first installed in Wilsele, Belgium. During each reuse, FC is always relocated at 100 km from the previous site. B&M is installed at 80 km from the brick retailer. The mortar is transported over 5 km to the construction site. At end-of-life, both products are transported to the waste treatment plant over 30 km. All transport distances remain constant for each use cycle.
- Upon recommendation of SETAC [8], two waste treatment scenarios are compared: (1) an "average for Belgium" baseline waste treatment scenario, based on the BE-PCR[5] [12] and (2) an "improved plastic recycling" scenario, in which all HDPE is recycled. Both scenarios are defined as a mix of recycling, incineration, and landfilling per material category.
- In this model, B&M is not reused, therefore $R_{B\&M}$=0% by default. FC is reused with 5% losses over whole product (bricks, inserts and anchors), R_{FC}=95%.
- As for the number of use cycles (N), FC can be disassembled and reassembled up to five times. For the baseline scenario, N varies thus from 0 to 5.
- The service lifespan of all parts of the products is considered higher than the period of analysis (80 years). Consequently, replacements of sub-products are not considered.

3.4. Results

In this baseline waste scenario (FC1) and N=0 (i.e. no intervention), the *Facadeclick* (FC) product has a potential environmental (E_{FC}) impact of 6,0 points, that is 63% higher than the *bricks & mortar* (B&M) product ($E_{B\&M}$=3,7 points) (Figure 3). When one intervention occurs (N=1), both products have close E (6,6 and 7,4 points). From two interventions (N>1), FC is more environmentally efficient than B&M (7,2 and 11,1 points). In the "improved plastic recycling" scenario, in which the inserts are fully recycled at the end-of-life (FC2), FC has a lower E than B&M already after its first reuse (4,1 and 7,4 points).

As shown in both waste scenarios, when R_{FC} is high (95%), E_{FC} is almost no dependent on a variation of N, because each new cycle does not contribute much to E. Consequently, FC is more resilient to

[3] Default allocation in Ecoinvent 3.1 considers average supply market, unconstrained, and economic allocation of multiple outputs [11].

[4] The product manufacturers are 'Snel Bouwsysteem' and 'Nelissen'.

[5] In this BE-PCR waste scenario: Bricks: 5% landfilled; 0% incinerated; 0% reused; 95% recycled; Metals: 5% landfilled; 0% incinerated; 0% reused; 95% recycled; Polyolefins (PP, PE): 10% landfilled; 85% incinerated; 0% reused; 5% recycled.

changes than B&M. Therefore, the LCA of reusable products is more robust. A similar conclusion was drawn by Galle for the life cycle costing of reusable products [13].

With the environmental profiles of both products, we can discuss the choice of parameters' value for the baseline scenario. The demolition of B&M is probably generating environmental impact from the use of building machines and water spraying to control dust emission. If these flows were included in the inventory, it would not invert the interpretation of the results.

The FC's potential environmental impact for the baseline scenario ($E_{Baseline}$) depends on transport distance for the product relocation and the reuse rate during relocation (R), among other parameters. The sensitivity to those two parameters is assessed for two interventions (N=2). Comparing the impact of a 10% variation of transport distances and R for N=2, we see that $E_{Baseline}$ is especially sensitive for change of R (table 1). When R decreases 10% (R=85% instead of R=95%), $E_{Baseline}$ decreases 15%. E is much less sensitive to the transport distance: a 10% longer transport distance results to only 1% increase of $E_{Baseline}$. When the FC product is relocated twice (N=2), it must be reused at minimum 60**%** to equal the impact of the bricks-and-mortar, as shown by the variation of the E_{FC} to R (Figure 4). Consequently, losses during relocation FC should be limited to 40% (in mass) to perform environmentally better than the conventional system.

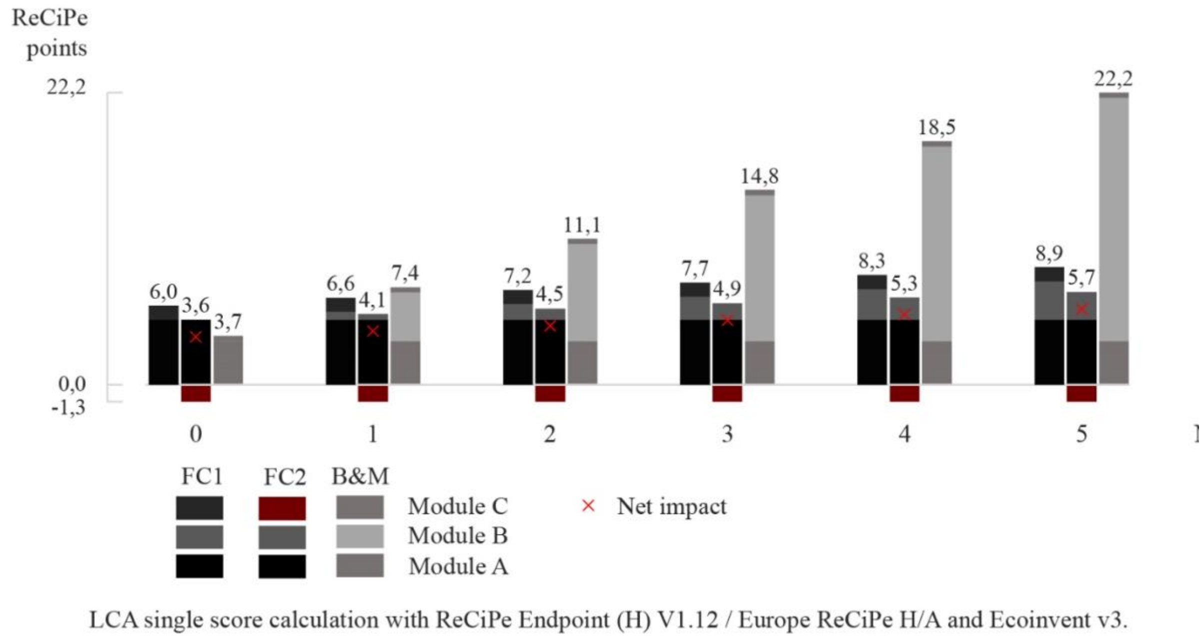

Figure 3. Environmental impact of FC and B&M brick veneers according to the amount (N) of interventions occurring during the period of analysis. In the 'average for Belgium' waste treatment scenario (FC1), the reusable product performs environmentally better than the B&M system from the second reuse (N=2). In the "improved plastic recycling" waste treatment scenario in which the plastic inserts are fully recycled at their end-of-use (FC2), the dry brick system performs environmentally better after the first reuse (N=1).

Table 1. Sensitivity analysis of the parameters influencing the LCA results of the dry brick wall, considering N=2 and $E_{Baseline}$ = 7,08 Points. The most sensitive parameter is the Reuse Rate (R).

Input parameters	Input parameters' value			Resulting E			
	Baseline	$\Delta_{10\%, min}$	$\Delta_{10\%, max}$	E_{min}	E_{max}	ΔE_{min} [relative]	ΔE_{max} [relative]

Transport distance [km]	100	90	110	7,03	7,13	0,56 [1%]	0,05 [1%]
R [%]	95	85,50	/	8,18	/	1,09 [15%]	/ [/]

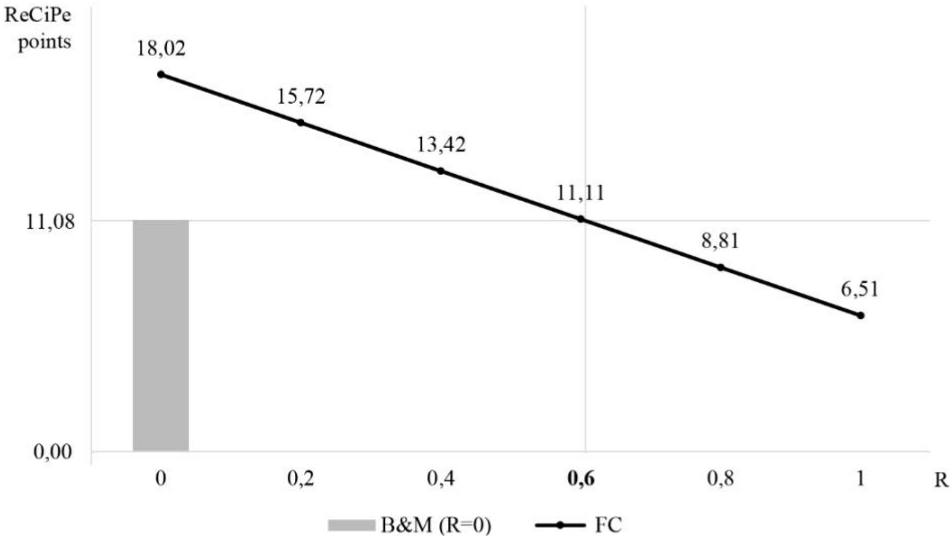

Figure 4. Sensitivity analysis of the Façadeclick's environmental impact to reuse rate (R) value. Considering two interventions (N=2), 60% FC must be reused to equal the impact of the bricks-and-mortar product (11,08 ReCiPe points).

An assumption which is worth discussing is the service lifespan of the sub-products. The service lifespan of all parts of the products is considered higher than the period of analysis (80 years), while the plastic inserts could age faster than the bricks and fail the technical requirement before 80 years. In the model, each time FC is relocated, 5% of the new FC is produced to compensate losses (flows occurring in stage B4 – Replacement of the product life cycle). The remaining service lifespan of these 5% is considered equal to the remaining service lifespan of the other 95%. As a result, the whole product is treated as waste after 5 interventions, although only 75% have effectively reached the end of their technical lifespan and 25% could still be reused.

4. Summary of findings

The case study yields both findings about the environmental impact of the brick veneers and about the parametric life cycle assessment (LCA) method.

4.1. Findings about the environmental profile of the reusable brick veneer

The potential environmental impact of the reusable (E_{FC}) product is 63% higher than the brick-and-mortar ($E_{B\&M}$) product when the veneer is never altered. It is almost similar to $E_{B\&M}$ when the veneer is altered once over the period of analysis and lower than $E_{B\&M}$ when the veneer is altered at least twice. When the plastic inserts are fully recycled, the initial additional environmental impact is always compensated, even without intervention, making both systems almost competitive from the start. These results depend on the simplifications and assumptions detailed in Section 3. E_{FC} is most sensitive for changes in reuse rate (R), while $E_{B\&M}$ is sensitive for changes in the number of interventions (N). When a product is efficiently reused (high R), the product environmental impact is almost not sensitive to N.

4.2. Findings about the parametric LCA method

As shown in the case study, the parametric LCA method proposed in Section 2 allows us to compare reusable and non-reusable products. To assess the LCA of the reusable product, we opt for a system expansion. Therefore, we avoid a complicated distinction of the ‘new reusable’, ‘reused reusable’ and ‘reused non-reusable’ products.

The analysis mixes product and building levels without any problem: the LCA is performed at product level (i.e. the brick veneer), considering use scenarios that are defined at building level. The LCA of the product is made at product level, upon recommendations of the SETAC report [8] and to draw possible use scenarios. For the sake of comparability, reusable and conventional products experience the same amount of use cycles, although this scenario is maybe unprobeable.

The proposed parametric LCA method clarifies how design and use parameters influence the environmental performance of (reusable) products. It shows the potential benefits of Design for Disassembly and Reuse. Thanks to the use of parameters, it also indicates the necessary conditions to realize these potential benefits (e.g. maximum losses, transport distance), which gives a target-based assessment. With the sensitivity analysis, the importance of the different parameters can be qualified and quantified. Common to other LCA studies, the bar chart shows which life cycle module contributes the most to the total environmental impact.

5. Conclusion

As designing a product for future reuse is no guarantee for environmental savings, a life cycle assessment (LCA) is necessary. However, the LCA standards remain ambiguous when the product has more than one use cycle. The main difficulties lie in the selection of the right perspective (building or product), the system boundary and the use scenarios. Additionally, considering many different use scenarios can be very time-consuming.

To overpass those difficulties, we proposed a parametric LCA at product level, with use scenarios defined at building level, combined with a system expansion approach to include the largest amount of use cycles as the product can technically withstand. This parametric LCA provides also good insight about the sensitivity of the model to different parameters (e.g. R, N). More than providing a binary ‘*yes or no*’ answer to the question ‘*Does product A perform environmentally better than product B?*’, this method shows how the environmental impact relates to both design and use parameters. Furthermore, the method can be used as target-driven LCA to support decision-making for the design and the use of building product.

The application of the parametric LCA method to the comparison of reusable and brick-and-mortar veneers shows the competitiveness of the reusable veneer. Considering a baseline waste treatment scenario, this product has a higher production environmental impact than a brick-and-mortar veneer but is competitive when the veneer is altered once. The more interventions, the more beneficial the reusable system becomes compared to the brick-and-mortar veneer. When the plastic inserts are fully recycled, the initial additional environmental impact is directly compensated by savings, from the first use cycle. When the reusable product is relocated and reused twice, the material losses should be limited to 40% (in mass) to compete with the brick-and-mortar veneer.

As illustrated by this case study, the proposed parametric LCA is an insightful yet simple method to evaluate the E of reusable construction products. It can provide product manufacturers with useful insight about the environmental profile of their product and the conditions to use it efficiently. However, the method has been developed according to this specific case study. Further research should verify the applicability of the method to other types of reusable products. Also, the service life modelling could be refined at sub-product level by specifying different R, N and technical lifespan per sub-products.

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Outcomes of a Student Research Project on Circular Building Systems – Focus on the Educational Aspect

Janssens B, Knapen E, Winkels P, Verbeeck G

Faculty of Architecture and Arts, Hasselt University, Diepenbeek, Belgium

bart.janssens@uhasselt.be

Abstract. The growing need to shift from a linear to a circular economy has inspired producers of building materials and systems to innovate their products to match the requirements of a future circular economy. Others have been developing modular systems in the past to simplify the building process and are now reconsidering these products for their potential in a circular economy. However, at this early stage on the road towards a circular economy, claims of circularity are often made too easily and many producers as well as architects and builders are still struggling with the practice of circular building. In this context and within an assignment for master students in architecture, three cavity walls, each 9m² and composed with a different system for the inner and the outer wall, have been constructed and disassembled in order to test their potential for circularity. The extent of circularity has been critically analysed with an existing framework of evaluation criteria for design for change: three criteria on interface level (reversibility, simplicity, speed), three on component level (compatibility, durability, manageability) and three on composition level (independence, pace-layering, prefabrication). This analysis was complemented with an environmental assessment of the materials used and with interviews with contractors who have experience with these systems. In a final step, proposals for improvement of the products and systems have been made and tested on a mock-up scale, in order to better fit a possible future circular economy.

1. Introduction

The exploitation of resources and the linear way in which materials are harvested, consumed and discarded cannot be sustained anymore. The current economy must be transformed to a circular economy model in which a careful use of resources is part of managing a sustainable development. Strategies on an institutional level [1] (e.g. Flemish policy action 'Vlaanderen Circulair': https://www.vlaanderen.be/nl/vlaamse-regering/transitie-circulaire-economie), indicators and research projects have been initiated. Circularity in the building sector is high on public (nationally and internationally) and corporate agendas. As circular building will become key in the professional field, it is necessary that architecture students are being prepared.

Incorporation of circular principles has only begun recently. Producers of building materials and construction systems are rapidly taking the first steps and develop or redevelop products in view of the requirements for circular building. However, the risk is high that in the rush to quickly develop products, claims of circularity are made too easily.

Within this context, master students in architecture of the Faculty of Architecture and Arts of Hasselt University studied the potential for circular building of specific building systems. The objectives were threefold, in order of importance: educational, research methodological, niche development. The educational aspects included i.a.: trigger and train students to become architect-designers with a strong focus on circularity; and the competence to conduct research in a collaborative and critical way. The research methodological objectives consisted of exploring possibilities for actively involving architecture students in research on building-technical aspects (the nexus education – research*)*. The niche development objective fits the research field of the research line 'Sustainability' within the Research Group Arck of the faculty, framed within the 'civic university' model adopted by Hasselt University. Research is conducted on building-technical niches with a societal relevance, in this case building systems that enable circular building and enhance a circular economy model.

Primary aim of this paper is to present and discuss the concept of the student research. Secondary aim is to present tentative and illustrative outcomes of selected circular building systems.

After this first section, this paper consists of four more sections. The second section provides a description of the concept of the student assignment. The third section presents selected systems and composed cavity wall ensembles for the student research. In the fourth section, illustrative results are given and discussed on both the concept of the research as on selected systems and composed ensembles. Finally, a conclusion wraps up findings and perspectives.

2. Concept of the research

2.1. Description of the assignment

2.1.1. Positioning within the curriculum. The master programme of architecture at Hasselt University includes elective research seminars in which the nexus 'education – research' is operationalized. Each of the four defined seminars is linked to a research line of the research group Arck. The seminar 'Building concept' is substantiated by the research line 'Sustainability' of which the research is closely linked to the growing need to deal with the built environment in a more sustainable way. The objectives of 'Sustainability' are (1) to contribute to the scientific founding of sustainable architecture mainly at building level and with a focus on comfort, energy and material performance, and (2) to contribute to supporting the decision making process of both architects and building owners towards more sustainable designs, in line with the ambitions of the EU and Flanders for nearly zero energy buildings and more sustainable material use.

As from the academic year 2017 – 2018 onwards, the seminar 'Building concept' focuses on 'designing and building for/from circularity'. In a living-lab set-up, theory and experiment are used by students, as both designers and builders, to explore the concept of 'circularity' in the built environment. The focus alternates from year to year: one year theoretical models for circularity are studied by research by design on the building level; in the next year, specified circular building systems on the element level are tested. A constant throughout the two years is a critical analysis, a reflection and an optimization.

2.1.2. The assignment as such. Framed within the second part of the two-year cycle, academic year 2018 - 2019 focused on in-situ testing and improving circular building systems for cavity walls. Characteristic for cavity walls are a layered composition of an inside wall (mostly brick), thermal insulation, a narrow cavity, and a façade (mostly fancy brickwork) [2].

In three groups of each five students (mix of first and second master students), the aim was to test the potential of six preselected systems for circularity by the act of building, backed by an assessment with an existing framework of evaluation criteria for design for change and with an existing eco-design tool to evaluate and optimize the environmental impact of the materials used.

The assignment evolves from hands-on explorations, over analysis and assessment by desk-top research, to the formulation of improvements by design & build research. The research assignment consisted of six phases. In the first phase, manufacturers of selected systems presented their products to the students. In the second phase, cavity wall compositions were developed by using two circular building systems (one for the inner leaf; another for the outer leaf). During the third phase, students had to detail the building knots (scale 1:20 to 1:5) of a given in-situ building experiment. The act of building, build and disassemble, was operationalized in phase four. In overlap with phase four, phase five consisted of an assessment. In the sixth and final phase, possible improvements, material wise and/or building-technical wise, were explored and tested in mock ups.

2.1.3. Learning objectives. The set-up of the research seminar holds three learning objectives. A first, and most obvious, objective is to trigger and train students to become (better) circular-thinking architect-designers and builders. The two other objectives, explained in paragraphs below, have a more generic feature: learning and preparing to work in a collaborative way; and the development of critical thinking skills.

In recent years, focus is laid on an 'Integrated Design Process' (IDP). An IDP is a process that purposefully brings together the work of various design and engineering disciplines in order to achieve successful projects outcomes. Following Rovers [3], the IDP is characterized by the integration of several activities in a project team. During an entire project development process, several disciplines/stakeholders (the client, the architect-designer, the specialist-engineers), or the Integrated Design Team (IDT), are involved. The IDP implies a social process between the members of the IDT. "Projects participants work and make decisions not in isolation, but rather within a framework of social interaction". One of the key features of an IDP is working in a group. Due to the growing degree of specialisation of the aspect of designing and building this collaborative way is urged [3-4-5], and therefore seen as an important learning objective.

To prepare students for the complex and dynamic world of the 21st century, professionally, socially and personally, it is necessary to develop critical thinking skills. This is a core theme in contemporary education made explicit by the World Economic Forum [6]. Critical thinking helps to: make informed decisions without being biased; handle, deal with the abundance of information available; understand the learning material and to use it in different contexts; continue learning; deliver a respectful and rational contribution to society; support the transition from the study time to the professional life.

2.2. Framework of evaluation criteria for design for change

For the fifth phase of the assignment, the assessment, the design guidelines for 'design for change' on the element level developed by the Flemish agency for waste management (OVAM) based on Vandenbroucke [7] were used. Nine criteria are differentiated in three aspects: *interface*, which focuses on the interaction between components, holds the criteria 'reversibility', 'simplicity', and 'speed'; *components*, which focuses on the features of the parts, holds the criteria 'compatibility', 'durability', and 'manageability'; and *composition*, which focuses on the whole, holds the criteria 'independence', 'pace-layering', and 'prefabrication'.

2.3. Complementary assessment

In order to have a more complete and a non-univocable evaluation, the environmental impact of selected building systems was assessed with the Ecolizer tool (http://www.ecolizer.be/), an eco-design tool for product design made available by OVAM.

By initiation, complementary assessment was targeted with interviews with contractors who have experience with the systems. However, this was canceled due to time restrictions.

3. Selected systems, composed cavity wall ensembles and set-up building experiment

3.1. Systems

Six manufacturers were willing to collaborate in the research: system 1 – Construclick; system 2 – Facadeclick; system 3 – Systimber; system 4 – Clickbrick; system 5 – Steko; system 6 – Facatile.

Figure 1. The six building systems selected.

3.2. Compositions

Focused on the aspect of cavity walls and taking into account the availability of testing materials, two cavity wall compositions were retained by the tutors, and detailed by the students: composition 1 - Construclick/Facadeclick; composition 2 – Systimber/Clickbrick (see figure 2).

3.3. Set-up building experiment

The in-situ building experiment was conducted at the faculty. Framed within an existing floor, concrete columns and beams, two set-ups of cavity wall constructions of 9m² including a window (A, with a corner; B, without a corner) were designed, built and disassembled (see figure 2).

Figure 2. Left, the two compositions 1 & 2; right, the two set-up building experiments A & B.

4. Results and discussion

Following outlined objectives, this section provides and discusses results: first, regarding the educational and research set-up; second, regarding the studied systems and compositions. The objectives were three-fold, in order of importance: educational, research methodological, niche development.

4.1. Educational aspects

4.1.1. Students' perspective. After the research, students had to submit a self and peer assessment, including a personal reflection on the assignment. These submissions provided valuable insights in the students' perspective on the seminar.

The in-depth focus on materials and construction methods, and having the time and space to experiment with details of/for new ways of building, was believed to be an added value for the curriculum. The set-up of the seminar, with its structure and balance between theory and practice, enabled to gain good insights in circular building, regarding the challenges and opportunities, both for architects and product developers. In addition, the seminar enabled to develop critical thinking skills, inter alia by including an assessment tool. This assessment tool appeared to be both a blessing and a curse, as it was found to be time consuming.

Students appreciated the differing learning process than they are used to. Especially the practice-based approach with the hands-on experimenting was interesting and helpful to gain insights into circular design aspects. In fact, students state that, although it requires a lot of work, more hands-on learning activities in the curriculum would be welcomed. To strengthen their vision, suggestion was made to complement the assignment with a real-life full design/build project such as a small pavilion or a tiny house. This way, students could go beyond analysing materials/products/systems and use their creativity not only as builders but also as designers of spaces and places.

The peer assessment showed that the necessity of working in groups had both positive and negative aspects. Positive was the fact that students with other abilities and points of interest can work together, strengthen the quality of work and learn from each other. Negative part was that working in a team could be difficult, especially when students do not know each other well, when students only see their own opinion, or when students do not show interest or do not collaborate.

4.1.2. Tutors' perspective. Despite the labour intensive preparation, both the collaboration/interaction with system manufacturers and the hands-on approach were seen as promising for the research seminar and will be retained for and even elaborated in following editions. Three issues that must be addressed and need improvement are: (1) the aspect of working in group by students; (2) the aspect of (learning to) assess(ing) in an objective way; and (3) the aspect of encouraging/stimulating/feeding innovation during the development of improvements by the tutors.

4.2. Research methodological aspects in view of the nexus education – research. The nexus worked well mainly due to three aspects. First, the research topic is linked with the architecture and building practice, and has a strong societal relevance. Second, used research methods include tangible aspects (hands-on), and enable to expose outcomes (visibility). Both aspects enable to engage students more easily. Third, an assessment tool is included in the assignment, so outcomes can be validated and incorporated in scientific/academic research. Regarding the latter, a quantitative assessment method is preferred in order to avoid subjective assessments.

4.3. Niche development aspects

For each of the systems and compositions, students proposed and developed improvements based on issues identified by the assessment conducted. This subsection provides some illustrative proposed improvements.

4.3.1. Systems 1 & 2 – composition A. For systems 1 (Construclick) and 2 (Facadeclick) as a whole, three suggested improvements are discussed: a) a circular connection of the systems with the foundation; b) a circular fixation of the watertight slab in connection with the foundation; c) an alternative cavity anchor (see figure 3).

Within the 'reversible' criterion, the assessment showed that the connection with the foundation of both the inner and outer leaf of the composition, respectively system 1 – Construclick and system 2 –

Facadeclick, does not fit the idea of circularity. The application guidelines of both systems prescribe the use of a mortar layer. Students experimented with a mounting lath on a levelled basis (foundation).

The watertight connection between the foundation and the inner leaf is not 'reversible', at least not in the sense of reusing materials. Normally the watertight slab is glued on the outer side of the inner leaf. In order to eliminate this gluing, students thought of a connecting block which can be inserted in the gloves of the inner wall (to fix the cavity anchors). By means of rubber washers and metal screws the watertight barrier can be fixed to this connecting block.

Within the assessment criterion 'simplicity' and 'durability', the used cavity anchors demonstrated weaknesses. The form of the metal anchors needed some adjustments (bending) in order to be placed correctly in the spacers of the inner and outer leaf. This bending was also needed during disassembly so cavity anchors showed usage damage. To tackle this, students designed a compressible anchor which facilitates an easy placement and prevents usage damage.

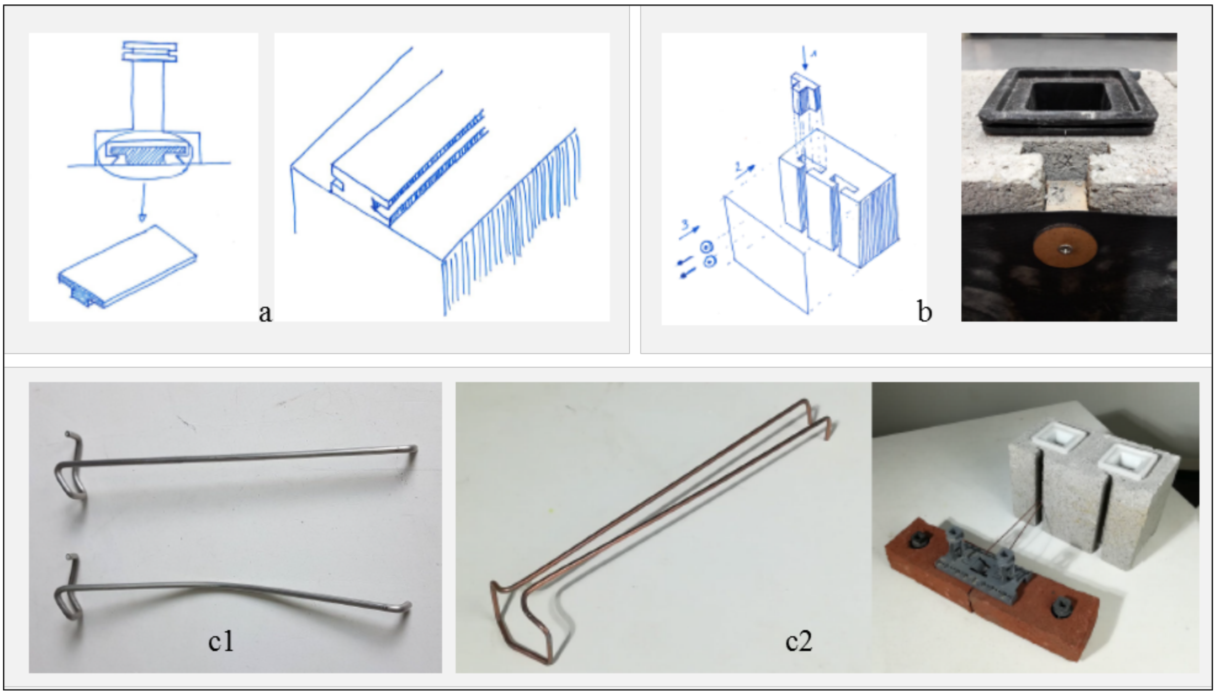

Figure 3. Three suggested improvements for systems 1 & 2 – composition A: a) a mounting lath for a circular connection with the foundation; b) a connecting block to fix the watertight slab between foundation and inner wall; c) with c1 the existing cavity anchor, and c2 an alternative cavity anchor.

4.3.2. Systems 3 & 4 – composition B. For both systems, Systimber (system 3) and Clickbrick (system 4), two suggested improvements are discussed (see figure 4).

During disassembly, it became clear that the metal spacers to connect the wooden beams of the Systimber system were not 'reversible'. Due to a limited grip of the screw machine cap on the head of the spacer, spacers showed such damage that reuse is impossible. Students experimented with wider grip surfaces of the head of the spacer.

Within a cavity-wall composition, Systimber is only limited circular as cavity anchors are drilled in and leave boreholes after disassembly. This may limit the potential for reuse. To prevent this, students designed two possibilities to anchor cavity anchors without leaving traces: first, a slidable two-part connector, in which one part is fixed permanently on the wood and where on the other part the cavity anchor is fixed; and second, the integration of a U-shaped profile in the wood with vertically slidable hooks on which cavity anchors are fixed.

Similar as in systems 1 & 2, the Clickbrick system lacks a circular connection with the foundation. Taking into account the specificities of the system, students designed a metal plate which must be screwed on a levelled basis (foundation).

Regarding the cavity anchors included in the Clickbrick system, a problem of 'reversibility' may appear as it is difficult to unscrew them. Students propose to provide the anchors with a screw head so they can always be screwed out easily.

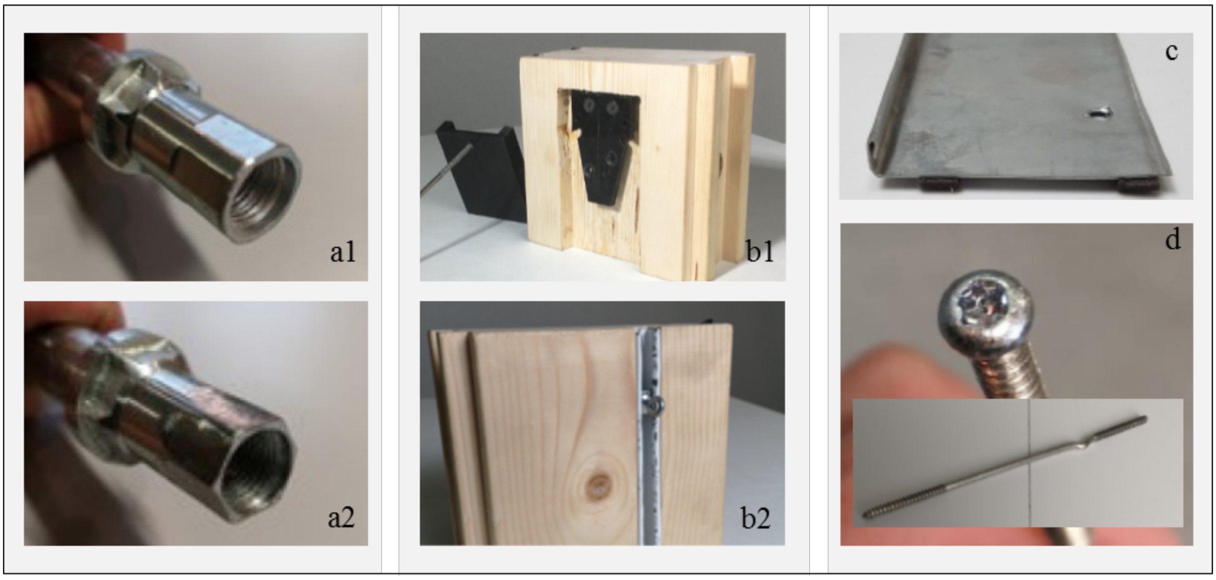

Figure 4. Three suggested improvements for systems 3 & 4 – composition B: a) wider grip surfaces of the spacer (with a1 the existing grip); b1 + b2) two anchoring solutions for cavity anchors; c) metal plate for a circular connection with the foundation; d) a screw head of the cavity anchors.

5. Conclusion

This paper presented and discussed the concept of the student research on in-situ testing and improving of circular building systems for cavity walls within the context of the research seminar 'Building concept' of the architecture programme of Hasselt University.

Based on reflections of both students and tutors, it can be concluded that the concept of the nexus education - research was successful and only needs minor revisions. Students appreciated the focus on new ways of building with a strong societal relevance, the balance between theory and practice and the hands-on experimenting. From the tutors' perspective, the collaboration/interaction with system manufacturers and the hands-on approach was evaluated positive.

Perspectives for future editions of similar student research are: regarding the topic, complementing the assignment with a real-life full design/build project; regarding the educational perspective, including a team building activity in order to improve the aspect of working in a group, and using tailored pedagogical methods to encourage/stimulate/feed innovation during the development of improvements by the students; from a research point of view, selecting a quantitative assessment method which avoids subjective assessments, and which is easy and quick to use by students.

Concerning the circular building systems, the research demonstrated that all systems as such work, are easy to use and fast to assemble and disassemble. Small-scale incremental improvements, as proposed by the students, on the individual system level are required. However, fundamental improvements and research regarding following aspects (non-exhaustive) are believed to be crucial for a full and successful application of the idea of circular building: circular connections between circular building systems and other building components (e.g. foundation, windows, roofs), compatibility (e.g. dimensions, connections) with other circular building systems, watertight and vapor tight sealing of both surfaces and joints, diversity of products within circular building systems (e.g. tailored lintels, corner solutions), broad building type (in view of needed performances) and project type application range (e.g. renovation); prefabrication potential, lowering the environmental impact (e.g. especially of connecting components) of existing circular building systems, and more broadly development of new circular building systems based on renewable and regenerative resources and considering open source knowledge and system development to maximize the development and implementation potential of circular systems.

Acknowledgements
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Integrating Earthen Building Materials and Methods into Mainstream Construction Using Environmental Performance Assessment and Building Policy

Ben-Alon L[1], Loftness V[1], Harries K A[2], Cochran Hameen E[1]

[1] School of Architecture, Carnegie Mellon University, Pittsburgh, PA 15217, USA
[2] Department of Civil and Environ. Engineering, University of Pittsburgh, Pitt, PA 15260, USA

rbenalon@andrew.cmu.edu

Abstract. Earthen building materials offer an environmentally sustainable alternative to conventional materials because they are locally available, minimally processed, and waste-free. However, they have not been comprehensively implemented because their technical data is highly variable, and they are not fully represented in building codes. To address these hurdles, this paper presents an environmental assessment and a policy repair review, including an environmental embodied impact analysis, and a discussion of the regulatory development required for earthen construction. The results of the environmental assessment show that earthen wall assemblies significantly reduce environmental impacts by 62-99% when compared with conventional assemblies such as timber frame and concrete blocks. Additionally, the policy discussion provides recommendations to overcoming materials variability and regulatory organizational collaboration. Overall, this paper highlights the importance of environmental and policy measures that could be used by policy makers and earthen building advocates in their endeavours to catalyse the representation of earthen building materials and methods in mainstream construction.

1. A brief history of unsustainable architecture

Throughout history, human building practices followed the path of building shelters out of locally abundant materials, where the building components were always mined and curated from the nearby environment: earth, stone, trees and grasses. The evolution of these various shelters was developed in different cultures by improving materials, energy, water, and waste solutions, adjusting from generation to generation to meet new needs and opportunities [1,2].

It is only in the last few centuries that our relationship with buildings has changed. Cementitious materials started playing a vital role in the ancient world: the Egyptians obtained cementitious material by burning gypsum; the Greeks used lime by heating limestone; and the Romans developed hydraulic cement by adding crushed volcanic ash to the lime [3]. These techniques were re-developed and patented in western Europe as “Roman ––Cement” (in 1794) and “Portland Cement” (in 1824) [2,4].

These last developments, accompanied by the industrial revolution, changed the way building materials were produced and the techniques used for construction. Started as a wave in Western Europe, these highly-processed building materials and methods are still spreading into less-developed parts over the world. Thousands of new building products have been developed and replaced local traditional materials in ways that minimize labor and allow an increase in the pace and amount of construction. Nevertheless, these modern building practices require the extraction, transportation, and heavy processing of (often toxic) building products in ways that contribute to the consumption of large amounts of non-renewable resources, contributing to the deterioration of our global environmental [5].

In terms of building materials standardization, conventional modern construction materials, mostly made of steel reinforced concrete, wood, and synthetic insulation, are being implemented in the majority of modern buildings while meeting a wide variety of building codes and standards. Therefore, in light of the environmental impacts specified above, these building codes and standards (that were initially developed to ensure individual safety and public general welfare) are currently neglecting larger, ecologically-based risks to natural systems upon which everyone's safety and health ultimately depend [6]. Nonetheless, due to an increased interest in sustainable and green building practices, additional non-mandatory regulatory and rating systems have been developed that support materials and resources considerations in projects, as shown by the growing numbers of L.E.E.D^{TM} certified projects [7,8].

2. Why earth? The case for earthen building materials and methods

Parallel to the interest in sustainable and green building practices, there has been a growing interest in ecological and natural building materials and methods [8]. These are defined as minimally processed and locally available materials that enhance their local environment and economy, rather than only mitigating negative impacts [9]. Examples of natural building materials include natural fibers like straw and hemp, and earthen materials like sand and clay. Specifically, earthen materials exhibit various advantages; they provide high thermal inertia and offer better structural capacity in compression. As opposed to trees and crops, earth is usually abundant in and around the construction site. As opposed to cellulose-based materials, it has better resistance to fungi, insects and rodents. Furthermore, it allows a diversity of forms and styles, from sculptural monolithic assemblies to modular components [10].

Earthen architecture can be defined as building materials and methods in which clay is used as a binder [11]. It is also often referred to as a traditional and/or vernacular building material and method [12]. However, some earthen building techniques were developed in the past few decades (e.g., compressed earth blocks), while others were used traditionally and currently receive a new architectural interpretation (e.g., rammed earth) [13,14]. More specifically, in recent decades, material science has come to know much more about how clay works as a natural binder in building materials. Therefore, earthen building materials are recently suggested to provide a natural concrete alternative, namely a low-carbon, clay-based concrete [11].

Despite their benefits, earthen building materials and methods remain mostly unrealized in the mainstream construction industry from various reasons. First, the literature lacks aggregation of technical data that could quantify the performance of earthen materials for different climate and seismic conditions [15,16]. Second, there is a broad and often mistaken perception of these materials as being low-tech and having poor overall performance [8,17]. Lastly, one of the main barriers that is especially evident in the case of cob and earthbags is the lack of complete and user-friendly codes and regulations that could give rise to the conventional implementation of, for instance, affordable homes [6,18].

These concerns are broadly echoed in the literature. Woolley (2006) concludes that public policy incentives, particularly formal codes and regulations, should be developed for earthen materials, accompanied with financial incentives, in order to give rise to real-estate investments. Similarly, Swan, Rteil, and Lovegrove (2011) suggest that future research should a) aggregate the existing experimental engineering studies; b) provide analytical and numerical insights that could facilitate the design process and allow the inclusion of earthen materials in building codes; and c) provide a life cycle analysis of earthen construction assemblies.

3. Performance-based assessment of earthen building materials vs. conventional assemblies

The performance of a building material describes its functioning in terms of declared characteristic properties. Depicted though levels, classes or short descriptions, these performance parameters can portray the main features of earthen materials as opposed to conventional assemblies.

Table 1. Technical performance of earthen materials as opposed to conventional materials

	Performance Parameter	Earthen Building Materials			Timber Frame [19]	Concrete Masonry [20] uninsulated (insulated)
		Cob	Rammed Earth	Light Straw Clay		
Thermal	Thermal Resistance (m^2K/W per inch)	0.051 [21] to 0.106 [22]	0.025 [21,23] to 0.06 [24]	0.14 [25] to 0.26 [26]	0.5-0.7 (with fiberglass batt)	0.05 (0.15) [27]
Thermal	Thermal capacity (kJ/m^3K)	1655 [28]	1830 [29]	400 [26]	10 [26] (25) [30]	170-380, depending on grouting [31]
Thermal	Decrement factor time lag (hour)	12 [21]	18.5 [26]	6.5 [26]	9 [26]	14 [26]
Thermal	Indoor RH amplitude			13.7% [25]		(22.6%) [25]
Environmental (Sec. 4.	Embodied energy MJ_{eq}/m^2	86.4	71.1	65.4	241	226 (uninsulated), 491(insulated)
Environmental (Sec. 4.	Global climate change $kgCO^2_{eq}/m^2$	13.2	11.1	10.6	62.7	53.1 - 74.8
Environmental (Sec. 4.	Air acidification $kgSO^2_{eq}/m^2$	0.00679	0.00279	0.0125	0.0781	0.061 - 0.142
Environmental (Sec. 4.	Air particulate pollution $PM_{2.5eq}/m^2$	0.00247	0.00145	0.00225	0.0574	0.130 - 0.143
Structural	Compression modulus (N/mm^2)	72 [32,33] to 650 [16]	550-960 [34]	Not load bearing	7,000-18,000 along grain [34]	15,000 - 60,000 [34]
Structural	Rupture modulus (N/mm^2)	0.17 [32] to 0.98 [33]		Not load bearing		
Others	Sound Transmission Class (STC)		57 [10]		33 [10]	55 [35]
Others	Fire resistance	Fire resistant [34,36]		Fire retardant [34,36]	Combustible requiring treatment or oversizing (ISO type 1).	Semi Fire Resistive (ISO type 5).

4. Environmental embodied impacts of earthen construction vs. conventional assemblies

Environmental LCA has become a common tool that is used to evaluate building products and processes. It is considered a powerful tool for the evaluation of and contribution to sustainable building development. [37]. However, LCA progress is slower in the building sector than other industries, especially due to buildings' complicated production process. Although the environmental LCA of earthen materials has not been comprehensively studied, it has been argued extensively that earthen materials and methods can potentially require less energy and emit less Green House Gasses (GHG), due to their self-sustaining, socially sustainable, cradle-to-cradle life cycle, as shown in Figure 1 [34].

Only a few studies have enumerated the environmental impacts of earthen building materials, including the LCA of adobe bricks [38,39], rammed earth [40,41], and earthen plasters [42,43]. Though significant, these studies are not comparable with conventional assemblies, due to the location and process-specific data used. To address this limitation, this study compares the environmental impacts of different earthen construction techniques to benchmark conventional techniques.

The presented LCA was implemented following the ISO Standard 14040 and 14044 format and methodology [44,45], using the SimaPro software [46], the US-LCI database [47] where possible, and EcoInvent [48] processes that are globally applicable otherwise (i.e., RoW processes). Six wall assemblies are compared: 3 earthen walls (cob, rammed earth, and light straw clay) and 3 conventional walls (timber frame, insulated and uninsulated concrete block). The functional unit used is 1 square meter of a single-family housing wall, located in warm-hot climates in the US, defined as IECC climate zones 1 through 4 [49]. The system boundaries consider embodied environmental impacts from cradle to construction site, including the extraction and processing of raw materials, manufacturing, storage, and transporting to the construction site.

Figure 1: Cradle to cradle life cycle diagram of earth as a building material (edited from Schroeder, 2016)

The Life Cycle Impact Assessment (LCIA) includes embodied energy demand, global climate change impacts, air acidification, and human health (HH) air particulate pollution. The impacts were assessed using CED (Cumulative Energy Demand) factors for fuels and sources of energy [50] and the TRACI (Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts) for inventory emissions [51]. Weight distribution was calculated for each of the earthen wall components: straw, sand, clay-rich soil, and clay plaster. The cob and rammed earth walls were assumed to have an average 460 mm thickness [52,53], and the light straw clay wall a 300 mm thickness [54]. Clay-rich soil was assumed to contain 50% clay and the study accounts for a scenario in which this soil is not available on site and thus is processed and transported from a quarry. The LCA of the benchmark wall assemblies was assessed using existing LCI results. Specifically, the wood frame LCI incorporated lumber [55], plywood sheathing [56,57], gypsum board [58], and fiberglass batt. The concrete LCI incorporated concrete blocks [61], rigid polystyrene insulation [59], and Portland cement stucco [60]. These LCIs were selected according to their corresponding system boundaries of cradle to gate and geographical context of North America.

The impact assessment results, shown in

Figure 2, illustrate that all earthen wall systems have significantly lower environmental impacts as opposed to the benchmark wood and concrete block assemblies. Embodied energy demand of earthen walls is reduced 62-71% from that of conventional construction; embodied global climate change impacts are reduced 85-91%; embodied air acidification is reduced 79-95%; and embodied particulate pollution is virtually eliminated. These comparative results depict the environmental urgency of using earthen materials.

Specifically, transportation distances and amount of straw have the strongest effect on the environmental impacts of the different earthen walls. Among the earthen walls, light straw clay accounts for the least energy demand and global climate change impacts, due to its smaller thickness, as well as the absence of the sand and soil that require truck transportation. The rammed earth wall, with the same thickness as cob, results in fewer environmental impacts than cob for all impact categories due to its absence of straw that requires large amounts of chemicals for production. For the same reason, light straw clay has the highest impacts in terms of air acidification, following by cob, due to the straw production-stage emissions of methane (CH4), sulphur dioxide (SO2), and nitrogen oxides (NOx), associated with the use of pesticides and fertilizers.

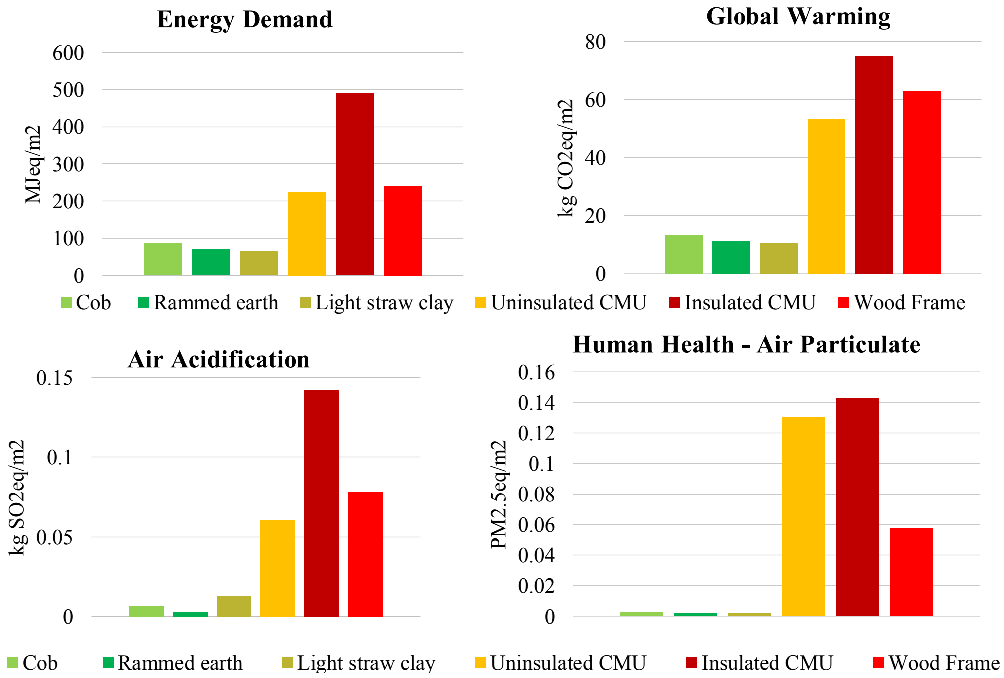

Figure 2: Environmental embodied impacts comparison among the different wall systems: cob, rammed earth, light strw clay, uninsulated Concrete Masonry Unit (CMU) blocks, insulated CMU, and wood frame (Source: authors)

5. Required Improvements to Earthen Building Policy

5.1. The Importance of Earthen Codes and Standards

The importance of earthen building materials standardization lies in both technical and sociocultural realms. In terms of their technical significance, standards for earthen materials gather accurate design values as well as provide a common frame of reference for the user community – a lingua franca of sorts. Technical performance tests could be compiled to obtain a more reliable understanding of the material's properties based on a statistical analysis which can lead to the refinement of, and confidence in, design values. This, in turn, could lead to a broader integration of the material in the construction community. Such integration, coupled with advocacy, can lead to broader social acceptance of what was previously considered a marginalized vernacular construction method [62]. While approximately a third of the world population lives in earthen structures, in both developing and developed countries, the existence of appropriate codes is of importance. However, current building codes are based on heavily processed materials such as concrete and steel products, earthen techniques that cannot fulfil heavy load bearing and high insulation requirements were excluded [63].

5.2. Challenges and Suggested Solutions to the Development of Earthen Codes and Standards

In order to embed earthen building materials in building standards and codes, their performance should be assessed through the work of universities, laboratories and professional organizations. To date, earthen building materials and methods are still considered nonconventional and their standardization is in its earliest stages; design, construction, testing protocols and technical terminology, even among experts, is fragmented and requires further evolution. However, in this context, even conventional construction materials such as steel, timber, and reinforced concrete were once unconventional and unproven materials and their acceptance was achieved through decades of testing, analysis, and experience. Codes and standards development has been described as "a long and onerous" process (Mottram 2017). Particularly for materials having few existing precedents, the task is daunting and meets resistance at many steps. The following lists many of the challenges and possible strategies to overcoming these.

5.2.1. Overcoming Materials Variability. One of the main challenges to the emergence of earthen materials standards is their high variability and reliance on local construction methods. Additionally, earthen materials are often locally sourced and processed or mixed on site. Such variation effects both the construction process (e.g., workability, drying time) and the performance of the building outcome (e.g., structural, thermal, durability). For instance, in an experimental study of cob technical performance, specimens were collected from local builders, resulting in a high coefficient of variation among the different mixtures [32]. In terms of building standards, this high variability could reduce characteristic strength values that could result in inefficient utilization of the material. This, in turn, could potentially lead to unrealistic required building element dimensions and higher environmental and monetary costs. Furthermore, due to their variability, and in order to verify their code compliance and desired performance, natural materials require frequent field tests.

The challenge of material variation could be addressed by various strategies. By using wood as an example for a natural building material with large variability, we can identify the ways in which we developed both prescriptive and performance standards for timber. While the number of wood species is great, the main strategy used in timber standardization is to group species according to their structural properties and appearances, prescribing uniform grade-use data for each group. Similar to timber codes and standards, a homogenization approach grouping different species or 'classes' of clay materials should be developed for earthen materials to ensure adherence with format and objectives of conventional standards.

Figure 3: Homogenized soil classification, assessed in accordance with Australian Standard [64]

5.2.2. Establishing Collaborative Standardisation Framework to Overcome Financial Challenges. Earthen building materials are non-commodified systems that have no 'industry association'. Often, they cannot be developed into products and cannot be patented. This leads to a lack of financial support and advocacy of nonconventional and vernacular materials at code and standards organizations and committees, whereas established conventional building materials representation is often compensated by their organization [65]. Additionally, national standard-writing organizations with limited resources and volunteer committees have little incentive to address technology that is often considered marginal.

One way to overcome this situation is to have existing experts organize in a way that can produce valuable exchange of experience and technical documents. For instance, in the case of the New Zealand earth building standards, the Earth Building Association of New Zealand (EBANZ), with the participation of local engineers and architects, first developed a set of guidelines in 1991. Thereafter, New Zealand Standards (NZS) took responsibility for the project and joined together with Standards Australia in 1993 to develop a joint standard with an enlarged committee [66]. The collaboration was discontinued in 1997 mainly due differences in seismic requirements, yet the exchange of information and expertise was valuable. One year later, NZS published the New Zealand earth building standards (NZS 4297, NZS 4298, NZS 4299), which comply with the local Building Code. Simultaneously, Standards Australia developed *The Australian Earth Building Handbook* (HB-195 2002) and the Earth Building Association of Australia (EBAA) developed the *Building with Earth Bricks and Rammed Earth in Australia* (EBAA 1997). The hybrid approach of Standards and non-standards bodies' development of construction guidance for earthen material is summarized in Figure 4.

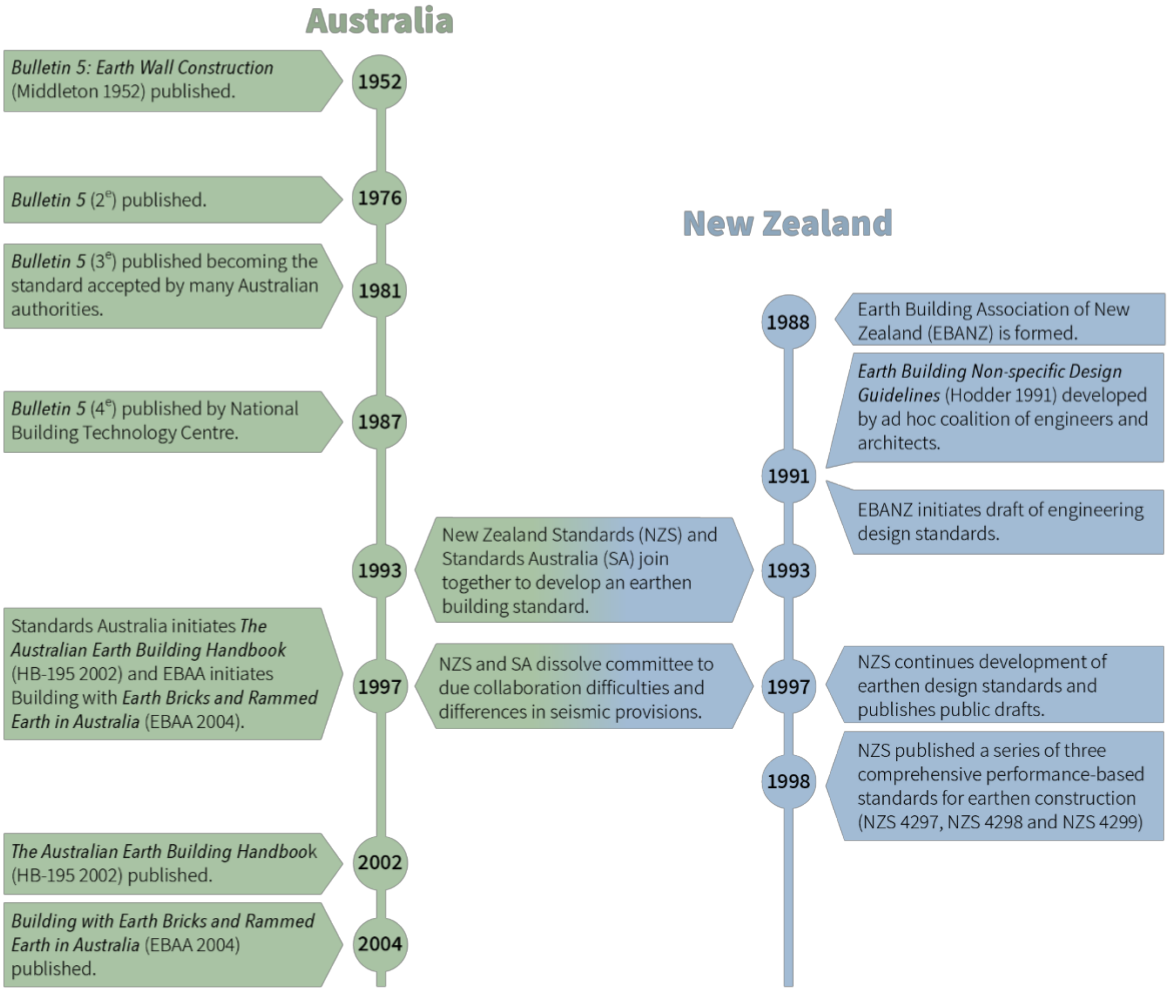

Figure 4: Timeline of New Zealand and Australia Earth Building Standards development process (Source: authors)

Additionally, using verb form is crucial to earthen building regulatory development. Similarly to NZS, Code-compliant mandatory language could allow reference from within building codes. Enacting documents or clauses – those that represent a legal obligation – are conventionally required to provide unequivocal and imperative requirements: "shall". Recommendations ("should") and permissive language ("may") are relegated to non-mandatory appendices or documents and are legally unenforceable, such as in the case of ASTM E2392.

5.2.3. Enriching traditional techniques with modern knowledge. Experience from previous generations that is well preserved in local tradition and dutifully transmitted to people living today can be the basis of an informal, non-codified "standard". For instance, bamboo standards consider the use of traditional practices as those constituting an "old and pure tradition" or treated as "general wisdom" within a community. The application of such traditional expertise is limited to similar scenarios and may not be extrapolated in terms of dimensional scale or locale [67].

Codes and standards reflect state-of-practice rather than the state-of-the-art. Therefore, the development of a sound 'engineering judgement' is an iterative process of continuous improvement and is reflected in the maintenance of standards worldwide. For this reason, standard development for earthen materials must begin with synthesis of the existing engineering data, as well as documentation and enhancement of local practices. Such synthesis requires using consistent test procedures in materials test studies, as well as proper documentation and analysis of results. To date, researchers studying earthen materials have adopted different established test methods – some for concrete materials, others for masonry units, and even others for masonry assemblies – and their attendant specimen geometries. These result in a considerable range of reported data that cannot be directly compared. In some cases, test method selection results in a bias in reported properties. For example, it has been shown that different studies report the compression modulus of cob material to vary by an order of magnitude depending on the test method used [68].

5.2.4. Establishing Clarity and User Friendliness in Earthen Building Codes. "Usability" of a standard, as the word implies, must be based on the needs and expectations of the user. An alternative to presenting design examples is to develop navigation flow charts for design standard provisions or typical design cases (for instance, as provided in [69]). These serve to improve ease of navigation but are also a tool the standard authors can use to ensure clarity and completeness. Development of a design work flow chart can identify provisions which are incomplete, lead to 'dead ends', or result in complex iterative procedures.

Additionally, the purpose of the code or standard should be clearly defined in order to reduce complexity and to refine its scope. For instance, a very specific scope statement is included in the New Zealand Earth Building Standards: *The objective of this Standard is to provide for the structural and durability design of earth buildings. The Standard is intended to be approved as a means of compliance with clauses B1 and B2 of the New Zealand Building Code* (NZS 4297). A more general suggested example may be an object *to codify existing knowledge in order to ensure structural safety, as well as to address common design situations while providing means of compliance with building codes and supporting innovative design*.

When considering earthen materials that are often nonconventional and vernacular, the user community might be further removed from the standards development process, increasing the risk of misinterpretation. This might lead to the standards simply not being applied at all. On one hand, the opportunity afforded by nonconventional materials for starting with a "blank page" when developing standards should be used to mitigate unnecessary complexity. On the other hand, existing codes and standards as well as committee constitutions that prove successful should be used as exemplars to avoid excessive complexity that results from "re-inventing the wheel".

6. Conclusions and Required Future Steps

Earthen building materials and methods offer a prominent solution to conventional highly processed materials. However, despite their advantages, earthen materials and methods have not been comprehensively implemented because their technical data is inconsistent, and they are not comprehensively represented in building codes. To address these hurdles, this paper begins with a comparative synthesis of the technical performance of earthen materials as opposed to conventional assemblies. Thereafter, the paper presents an environmental LCA that enumerate the environmental urgency of earthen materials, showing that the earthen walls save 62-71% of embodied energy demand, reduce 85-91% of embodied global climate change impacts, 79-95% of embodied air acidification and

98-99% embodied particulate pollution. Lastly, a discussion of the regulatory development required for earthen construction is presented, including main challenges and recommendations to overcoming these, including ways to overcome challenges of materials variability, collaborate between advocates and organizations, integrate traditional expertise with state-of-the-art knowledge, and establish language and scope clarity. Future studies on the environmental and policy measures should incorporate a full LCA that takes into account operational impacts, as well as develop inventories for a complete set of earthen and natural wall assemblies that could be used against inventories of benchmark wall assemblies.

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Comparative analysis of an existing public building made from natural building materials and reference buildings designed from common building materials

Medgyasszay P

Department of Construction Materials and Technologies, Budapest University of Technology and Economics, Hungary

medgyasszay.peter@epito.bme.hu

Abstract. The paper examines a public building constructed of partially natural materials and two imagined buildings with the same geometry, using LCC and LCA methods, with self-developed software. The imagined buildings were designed using the building materials and building mechanical systems commonly used in Hungary which fulfil the relevant energetic requirements in 2010 and in 2019. As a sensitivity analysis the LCA performance of buildings was examined with residential building function. The paper introduces the environmental benefits that can be obtained with natural materials and with other tools in case of the examined building. Based on the results, design strategies can be phrase for environmentally conscious design of buildings with similar scale and function.

1. Introduction

The building industry, despite of the noteworthy increase of environment-conscious attitude, has a significant role and responsibility to handle the challenge of climate change, as one of the most important present problem of humanity. The buildings and construction are still responsible for the 36% of global final energy use and 39% of energy-related carbon dioxide emissions. According to the forecasts by 2060 230 billion m^2 new building floor areas will be constructed. This floor area is equivalent to the field area that in the next 40 years every single week the territory of city Paris would be inbuilt. [1]

To reduce the building industry-related energy consumption has several possibilities and strategies. Based on the publication of Global Alliance for Buildings and Constructions for 2050 the aims *"Achieving a large diffusion of net zero energy buildings"* and *"Reducing embodied energy and GHSG emissions"* have significant priority in the next 10 years. [2] The combination of these two aspects is also important because more and more building materials have to be produced in order to achieve better insulation. By using life-cycle approach analysis, like Life Cycle Assessment (LCA) with environmental focus or the Life Cycle Cost Analysis (LCC) with economic focus, we can find the optimum of the two, sometimes conflicting goals. Our previous research confirmed that natural building materials can achieve a low value in both embodied and operational energy need, because of their low primer energy content. [3] [4]

In the paper, a realized and two imaginary public buildings will be analysed with LCA and LCC methods. The imaginary buildings are the same as the realized building, but their material use and building service systems are representative for the age of the design and the present days. As a sensitivity analysis, beside the public building function the calculations were carried out also for a residential building function. The goal of this paper is to highlight the magnitude of environmental benefits that can be gained through natural materials and other measures.

2. Methodology

2.1. Case study building: realized building.

The constructed case study building was designed in 2010 by the Belső Udvar Architect and Expert Office by Péter Medgyasszay, Ágnes Novák and Péter Büki architects. [5] The whole project was introduced in details in previous publications. [6] [7] In the following, only the examined two-building complex Demonstration Centre will be described, where a small restaurant and kitchen on one side, the reception, auditorium and other functions on the other side are located. The two buildings form an inner yard, surround an artificial lake (figure 1). One end of each building is lower by 80 cm than the other. This arrangement of curved walls results in a sense of fake perspective in the enclosed space of the two buildings. Each building is in the scale of a Hungarian country-house (approx. 8,5x28 m), but because of the non-conventional wall shape and the large roofs, the two-building complex has a unique view (figure 2 and figure 3).

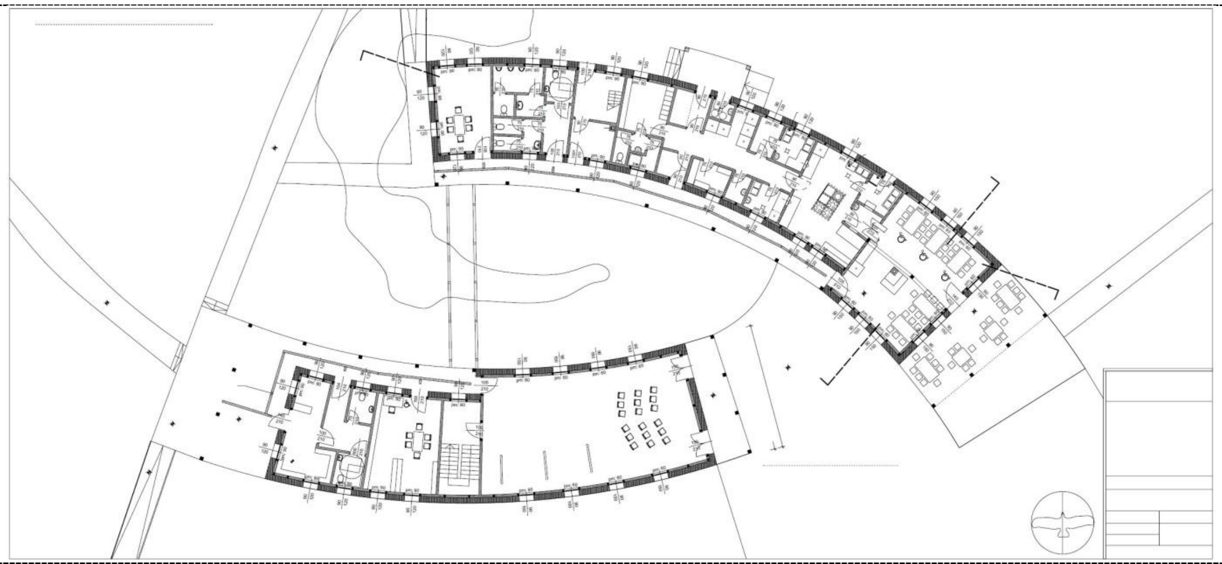

Figure 1. Ground floor layout of the Demonstration Building [5]

Figure 2. View of the Demonstration Centre from the parking. [Medgyasszay]

Figure 3. View from the terrace with the inner yard and the artificial lake [Medgyasszay]

The Demonstration Centre, also to demonstrate the environmental goals of the whole project, was built partially from natural building materials. Due to the deep loadbearing soil level and the considerable movement of the underground water, it was necessary to use pile foundation and beam grid under the walls. The beam grid structure was highly insulated due to low energy demand of the building. The external wall structure is constructed from a wooden post and beam structure. The wooden "ladder" frame consists of 10/15 cm pillars at the inner side and 5/10 cm pillars at the outer side at an average of 90 cm distance. The 15 cm thick adobe wall was positioned between the wooden loadbearing columns. The adobe hand-made bricks were produced in 20 km distance from the building site. The outer side of the walls are insulated with 35 cm thick straw bales harvested and collected from the nearby fields. The wall was plastered on both sides with adobe-plaster and painted with limewash. The roof was covered with tiles. The doors and the windows were made from wood with triple glazing. The floors were covered with ceramic floor tiles, brick and wood (figure 4).

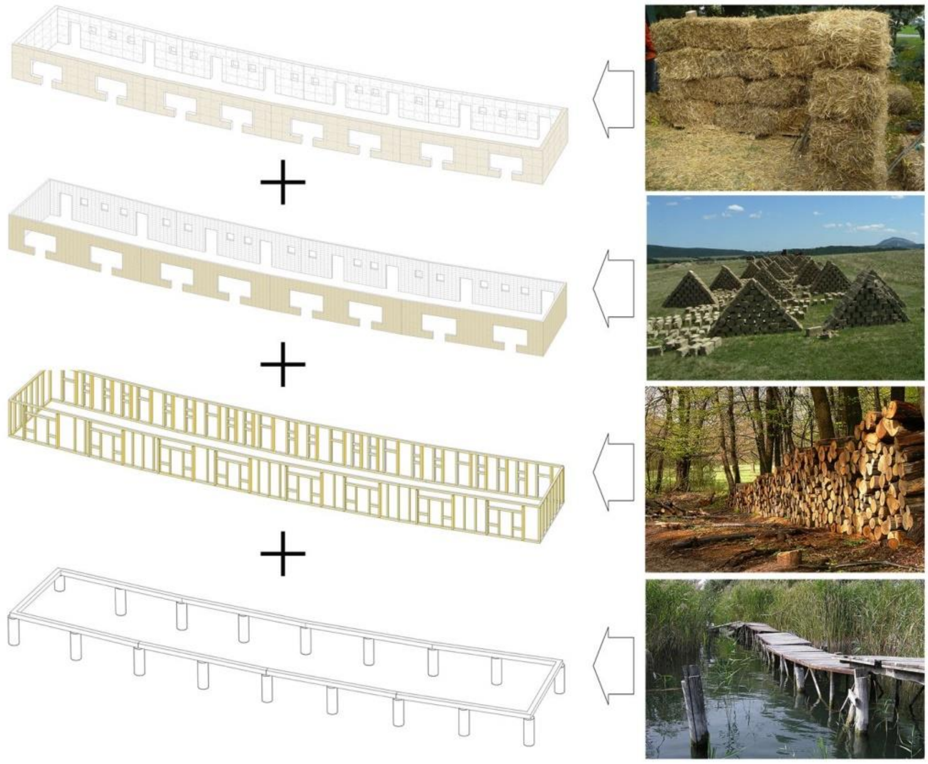

Figure 4. Structure and materials of the external wall, the foundation and the roof [6]

As heating system a wood chip boiler was installed with low temperature floor heating. A ventilation system was installed only in the kitchen area. Because of the good heat storage and heat insulation capacity of the constructions, no air-conditioning system was designed. The hot water need of the building was also covered by the wood chip boiler.

2.2. Case study building: imaginary building 2010

The design principle of the "imaginary case study building 2010" was to define an average Hungarian building from the year of the design what fulfil the actual energetic requirements with the same geometry as the constructed one. The external load-bearing wall was designed from brick (Porotherm 38 N+F), and in the slab on the ground construction 6 cm expanded polystyrene insulation (EPS) was planned. In the roof construction 15 cm rockwool was planned and the openings were assumed as wood construction with double glazing. The rest of the building was conceived with the same structures as the built building.

The heating system was imagined, as a common Hungarian system, with low temperature gas-boiler and radiator units. Like the realized building, the ventilation system was designed only for the kitchen, and no air-conditioning unit was applied. [8] [9]

2.3. Case study building: imaginary building 2019

The design principle of the "imaginary case study building 2019" was to define an average Hungarian building from the year 2019 what fulfils the present energetic requirements with the same geometry as the constructed one. The external load-bearing wall was designed from brick (Porotherm 30 N+F) with 10 cm EPS, and in the slab on the ground construction 12 cm EPS was planned. In the roof construction 25 cm rockwool was planned and the openings were imagined as wood construction with triple glazing. The rest of the building was conceived with the same structures as the realized building.

The heating system was imagined, as a common Hungarian system, with condensing gas boiler and radiator units. Like the realized building, the ventilation system was designed only for the kitchen, and no air-conditioning unit was planned. The following table introduces the differences of three building (table 1).

Table 1. Comparison of the structures, building services and energy demands of the realized and imagined buildings

	Realized building	**Imagined building 2010**	**Imagined building 2019**
Foundation	pile foundation	pile foundation	pile foundation
External wall	wood frame, adobe brick and straw bale insulation U=0,15 W/m^{2}K	brick wall U=0,45 W/m^{2}K	brick wall with 10 cm EPS U=0,22 W/m^{2}K
Roof and attic floor	wood frame, 25 cm rock wool insulation U=0,15 W/m^{2}K	wood frame, 15 cm rock wool insulation U=0,24 W/m^{2}K	wood frame, 25 cm rock wool insulation U=0,15 W/m^{2}K
Slab on the floor	flooring, concrete, 5 cm EPS, 5 cm XPS insulation U=0,33 W/m^{2}K	flooring, concrete, 6 cm EPS, insulation U=0,49 W/m^{2}K	flooring, concrete, 12 cm EPS, insulation U=0,3 W/m^{2}K
Openings	wood frame, triple glazing U=0,8 W/m^{2}K	wood frame, double glazing U=1,4 W/m^{2}K	wood frame, triple glazing U=0,8 W/m^{2}K
Heating, HWS	wood chip boiler	gas boiler	condensing gas boiler
Air conditioning	no	no	no
Ventilation	only in the kitchen	only in the kitchen	only in the kitchen
Primary energy demand of heating (kWh/m^{2}a)	9 as public building, 41 as residential building	25 as public building, 86 as residential building	12 as public building, 54 as residential building
Primary energy demand of hot water (kWh/m^{2}a)	5 as public building, 16 as residential building	15 as public building, 38 as residential building	15 as public building, 37 as residential building
Primary energy demand of ventilation (kWh/m^{2}a)	16 as public building, 0 as residential building	18 as public building, 0 as residential building	18 as public building, 0 as residential building
Primary energy demand of lighting (kWh/m^{2}a)	9 as public building, 0 as residential building	9 as public building, 0 as residential building	9 as public building, 0 as residential building

2.4. Calculation method: energy demand and vapour calculation

All calculations performed for the case study were made with the Belső Udvar E-P-LCC-LCA software. [10] The software development started in 2006 according to the methodology described in the Hungarian Government Decree on the Energy Performance of Buildings. [11] In addition to the initial, simplified energy calculation method, the software used a detailed method from 2010 onwards. The so called "detailed method" with the calculation of the solar gain depending on the orientation of the glazed surfaces and the length of the heating season enabled the software to calculate the energy demand of low-energy buildings with a good approximation. The building, as a specific public building, has different user behaviour profile from a common house. The spaces are not heated in the whole heating season, but in the kitchen area intensive ventilation (8 1/h) is necessary. As basic energy data the following parameters were taken into account:

- average air-change rate: 1,16 1/h,
- internal heat gain: 7 W/m^2,
- correction factor because of intermittent use: 0,4,
- net specific energy demand of lighting: 6 kWh/m^{2}yr,
- reducing factor of lighting: 0,6,
- nett specific energy demand of hot water supply: 7 kWh/m^{2}yr.

During the energy calculations the avoidance of interstitial condensation in external constructions was also checked. A vapour module was developed in 2008, which allows steady-state investigation of water vapour adsorption in structures according to the Hungarian calculation method [12].

2.5. Calculation method: Life Cycle Cost Analysis

The LCC module of the software was developed in 2011 in the framework of research financed by the JRC. [13] The global costs were calculated according to the European Directive 244/2012/EU and its guideline. [14] [15] To the investment costs were added the sum of annual costs for every year (energy costs, maintenance, replacements, etc.) and was reduced with the residual value, all expressed as Net Present Value referring to the starting year. It is important to emphasize that if the investment has shorter lifetime than the calculation period (e.g. mechanical equipment) additional investment (replacement cost) was calculated. [15] The lifetime of mechanical equipment was calculated according to the EN 15459. [16] The lifetime of each layer of building constructions was calculated according to the recommendation of Bundesministerium für Verkehr, Bau und Stadtentwicktung. [17] As economical basic data the following parameters were taken into account:

- calculation period: 30 years,
- discount rate, excluding inflation 4%,
- long-term energy price escalation: 2% for electricity and wood and 2.8% for natural gas.

The investment cost of building materials and mechanical systems materials, including the price of material and labour, were taken from cost databases [18], manufacturer data and quotes. The cost of heating and domestic hot water production was 50 HUF/kWh for electricity, 8,3 HUF/ kWh for wood chips and 16 HUF/kWh for natural gas.

2.6. Calculation method: Life Cycle Assessment

The LCA module of the Belső Udvar E-P-LCC-LCA software was developed in 2012 based on previous research. [19] [20] For the calculation of the environmental impacts, the method of life cycle assessment (LCA) was applied, following the norms ISO 14040 and ISO 14044. The functional unit was one building per one year. The environmental data of building materials and mechanical systems were divided by their life time, as the environmental data of operation was calculated according to the energy calculation. Environmental data from the Swiss ecoinvent 2.0 database were used, with certain modifications to account for the Hungarian circumstances where necessary. [19] Due to the typical environmental impact caused by the construction industry, only three impact categories were considered: [21]

- non-renewable cumulative energy demand (CED, n.r.) [MJ]
- global warming potential (GWP100a, CML 2001) [kg CO2-eq]
- acidification potential (AP, CML 2001) [kg SO2-eq]

2.7. Sensitivity analysis

In addition to the results calculated for the special public building, LCA tests were carried out for a more general function, examining the function-sensitivity of the findings. The building was also examined as a residential building according to the user behaviour profile described in TNM 7/2006. [11]

3. Results

During the LCC investigations, the problem appeared that due to the economic crisis of 2012 and the change of the Hungarian energy price support policy, the buildings from 2010 and 2019 are not comparable from economic point of view. Because of this reason, for the LCC result only the value of the Realized building and of Imagined building 2010 are introduced, both as public building and as residential building. (figure 5-6)

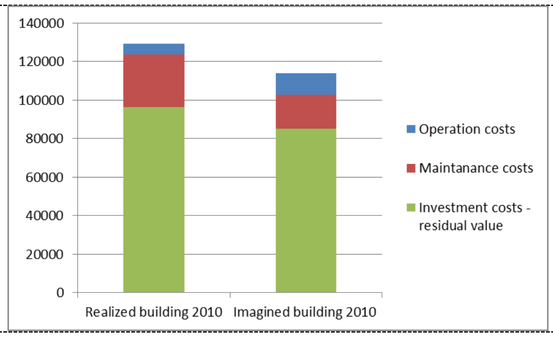

Figure 5. Global costs of the case study building from 2010 with public building function [1000 HUF]

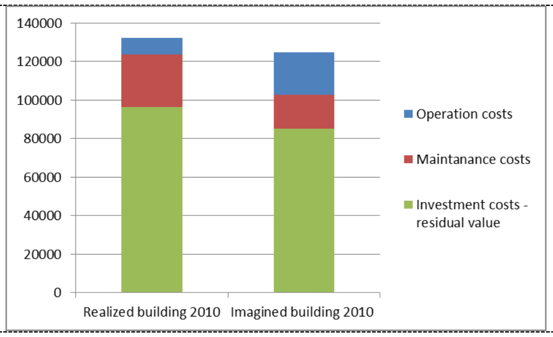

Figure 6. Global costs of the case study building from 2010 with dwelling function [1000 HUF]

The global cost of the Realized building, with higher energy quality and using natural materials, is higher than the global cost of the Imagined building. The higher global cost is caused by the higher cost of investment and maintenance, which was not compensated by the lower operating costs. It is important to emphasize that the higher installation costs (difference of 11,5 mFt) were only partly caused by the additional cost of the wall structure based on natural building materials (1 mFt). The other extra cost (10,5 mFt) was the difference in the cost of the higher energy-quality slabs, roofs and doors, as well as the higher cost of the mechanical equipment. If the building is used more intensively as a residential building, with the higher operating costs the global cost difference decreases (from 16.3 mFt to 7,3 mFt), but in the case study examined, the building with lower investment cost still has a lower global cost.

Figure 7-12 show the LCA results of three buildings as a public building and as a dwelling. In the realized building, the use of natural materials was primarily realized in the construction of the wall structure. Therefore, in the diagrams describing the results, the environmental loads associated with the construction of the wall structures are separately identified. It is also possible to identify separately the environmental load associated with the installation and the operation, the sum of which gives the whole lifetime value.

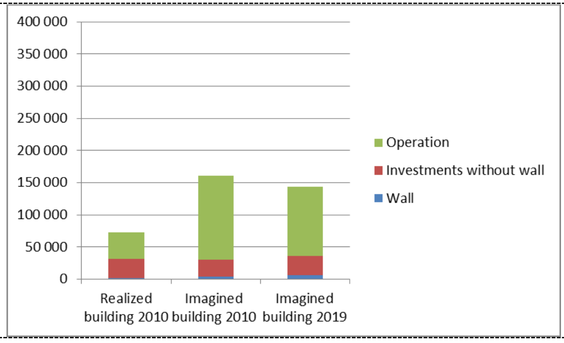

Figure 7. Cumulative energy demand of case study buildings with public building function [MJ/yr]

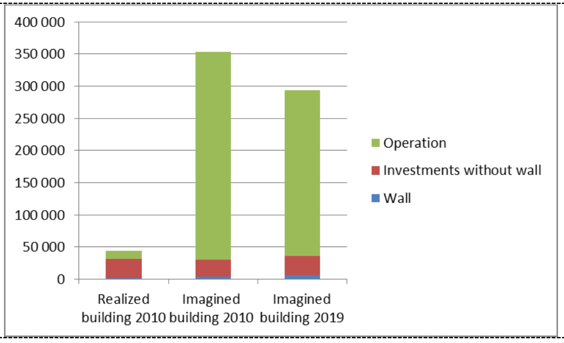

Figure 8. Cumulative energy demand of case study buildings with dwelling function [MJ/yr]

Figures 7-8 show that building structures made of natural materials are significantly more advantageous in terms of cumulative energy demand than conventional structures (1394: 4090: 5766 MJ/yr). However, the significant difference is due to the biomass-based heating system in the examined case studies. The greater is the importance of operation phase, the greater are the savings.

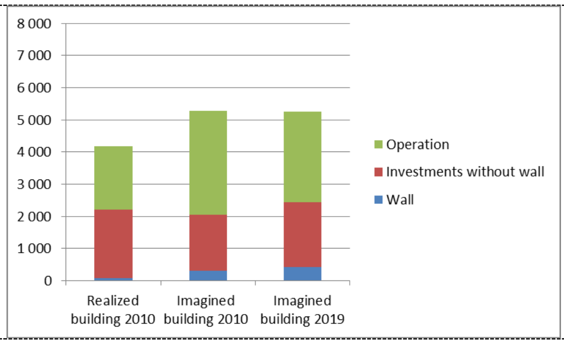

Figure 9. Global warming potential of case study buildings with public building function [kg CO_2-eq/yr]

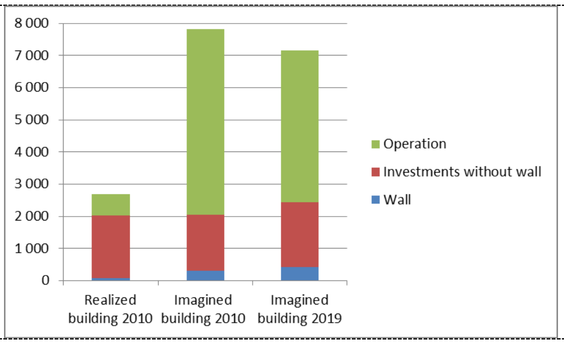

Figure 10. Global warming potential of case study buildings with dwelling function [kg CO_2-eq/yr]

Figures 8-9 show similar lessons to Figures 6-7, but the construction phase has a greater role than the operation phase. Savings in global warming potential by natural building materials are more significant than the savings in cumulative energy demand.

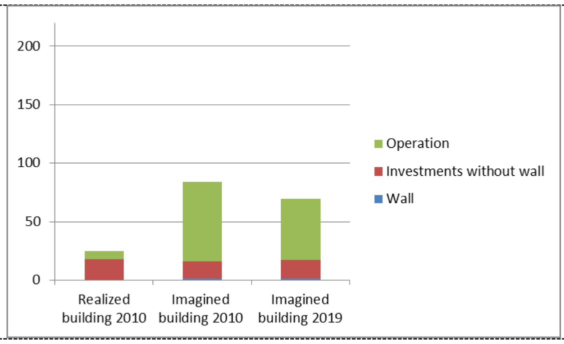

Figure 11. Acidification potential of case study buildings with public building function [kg SO_2-eq/yr]

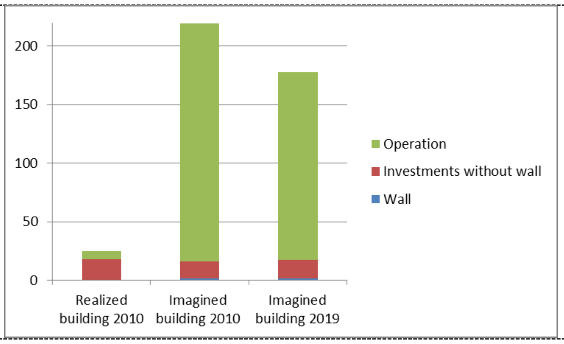

Figure 12. Acidification potential of case study buildings with dwelling function [kg SO_2-eq/yr]

4. Conclusions

The case study in this paper proved that natural materials can be used to achieve environmental savings. The wall structure made of natural materials is significantly more favourable in all calculated environmental parameters than commonly used wall structures (e. g. 66-76% saving in CED content). It is important to note that the wall structure of the "Imagined 2019" building results higher environmental impact than the "Imagined 2010" building due to higher energy requirements. It means that the environmental benefits of using natural materials will become more and more important in the construction of increasingly energy-intensive buildings.

However, the use of natural materials has in many cases technical limits, and in several constructions it is not appropriate to achieve the desired construction quality. In the examined case studies, the environmental savings associated with natural materials are not significant compared to the environmental impact of the whole building. In the case study, the greatest environmental benefit is not connected to the construction phase but to the operation phase. The mechanical system based on non-fossil energy has always resulted significant savings. These benefits are even more significant in the case of a function requiring higher operating energy (residential building) than in the case of the examined public building function.

The most important practical experience of this case study is that from the point of view of LCC analyses the phase of construction, while from the point of view of LCA analysis the operation phase is dominant. This caused a major contradiction in terms of investor and environmental goals. The investor side is interested in the construction of the cheap, energetically and environmentally weaker quality buildings. In contrast to achieve the environmental goals the most energy-efficient building is needed that uses the most natural materials, but in many cases with larger investment cost.

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Environmental impact of timber frame walls

Steeman M[1], Himpe E[1], Vanroelen M[1], De Roeck M[1]

[1]Ghent University, Building physics research group

Marijke.Steeman@UGent.be

Abstract. Timber frame walls are increasingly applied nowadays due to the stringent energy performance requirements of buildings. The aim of this study was to investigate the environmental impact of this type of construction. Therefore, a cradle to gate analysis was used. The study consists of three consecutive steps. First the impact of the constituting materials was studied. The results show e.g. that the environmental impact of LVL studs is significantly larger than that of SLS studs or I-joists. Based on these results on material level, in the second stage three timber frame walls were designed and evaluated. All walls had the same thermal performance. When comparing the results, it was noted that the environmental impact of the wall with the highest impact is three times larger than that of the wall with the lowest impact. Finally, the study also looked at the additional impact of tapes for guaranteeing the air tightness of timber frame constructions and at the impact of fasteners. It could be concluded that the impact of tapes is negligible when looking at the total impact of the wall (less than 1%). The fasteners on the other hand, lead to an increase in environmental impact with almost 20%.

1. Introduction

Buildings have a large impact on our environment: 25% of the total primary energy use is related to the use of buildings while 40% of the CO_2-emissions are generated by fossil fuels used in buildings. On the other hand, a large amount of energy is embodied in the building materials. Studies show that in a typical Belgian dwelling 10 to 30% of the total environmental impact is caused by the building materials [1]. As the energy performance of buildings increases, the relative impact of the building materials will rise due to the lower operational energy use at the one hand and the larger amount of materials (i.e. insulation materials) on the other hand. Therefore it is important to gain insight in the environmental impact of construction elements.

As the energy regulations move the construction sector towards thicker insulation layers, timber frame construction elements become in favour. Figures show that in the past years timber frame is used more frequently. In 2011, in 5,9% of the new Belgian dwellings timber frame construction was used. In 2016 this figure was almost doubled (9,3%). It is expected that this number will further increase to 15 to 20% in 2020 [2].

Therefore the aim of this work is to gain insight in the environmental impact of timber frame walls. In a first step the environmental impact of the constituting building materials is studied. Based on these results on material level, in the second stage three timber frame walls were designed and evaluated. Finally, the influence of fasteners and air tight tapes on the total environmental impact is investigated.

2. Methodology

The analysis is carried out in Simapro version 8.4.0.0 with the Swiss Ecoinvent database v3.3 [3]. As many building materials that are used in Belgium are in whole or in part produced in Europe, the

European context is a good estimation for the Belgian context. Moreover, it is shown that the European electricity mix is a good assumption for the Belgian electricity mix [4].
Furthermore the allocation default model in Simapro is used. The building materials considered in this analysis are mainly primary materials. This means that materials do not consist of recycled or reused materials. In that way allocation is avoided.

The ReCiPe end point (h) method is used. The study includes a cradle to gate analysis, meaning the operational phase and the end-of-life phase are excluded from the analysis. Hence mining, production of materials and transport of materials to the building site are considered.

During forest growth CO_2 is captured in wood. This energy is released during wood incineration. When however, different life cycle phases are split up and the embodied energy in timber construction is analysed, the initial energy is of no interest because it is not related to production or transportation. When on the other hand, wood is used as a fuel (biomass), it is important to include the initial embodied energy [4]. Consequently, for this study the initial energy is not included in the analysis.

In the analysis replacements are only taken into account for finishing materials when looking at the environmental impact of the timber frame wall. It is expected that construction materials such as sheathing boards will not be replaced during the life span of the timber frame construction (60 years). The life span of the building materials that are used in timber frame construction is based on [4].

3. Impact analysis of constituting materials

The constituting materials are divided according to their functionality: structural elements, thermal insulation material, interior sheathing board, exterior sheathing board, interior finishing boards and exterior finishing materials.

3.1. Structural elements

Three types of structural materials are considered: I-joists, laminated veneer lumber (LVL) beams and massive spruce studs (SLS) The functional unit is the material that is needed for a structural part of 1 m^2 of timber frame wall of a typical single family dwelling with three floors. The wall has a heart to heart distance of 40 cm, which is typical for this type of construction. This results in three vertical studs per functional unit. Table 1 shows the material volumes that were taken into account. The life span of all structural elements is 60 years [4].

Table 1. Material data for timber frame structures

Category	Materials	Dimensions (mm)	Volume (m^3)
SLS	Sawnwood	45x184	0,025
LVL	Laminated timber	45x200	0,027
I-joist (45x200)	Sawnwood (web)	45x45	0,012
	Fibreboard (flanges)	6x126	0,002

Figure 1a shows the impact of the wood structure included in $1m^2$ of timber frame wall. As wood is used as a structural element, the impact on Land use is significant, which leads to a higher score on the Ecosystems category compared to Human Health (HH) or Resources. When comparing the three types of structural elements, it is noted that the impact of the LVL studs is larger than that of SLS or I-joists. Two explanations can be found: when applying LVL studs a larger material volume is used. On the other hand the material is used less efficient: to produce $0,027m^3$ laminated wood $0,053m^3$ softwood is necessary, while less is necessary to produce SLS studs. The I-joist clearly has the lowest impact in the Ecosystems category which is due to the lower amount of wood used. Furthermore the use of synthetic resin in LVL studs generates a high impact on HH and Resources. This is also the reason why I-joists have a slightly higher impact than SLS in these categories.

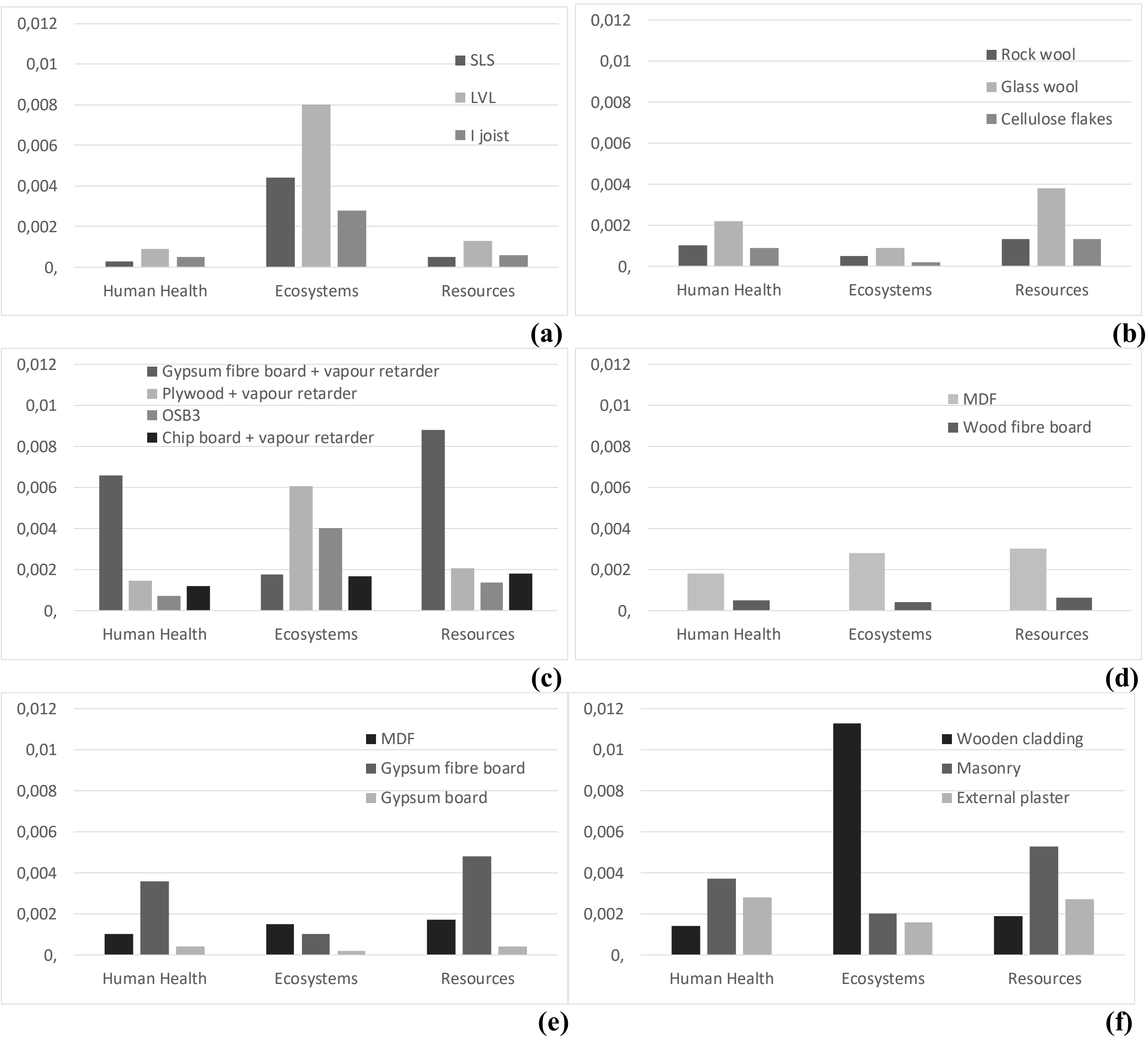

Figure 1. Normalized impact of wood frame structure (a) ; insulation material (b) ; interior sheathing board (c) ; exterior sheathing board (d); interior finishing boards (e) and exterior finishing materials (f)

3.2. Thermal insulation

Next, the environmental impact of three types of insulation material that are typically used in timber frame construction is evaluated: cellulose flakes, glass wool and rock wool. The functional unit is 1 m² of material with a heat resistance R_c of 4,17 m²K/W. This corresponds to a U-value of about 0,24 W/m²K which is a requirement for new walls in Belgium. Life span of insulation materials is 50 years [4].

Table 2. Material data for thermal insulation materials

Category	Thermal conductivity (W/mK)	Layer thickness corresponding with R_c = 4,17 m²K/W	Density (kg/m³)	Mass for 1m² wall (kg)
Cellulose flakes	0,040	0,167	50	8,33
Glass wool	0,039	0,163	40	6,50
Rock wool	0,035	0,146	45	6,56

Figure 1b shows that glass wool generates the highest impact, while cellulose flakes have the lowest impact. The production process of glass wool is energy-intensive, explaining the high impact on Resources. Furthermore polymerised synthetic resin based on urea is used during production, having an impact on HH. Cellulose flakes are produced from recycled newspaper. The impact on HH and Resources is due to the use of zinc during the production process where it is used for a better bond between the paper fibres and the boron salts.

3.3. Interior sheathing board

The impact of four types of interior sheathing board is compared: gypsum fibreboard, plywood, oriented strand board (OSB) and chipboard. All boards have a comparable thickness, representative for a typical thickness that is available on the market (Table 3). The functional unit is 1 m². In order to take exclude the risk of interstitial condensation in the timber frame elements, an additional vapour barrier is added for all sheathing boards except OSB. The life span of all sheathing boards is 50 years [4].

Table 3. Material data for interior sheathing boards and vapour retarder

Category	Thickness (m)	Density (kg/m³)	Mass (kg)	Volume (m³)
Gypsum fibreboard	0,018	1150 kg/m³	20,7 kg	-
Plywood	0,019	650 kg/m³	-	0,019
OSB3	0,018	600 kg/m³	-	0,018
Chipboard	0,019	680 kg/m³	-	0,019
Vapour retarder (PE film)	0,0002	-	0,188	-

Figure 1c shows the results. Gypsum fibre board has the highest impact on HH and Resources. This is explained by the use of zinc during production. The impact of the other sheathing boards is lower for these categories, and largely determined by the amount of binder that is used for compressing the wood into a plate material. The impact on Ecosystems varies for all sheathing boards and is the highest for plywood. This can be explained by the amount of wood used during production. E.g. in the production of chip boards a large amount wood residues are used, resulting in a relatively low impact on this category. Furthermore, the impact of the vapour retarder showed to be negligible [6].

3.4. Exterior sheathing board

The impact of wood fibre board (WFB) is compared with the impact of medium density fibre board (MDF). Both boards have a thickness of 0,018 m, which is a typical thickness available on the market. The functional unit is 1 m². The life span of the sheathing boards is 50 years [4].

Table 4. Material data for exterior sheathing boards

Category	Thickness (m)	Volume (m³)
WFB	0,018	0,018
MDF	0,018	0,018

Results can be found in Figure 1d. A large difference between MDF and WFB is observed. Though the impact of MDF is on average lower than the impact of other sheathing boards as shown in Figure 1c, it is clearly higher than the impact of WFB. The low impact of WFB is explained by the use of wood residues from saw mills (low impact on Ecosystems) and the use of lignin as a natural binder instead of synthetic resin glues during production (positive effect on HH and Resources).

3.5. Interior finishing boards

Gypsum fibre board, MDF and gypsum board (also known as plaster board) are commonly used as an interior finishing board. Once again, materials with a typical thickness available on the market are considered. The functional unit is 1 m², the life span of these materials is 50 years [4].

Table 5. Material data for interior finishing boards

Category	Thickness (m)	Density (kg/m³)	Mass (kg)

Gypsum board	0,0095	810,5	7,7
Gypsum fibre board	0,010	1150	11,5
MDF	0,010	760	7,6

Results can be found in Figure 1e. The impact of gypsum fibre bard and MDF was already discussed in Figures 1c and 1d. Note that the impact of MDF used as an interior finishing board is lower than when used as an exterior sheathing board due to its reduced thickness.

Figure 1e shows that the impact of gypsum board is the lowest for all categories. The gypsum used in the production of gypsum boards either is a natural product or it is originated from flue-gas desulfurization of brown coal power plants, explaining its low environmental impact. The production also requires zinc, which results in a higher impact on HH and Resources. Gypsum fibre board generates the highest impact of all three materials.

3.6. Exterior finishing materials

Three types of exterior finishing layers are considered: bricks, external plaster and wooden cladding. The material thicknesses that are considered in table 6 are based on a correct technical design. E.g. for the wooden cladding, vertical wooden battens (30 x 24 mm) are used, with a heart to heart distance of 60 cm. Hence, two vertical battens per functional unit of 1 m² of finishing layer are taken into account.

Note that the life span of the finishing materials differ: for masonry, external plaster and wooden cladding the life span is respectively 80, 15 and 30 years [4]. This means that for the external plaster and the wooden cladding replacement of materials has to be taken into account. During a life span of 60 years the plaster layer will be replaced 4 times, while the wooden cladding requires one replacement.

Table 6. Material data of exterior finishing materials

Category	Components	Density (kg/m³)	Thickness (m)	Mass (kg)	Volume (m³)
Masonry	Bricks	1900	0,075	116,15	-
	Mortar	1800	-	5,31	-
External (mineral) plaster	Fiberglass reinforcement	-	-	0,44	-
	Plaster	1700	0,015	99,20	-
Wooden cladding	Vertical wooden battens	450	0,030	-	0,0029
	Horizontal wooden boarding	600	0,018	-	2

Figure 1f shows the results of the impact analysis. The outlier in the Ecosystems category pops out immediately: the use of wood generates a large impact on Ecosystems. On the other hand, the impact of wooden cladding on the HH and Resources is relatively limited.

The impact of the brickwork is determined by the ceramic stones, the influence of the mortar in the joints is rather limited. The material mainly has an impact on Resources: on the one hand this is due to the high energy use in the burning of ceramic bricks requiring fossil fuels, on the other hand it can be explained by the exhaustion of mineral resources used for the production of ceramics.

The main resources needed for the production of mineral plaster are sand and cement. While sand is a natural product, the use of cement generates a high impact because of the high temperatures in the production process, causing a high energy demand. Because of the replacement during the total life span, the overall impact of plaster becomes larger. Due to this, the impact of plaster will be higher on HH and Resources than that of a wooden cladding.

When considering all three categories, from an environmental point of view the mineral plaster is favourable over the masonry façade and the wooden cladding.

4. Impact variation of timber frame walls

Based on the previous results on material level, in a second step the constituting materials are combined in three timber frame wall designs. Care is taken that the construction is correct from a hygrothermal point of view. All walls have a similar thermal transmittance U of 0,22 W/m²K.

Figure 2 shows the wall constructions: the first timber frame wall is constituted from materials with an overall low impact ("low impact wall"), while the constituting materials with an overall high impact are used in the "high impact wall". Finally the environmental impact of these wall types is compared with that of a typical timber frame wall design used in Belgium.

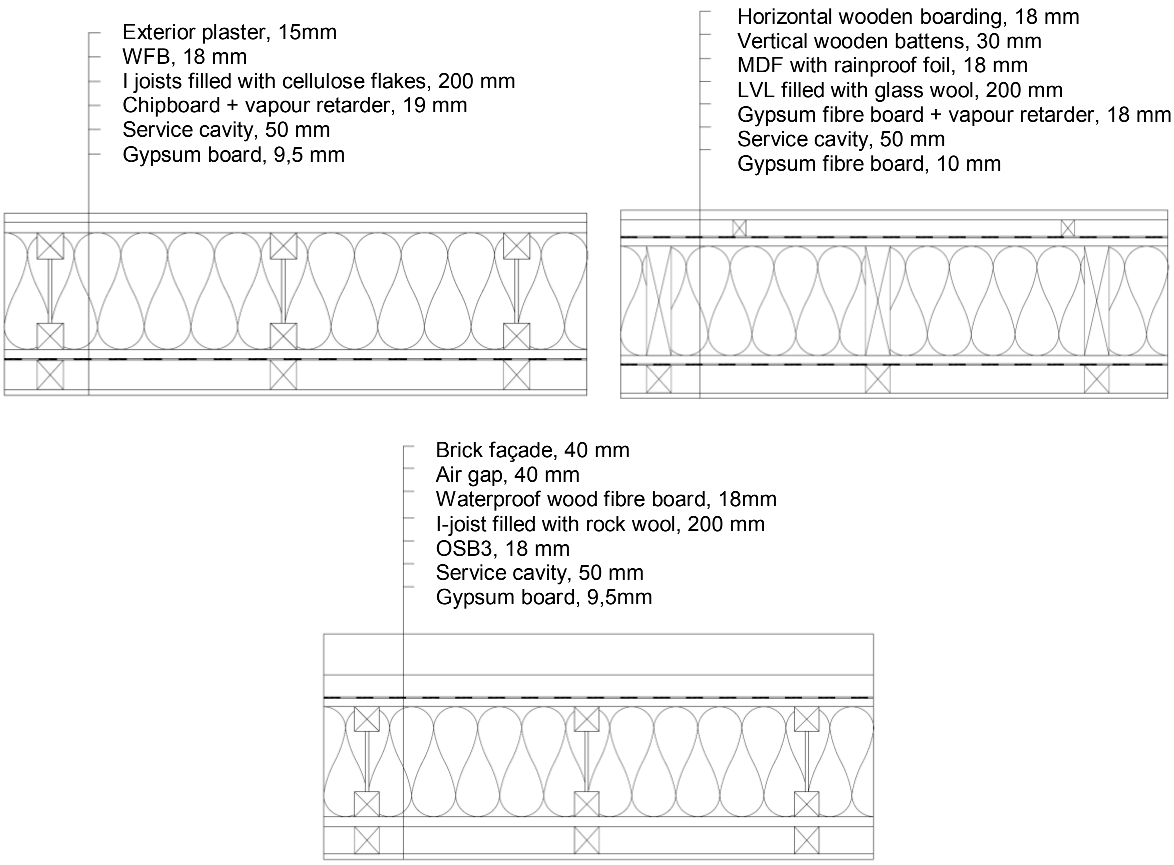

Figure 2. Low impact wall (upper left), high impact wall (upper right) and typical Belgian timber frame wall construction (below)

Figure 3 shows the environmental impact of the three wall types. It can be seen that the impact of the low impact wall is about three times lower than that of the high impact wall, for each of the impact categories. Furthermore it can be observed that the impact of the typical timber frame construction is more leaning towards the low impact wall: the impact on HH and Resources is comparable (slightly higher), while the impact on Ecosystems is about 25% higher.

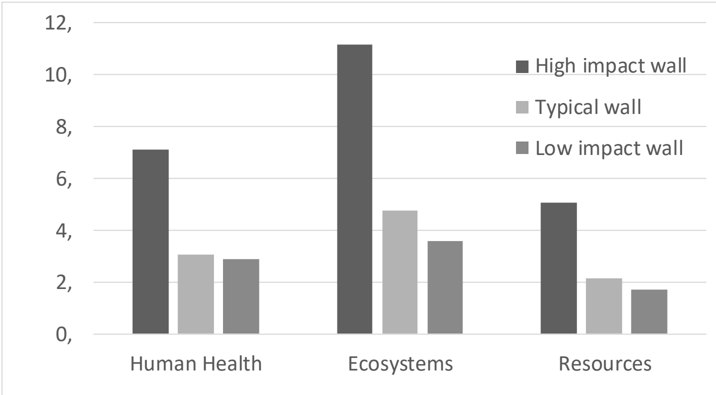

Figure 3. Impact variation between timber frame wall constructions

5. Impact of fasteners and tapes

In a last step the impact of fasteners and tapes that are necessary to guarantee the airtightness of a timber frame wall are included in the impact analysis. The impact analysis is based on the typical timber frame construction shown in figures 2 and 3. In order to evaluate the environmental impact a wall with and without fasteners and tapes is compared. A timber frame wall of 3 m length and 2,44 m height is considered (total area of 7,32m²). Taking into account a heart to heart distance of 40 cm, the timber frame wall consists of 8 vertical studs.

Following fasteners are included in the wall, based on typical practice:

- Cavity anchors: 4 per m² of brick façade
- Staples to fasten WFB (dimensions 600 mm width x 2500 mm height), spacing 100 mm
- Staples to fasten OSB3 (dimensions 600 mm width x 2440 mm height), spacing 100 mm
- Screws to fasten gypsum board (dimensions 1200 mm width x 2600 mm height), spacing 200 mm

The boards are cut to a height of 2,44 m and to the width between two vertical studs (40 cm). The amount of fasteners and their total mass can be found in Table 7. All fasteners are made of stainless steel (density 7930 kg/m³).

Table 7. Fasteners

Category	Number	Length (m)	Diameter (m)	Volume (m³)	Mass (kg)
Cavity anchors	30	0,160	4,00	-	0,44
Staples wood fibre board	196	0,042	1,48	0,000336	2,66
Staples OSB3	196	0,042	1,48	0,000336	2,66
Screws gypsum board	98	0,035	4,20	0,000047	0,38
Screws horizontal wooden beam	32	0,060	4,20	0,000027	0,21
Threaded rod	4	0,060	6,00	0,000007	0,05

Furthermore, airtight tape is considered:

- At all seams between the OSB3 boards (8 seams x 2,44 m height); and
- At the top and bottom of the timber frame wall (2 x 3 m)

Table 8 summarizes the total amount of tape used.

Table 8. Air tight tape

Running meter (m)	Width (m)	Mass (kg/m)	Mass (kg)
25,52	0,06	0,0277	0,71

The results show that the impact of a wall including fasteners and tapes is higher than that of the wall excluding fasteners and tapes. This finding is quite logical as an additional amount of material is added, i.e. 6,40 kg of stainless steel and 0,71 kg airtight tape. By taking into account these secondary materials, the impact increases with 17,75%. This means that one fifth of the total impact of a typical timber frame wall is due to the fasteners and tapes. When only air tight tapes are included in the impact analysis, the impact increases with only 0,81%. This shows that the impact of air tight tape is negligible, whereas 16,94% of the total environmental impact results from the fasteners.

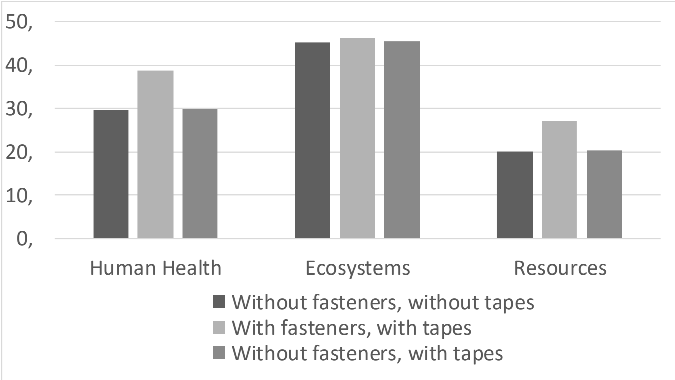

Figure 4. Impact of fasteners and air tight tapes

When analysing the impact categories, Figure 4 shows that the impact of fasteners and tapes on the Ecosystems category is negligible. The HH and Resources categories show the largest variation when including the fasteners.

Conclusions and future work

This paper discusses the environmental impact of timber frame walls. The results showed that the impact of timber frame walls can differ largely by the choice of constituting materials. For instance it was shown that choosing LVL studs results in a higher impact compared to I-joists. Naturally environmental impact is only one of the decision criteria in designing a sustainable construction. Furthermore, the analysis showed that external finishing materials can have a major environmental impact, especially when a brickwork façade is used. Also, it was demonstrated that fasteners have a significant contribution to the overall environmental impact.

In a next step the relative impact of fasteners should be assessed. Also the impact of alternative materials, such as plastic cavity anchors was not investigated in this study. Nevertheless, these fasteners could not only be favourable from a thermal point of view but also from an environmental point of view.

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Linking construction timber carbon storage with land use and forestry management practices

Forster E J[1], Healey J R[1], Dymond C C[2], Newman G[3], Davies G[4], Styles D[1]
[1]School of Natural Sciences, Bangor University, Bangor, LL57 2DG, UK
[2]Government of British Columbia, 727 Fisgard, Victoria BC, V8W9C5, Canada
[3]Woodknowledge Wales, Ffarm Moelyci, Felin Hen Road, Tregarth, LL57 4BB, UK
[4]Coed Cymru, The Forest Hub, Unit 6, Dyfi Eco Park, Machynlleth, Powys, SY20 8AX, UK

afp239@bangor.ac.uk

Abstract. Consequential life cycle assessment was applied to forestry systems to evaluate the environmental balance of expanding forestry onto marginal agricultural land to supply more timber for the built environment, accounting for land use effects and product substitution. Forestry expansion to supply timber buildings could mitigate UK greenhouse gas (GHG) emissions by 2.4 Gg CO_2 eq. per ha of forest over 100 years, though net mitigation could be halved if beef production were displaced to Brazil. Forest thinning increases wood yields and percentage conversion of harvested wood to construction sawnwood, resulting in 5% greater net GHG mitigation compared with unthinned systems. Optimising the environmental sustainability of construction timber value chains in a circular, bio-based economy will require holistic accounting of land use (change), forestry management and complex flows of wood.

1.. Introduction

Forests sequester and store carbon (C) from the air as they grow, and harvested wood products (HWPs) can continue to store carbon and/or displace fossil fuel (FF) combustion for energy generation or displace production of mineral construction materials, further mitigating GHG emissions. Life cycle assessment (LCA) studies have shown that timber use in buildings can reduce embodied GHG emissions due to displacement of mineral materials (Hafner and Schafer, 2017, Pajchrowski et. al., 2014) and the UK Committee on Climate Change (CCC) has recently recommended that by 2025 all new housing should be timber framed (CCC, 2019). The construction sector already accounts for 61% of UK timber consumption and there is no plan to address how an increased demand will be met. The UK imports 66% of consumed timber (98% of its sawn softwood) (TTF, 2017) and whilst UK (and global) timber consumption is rising (FAO, 2017), projected UK timber supply is in decline (FC, 2016). The UK is failing to achieve even half of its 20,000 ha/year planting target (CCC, 2018). Land for afforestation could be released through increased productivity of existing farmland and forests (CCC, 2018; Lamb et al., 2016) and reduced meat consumption. However, displacement of farming activities (e.g. beef production) could also lead to detrimental indirect land use change elsewhere (Searchinger et. al., 2018).

.... In commercial plantations, young trees may be thinned; i.e. a proportion of trees removed in order to create more growing space for the remaining trees, with the aim of increasing the yield of usable timber over the life of the crop (FC, 2015). Thinning can improve stand quality and reduce the time taken for trees to reach valuable sawlog size (Hibberd, 1991), but incurs additional costs. Decisions on thinning depend on current and anticipated timber markets, stand quality, risk of wind damage and costs (FC, 2015). Logs are sorted into different product quality categories during harvesting, with the best logs ultimately ending up as higher value sawn products with longer product lives. Therefore, thinning could increase the size of the harvested wood product (HWP) carbon pool and potentially improve the overall environmental benefit delivered per hectare of managed forest. However, to our knowledge there have been no LCA studies quantifying the environmental impact of shifts in HWP value chains as a result of thinning.

.... The main study objective is to evaluate the environmental balance of expanding forestry onto marginal agricultural land in the UK to provide more timber for the built environment, accounting for land use effects and product substitution throughout extended wood value chains. A secondary objective is to evaluate the impact of forest thinning on production of higher value timber products, and on the environmental balance.

2.. Materials and Methods

2.1Scope and boundary definition

Given the significant GHG mitigation potential of wood use as construction material and for bioenergy through substitution of mineral building materials and FFs, respectively, as well as the potential impact of direct and indirect land use change (LUC), we applied a consequential LCA approach (Weidema, Ekvall, & Heijungs, 2009) (Figure 1) to evaluate environmental impact. The functional unit is the total production from the reference flow of one hectare of land in the UK, converted from grassland used for low intensity beef production, to forest land, planted with 100% Sitka spruce and managed under a clear-fell system on a 50-year rotation. A 100-year study period was used to account for two forest rotations. Expanded boundaries encompassed: (i) LUC due to afforestation, and displacement of extensive beef production; (ii) forest establishment; (iii) forest growth; (iv) forestry operations; (v) debarking; (vi) sawmilling (including drying, planing and chemical treatment); (vii) wood panel production; (viii) paper and paperboard production; (ix) biomass energy generation; (x) credits for avoided use of FFs (energy generation and construction materials); (xi) carbon storage (and 'decay') in HWPs and (xiii) recycling and disposal of 'decayed' HWPs. The production and transport of all material and energy inputs were accounted for, as were the construction or manufacture of infrastructure and capital equipment.

2.2Life cycle inventory

This study assesses a simplified timber value chain in which production of construction-grade sawn timber is maximised. Forest growth, decay and harvesting volumes were calculated using CBM-CFS3 carbon model (Kull et. al., 2016), assuming 'average' soil type. We input to that model the best fit yield tables from Forest Yield (a PC-based yield model for forest management in Britain) (Matthews et. al., 2016), specifying 100% Sitka spruce and yield class 18. The thinned scenario assumes a single thinning in year 21 of each rotation, with 36% of the 'harvestable' material (i.e. logs only, not branches, leaves or stumps) being removed for HWPs). How CBM-CFS3 implements a thinning disturbance is to reduce the biomass components and transferring carbon out of the ecosystem or to the dead organic matter as appropriate. Then the next increments are assigned to the reduced biomass so in effect the same gross volume is eventually achieved. Clear-fell harvest is implemented in year 50 (a conservative average for this species in UK conditions), followed by immediate replanting, to enable a second clear-fell in year 100. Non-merchantable biomass was assumed to be left to decay on site. The carbon modelling results provide the quantity and year of harvested timber as well as the net ecosystem C change over the 100 year period.

The quantity of harvested material was converted into a product breakout (at the forest gate) using operational data from the forest management company Gresham House (GH) for 2,000 ha of commercial Sitka spruce plantations across the UK (47% unthinned, 54% thinned) (Table 1). The GH data show that thinned forest stands had 26% higher merchantable volume by the time of the final harvest (excluding thinning harvests) compared with unthinned stands (Table 1). The thinned stands also had greater conversion of harvested trees to higher value log products ('greens') (64% vs 57% of logs), with fewer logs going to chip/fuel/pulpwood (15% vs 21%) (see Table 1 for product definitions). Downstream product breakouts were calculated from data provided by the sawmills of James Jones & Sons Ltd (JJ) and from UK timber-use statistics (Forestry Commission, 2017). Detailed material flow tables were produced, along with Sankey diagrams (an example is provided in Figure 2). Around 40% of main crop harvests end up in construction materials (carcassing and wood panels) for both unthinned and thinned systems. However, a greater proportion of carcassing materials is produced from the thinned system (17.9% vs 15.9%). Conversion of harvested carbon from CBM-CFS3 to merchantable volume was

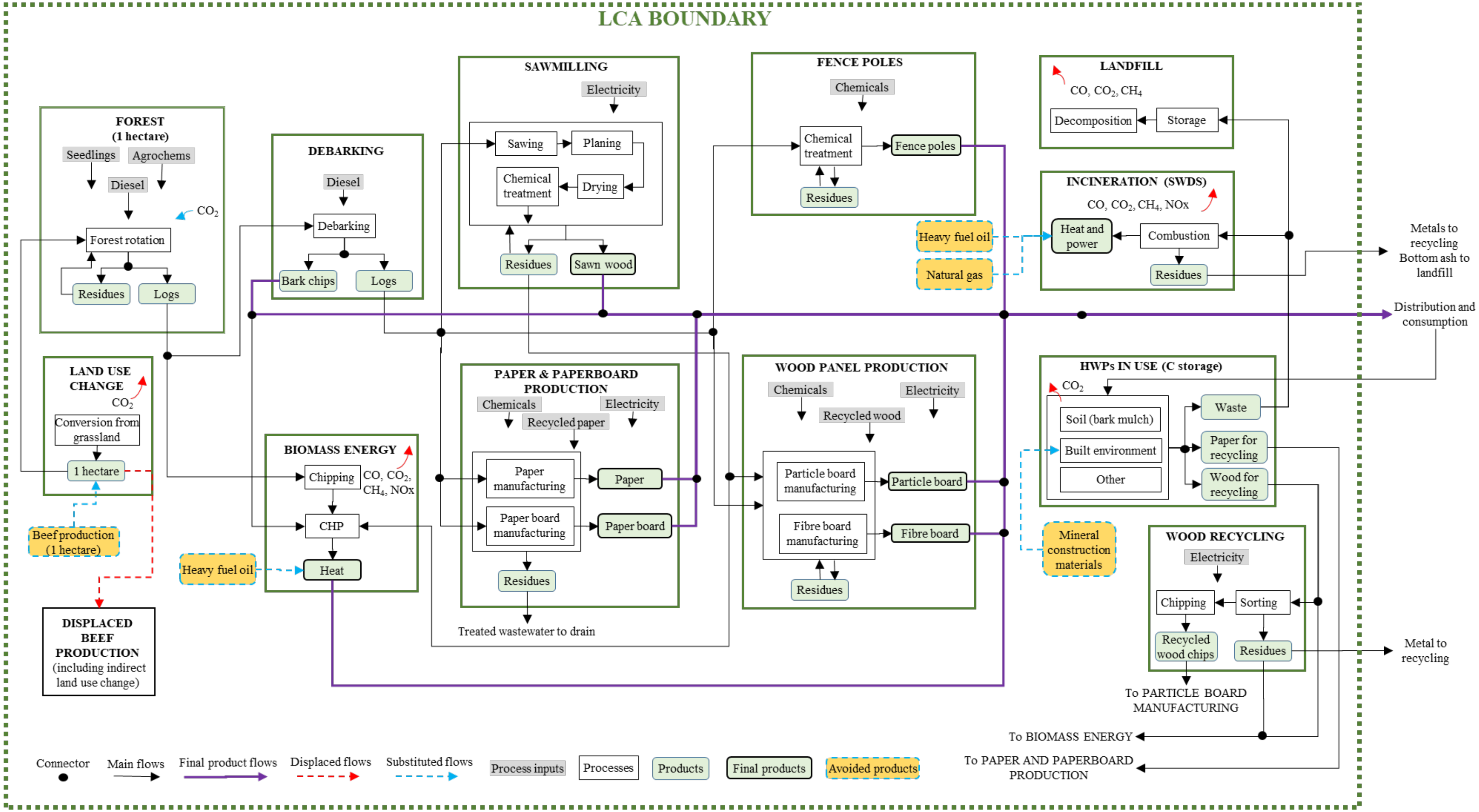

Figure 1. Main processes and inputs accounted for within expanded consequential life cycle assessment boundaries, including: storage of C in HWPs, recycling and disposal of HWPs; substitution of fossil fuels for energy production; substitution of mineral building materials.

calculated assuming 49.95% C content of dry wood, and the wood density factor 1.08 m3/tonne assuming 47% moisture content.

Table 1. Product break out from Sitka spruce stands (main crop harvest), listed in order of value. 'Red' and 'Green' refer to a threshold of acceptable straightness, taper and knots in a log, with 'Green' being the higher quality. Source: GH. Thinnings data are not collected by GH so an equal split between 'chip', 'fuel' and 'fence pole' logs is assumed. Merchantable volume is per clear fell harvest.

	Log quality categories (from low to high, left to right)					Merchantable volume
	Chip/Fuel/Pulp	Fence pole	Red	Bar/Pallet	Green	m^3/ha
Unthinned (main crop)	21%	5%	2%	15%	57%	499
Thinned (main crop)	15%	4%	2%	15%	64%	630
'Thinnings'	67%	33%	0%	0%	0%	unknown

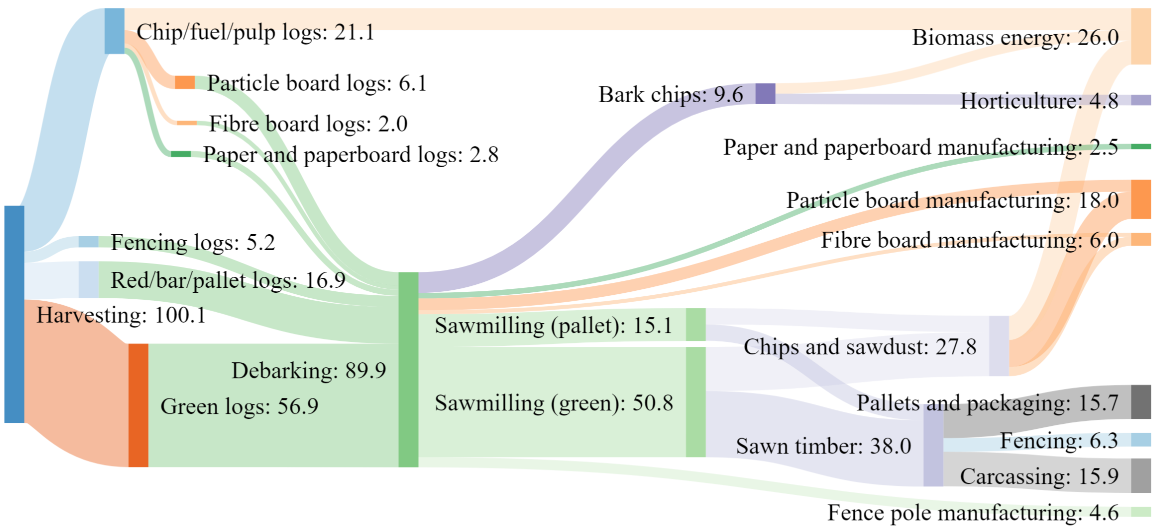

Figure 2. Biogenic carbon material flow of main crop wood harvest (from an unthinned forest). Units are percentages of original harvest. (A rounding error is present in the harvesting total.)

.... Table 2 summarises the main inputs and outputs along the value chain life cycle stages considered in the LCA. Input and output data were extracted from unit processes in Ecoinvent v.3.5, using OpenLCA v1.7.4 for all timber processing phases and scaled up in Microsoft Excel using the HWP material flow. Possible LUC consequences were modelled by accounting for displacement of beef previously produced on land areas converted to forest according to simple scenarios: intensification of existing UK beef production systems (Scenario 1), or expansion of beef production in Brazil, driving indirect deforestation (IPCC, 2006) (Scenario 2). Changes in direct emissions from beef rearing were also accounted for based on intensive UK and average Brazilian beef production footprints (Styles et al., 2018).

.... The rate of 'decay' of the HWPs is calculated according to IPCC methods (IPCC, 2006). As products 'decay' from the HWP C pool, they are recycled or disposed of (by incineration or landfill) in proportions calculated from Defra, (2018) (using 2016 data), respectively. Note that almost 100% of paper and paperboard is recovered and 80% of wood products are recovered (16% to biomass energy). All 'decay' of tertiary products is assumed to be disposed of. Horticultural mulch is assumed to decay at a rate similar to composted municipal solid waste (Bruun et. al., 2006) since no data could be found on the decay rate of tree bark. Wood fuel is not included in the HWP C pools owing to rapid oxidation.

All biogenic C emissions from oxidation of wood at ‘end of life’ is assumed to be zero (since the sequestration of this C is not accounted for in the net forest C sequestration).
.... All burdens associated with production and transport of inputs, as well as for all timber processing phases, were extracted from Ecoinvent v.3.5 (Wernet et al., 2016) using OpenLCA v1.7.4. Emissions from landfill disposal were calculated according to the IPCC First Order Decay (FOD) method (IPCC, 2006). Fuel-to-energy conversions factors (for natural gas and wood chips) from Ecoinvent unit processes were used to calculate fossil fuel substitution by biomass energy and wood waste incineration. Substituted FF is assumed to be natural gas, given a trend towards greener energy production and given the substitution occurs 21 to 100 years in the future.

In the absence of high quality data on direct product substitution ratios, preliminary estimates of the burdens avoided through substitution of mineral construction materials were made by first translating the final mass of construction timber per ha (129 and 150 tonnes per ha (20% moisture), for unthinned and thinned forests, respectively) into an equivalent area of timber-framed wall using industry standard design (0.0175 m^3 of timber per 1 m^2 wall). 1 m^2 of timber frame wall was assumed to replace 1 m^2 of single skin, 140 mm concrete block and mortar wall (typical of a UK house). This enabled avoided burdens to be calculated, using emissions factors from Ecoinvent for the manufacture of concrete blocks, sand and cement, scaled to the quantity of materials used per 1 m^2 of concrete block and mortar wall. To estimate the area of forest required to supply a prescribed number of houses, data on the volume of timber contained in a typical timber framed house was used (6 m^3 in the timber frame) (Suttie et. al., 2009).

Table 2. Inventory of key inputs and outputs for processes considered along the life cycle of forestry value chains derived from unthinned and thinned forest systems over 100 years. Emissions factors (EF) and their sources are indicated. FRDP is fossil resource depletion potential and GWP is global warming potential.

Process stage	Input/output/process	Activity data source	Units	Unthinned		Thinned		EFs		EF source
				In	Out	In	Out	FRDP	GWP	
Site establishment	Land		ha	1		1				
	15 tonne 360 Excavator	Expert estimate	hr	15		15		941	65	Ecoinvent
	Herbicide (glyphosphate)	Industry recommended	kg	1		1				Ecoinvent
Planting (1&2)	Tree seedlings	GH	Item(s)	50,000		50,000		1	0	Ecoinvent
	15 tonne 360 Excavator	GH	hrs	30		30		941	65	Ecoinvent
	Pesticides (acetamiprip)	Industry recommended	kg	2		2				Ecoinvent
Forest management	Harvester (diesel use)	GH	hrs	64		78		784	56	Ecoinvent
	Forwarder (diesel use)	GH	hrs	64		78		646	46	Ecoinvent
Forest growth	Net C sequestered	CBM-CFS3	kg C	222,077		206,928				IPCC 2006
	Harvested wood	CBM-CFS3, GH	m^3		1,321		1,426			IPCC 2006
Transport (forest to processor)	>32 t truck, EURO6	GH	t.km	2,823		3,046				Ecoinvent
Debarking	Harvested wood	CBM, GH	m^3	1,187		1,310				
	Diesel	Ecoinvent	MJ	1,395		1,543				
	lubricating oil	Ecoinvent	kg	1		1				
	bark chips	GH, FR CFs	kg		117,768		130,240	299	20	Ecoinvent
	Debarked wood	GH, FR CFs	m^3		1,060		1,169			
Sawing	Diesel (internal transport)	Ecoinvent	MJ	13,122		14,952				
	Electricity	Ecoinvent	kWh	8,775		9,999				
	Lubricating oil	Ecoinvent	kg	48		54				
	Debarked wood	GH, FR CFs	m^3	870		957				
	Sawnwood	JJ&S	m^3		502		572	363	25	Ecoinvent
	Sawmill residues	JJ&S	kg		170,307		192,502			

Process stage	Input/output/process	Activity data source	Units	Unthinned In	Unthinned Out	Thinned In	Thinned Out	EFs FRDP	EFs GWP	EF source
Drying (of sawn timber)	Electricity	Ecoinvent	kWh	8,384		9,553				
	Sawnwood	JJ&S	m^3	502		572				
	Sawnwood - dried (u=20%)	Assume no loss in volume during drying	m^3		502		572	403	29	Ecoinvent
Planing	Electricity	Ecoinvent	kWh	4,353		4,960				
	Sawnwood (carcassing) dried (u=20%)	JJ&S	m^3	502		572				
	Sawnwood (carcassing) planed	Vol loss accounted for in 'sawing'	m^3		502		572	469	35	Ecoinvent
	Sawmill residues	JJ&S	kg		170,307		192,502			
Chemical treatment	Electricity	Ecoinvent	kWh	46		54				
	Wood preservative	Ecoinvent	kg	64,953		75,122				
	Sawnwood (fencing) dried (u=20%)	JJ&S	kg	37,452		41,711				
	Debarked wood (fence poles)	GH,FR CFs	kg	27,501		31,331				
	Preserved wood	No vol. change	kg		64,953		75,122	0	0	Ecoinvent
Particle board production	Electricity	Ecoinvent	kWh	39,415		44,232				
	Heat	Ecoinvent	MJ	462,488		519,008				
	Resin	Ecoinvent	kg	19,329		21,691				
	Debarked wood (chip)	GH	kg	66,805		60,263				
	Sawmill residues	JJ&S	kg	153,277		173,252				
	Recycled wood	FC report	kg	261,906		303,546				
	Particle board	FR CFs	m^3		390		438	4,716	262	Ecoinvent
Fibre board production	Electricity	Ecoinvent	kWh	1		1				
	Heat	Ecoinvent	MJ	1		1				
	Debarked wood (chip)	GH, FR CFs	kg	22,268		20,088				
	Sawmill residues	JJ&S	kg	51,092		57,751				
	Fibre board	JJ&S, GH, FR CFs	m^3		53		56	1,064	98	Ecoinvent
Woodchip production (for biomass energy)	Electricity	Ecoinvent	kWh	2,118		1,955				
	Lubricating oil	Ecoinvent	kg	0		0				
	Harvested wood - 'fuel'	GH	kg	65,717		56,825				
	Recycled wood - 'biomass'	FC	kg	70,188		81,579				
	Wood chips	GH	kg, dry		135,904		138,404	0	0	Ecoinvent
Biomass energy	Electricity	Ecoinvent	kWh	19,061			21,293			Ecoinvent
	Wood chips	GH	Kg, dry	135,904		138,404				
	Bark chips	GH, FR CFs	kg	31		34				Conversion biogenic C to CO_2 eq
	Sawmill residues	JJ&S	kg	136		154				
	Heat	Ecoinvent	MJ		1,946,830		1,982,642	0	0	Ecoinvent
Graphics paper production	Electricity	Ecoinvent	kWh	16,421		11,673				
	Debarked wood - 'pulp'	FR CF	m^3	16		12				
	Paper, newsprint, virgin	FR CF	kg		5,815		4,133	16	1	Ecoinvent
Graphics paper production (recycled)	Electricity	Ecoinvent	kWh	8,529		4,044				
	Recycled paper	GH, FR CFs	kg	5,330		2,521				
	Paper, newsprint, recycled	Mass equal to recycled paper	kg		5,330		2,521	12	1	Ecoinvent
Paperboard production	Electricity	Ecoinvent	kWh	804		576				
	Debarked wood - 'pulp'	GH, FR CFs	GH	16		12				
	Board box	GH, FR CFs	kg		11,472		8,218	11	1	Ecoinvent
HWP in use	C accumulated in HWP	IPCC	kg C	568,622		618,548				IPCC 2006
Landfill	Waste wood	FC, Defra, IPCC	kg	2,100		2,434				IPCC, 2006
	Waste paper	FC, Defra, IPCC	kg	4,502		654				IPCC, 2006
Incineration	Waste wood	FC, Defra, IPCC	kg	55,343		64,140				
	Waste paper	FC, Defra, IPCC	kg	1		0				Conversion

Process stage	Input/output/process	Activity data source	Units	Unthinned		Thinned		EFs		EF source
				In	Out	In	Out	FRDP	GWP	
	Electricity	Ecoinvent	kWh		157,729		182,799			of biogenic
	Heat	Ecoinvent	MJ		21,370		24,767			C to CO_2eq
Avoided construction materials	140 mm concrete block and mortar wall replaced by timber frame wall	Industry standard	m^2	18,461		21,444		236	37	Ecoinvent
Avoided FFs	Avoided natural gas (hp)	Ecoinvent	m^3	77,593		82,540				Ecoinvent
Avoided beef production	Low intensity beef production, UK	Styles et. al., 2018	kg	18,315		18,315			33	Nguyen et al., 2010
	Sc1 - high intensity production, UK	Styles et. al., 2018	kg	18,315		-			22	Nguyen et al., 2010
	Sc2 – avge. intensity production, Brazil)	Styles et. al., 2018	kg	18,315		1			47	Nguyen et al., 2010
	Sc2 - iLUC (rainforest to grassland, Brazil)	Styles et. al., 2018	ha	1					723,259	IPCC, 2006

2.3Impact assessment and interpretation

Two environmental impact categories were considered in this study: global warming potential (GWP), expressed as kg CO_2 eq; fossil resource depletion potential (FRDP), expressed in MJ. Summary results are presented in the main body of the paper.

3.. Results and discussion

Afforestation of 1 ha of grass land to produce timber for construction offers significant CO_2 mitigation potential, for both unthinned and thinned forest management scenarios, with FF displacement of 4.3 TJ and 4.9 TJ, and GWP mitigation of 2.3 and 2.4 Gg CO_2 eq, respectively (Table 3) over 100 years. Thinning increases GWP mitigation by 5% and FRDP mitigation by 14% over 100 years (for scenario 1). Although unthinned forests achieve higher net forest C sequestration over this timescale, this is more than offset by the higher quantity of harvested timber produced in thinned systems, and improved conversion to sawnwood – which results in higher accumulation of C in HWP and greater emission avoidance via fossil fuel and mineral construction material substitution (Figure 3). When comparing scenarios 1 and 2, the burdens associated with displacement of beef production vary significantly (Table 3). The displacement of beef to intensive UK systems achieves further GWP savings via reduced emissions intensity of production, whereas displacement to average intensity production in Brazil increases GWP, mainly due to indirect land use change (deforestation) (Table 3 and Figure 3).

Table 3. Mitigation of fossil resource depletion potential and global warming potential achieved by converting 1 ha of beef production land to timber production forest, over 100 yrs. Displacing beef production to intensified UK production (Sc1) and Brazil on land converted from rainforest (Sc2).

	Scenario 1		Scenario 2	
Impact category	Unthinned	Thinned	Unthinned	Thinned
FRDP (TJ eq.)	-4.28	-4.88	-4.28	-4.88
GWP (Gg CO_2 eq.)	-2.30	-2.41	-1.12	-1.22

3.1Abatement potential - Construction use

Timber use in construction has significant abatement potential through both long-term storage of C in the HWP C pool and also displacement of mineral construction materials (Table 4). Thinning produces 16% more wood product for carcassing use (e.g. timber-frame walls) than unthinned systems per ha of forest. If used as external-wall timber framing, this additional 16% increases GHG mitigation by 110,176 kg CO_2 eq (over 100 years) due to displacement of mineral construction materials.

Table 4. Avoided CO_2 eq. emissions and FF depletion from displacement of mineral construction materials by sawn timber (used in external timber frame wall, replacing concrete block and mortar wall) from 1 ha of afforested land over 100 years.

GWP (kg CO_2 eq)		FF depletion (MJ eq)	
unthinned	thinned	unthinned	thinned
681,807	791,983	4,365,022	5,070,383

.... To build 100,000 new houses in the next 20 years (as projected for Wales: Welsh Government, 2018) using timber-frame construction would require 10,424 (unthinned) to 8,974 (thinned) ha of forest to supply the timber frames (not including supply of sawn timber required for roof and floor structures, and assuming forests are already established and ready to be harvested to meet demand). This would achieve 1.4 Tg CO_2 eq avoided emissions for mineral building material substitution. In addition, the forest supplying these houses (and their extended value chains) over a 20-year period could provide GWP benefits of -4.3 Tg CO_2 eq, and FRDP benefits of -8,753 TJ (for thinned systems).

3.2Conclusions

Expanding forestry onto marginal agricultural land with the aim of providing more timber for the built environment will provide significant environmental benefits, in particular mitigation of GHG emissions and fossil resource depletion. Mitigation is primarily driven by C sequestration in growing trees, storage of C in the HWP C pool and the substitution of FF and mineral construction materials. However, this mitigation could be significantly reduced at the global level if agricultural production is displaced internationally, causing “carbon leakage”. In particular, displacement of beef production to Brazil could drive indirect deforestation, which could offset 50% of the UK GHG mitigation effect. However, there is significant scope for forestry expansion to be accommodated by, or even to drive, “sustainable intensification” of existing land-use systems within the UK, further enhancing net mitigation potential.

.... This study highlighted the considerable potential to increase the resource efficiency of UK forestry, and to reduce the 98% import dependency for sawn-timber construction products. Currently, only around 40% of harvested timber ends up in buildings under best-case assumptions (16% carcassing plus 24% wood panels for unthinned systems; and 18% carcassing plus 23% wood panels for thinned systems). Thinning of forest systems improves resource-use efficiency by increasing productivity and timber quality, which reduces the area of land required to supply a given volume of sawn timber to the construction sector by 16%. This could be increased further by improvement of forestry management and processing efficiency, e.g. by greater use of thinning, which is currently carried out in only approximately half of commercial forests in UK. Resource efficiency could also be enhanced through increased recycling of wood products, with 80% (not including paper and paperboard) currently recovered (16% for biomass energy generation; 64% for non-energy uses) (Defra, 2018).

.... Further work will be carried out to elaborate impacts of: (i) alternative land-use change scenarios; (ii) alternative forest management systems; (iii) UK-specific substitution factors for displacing mineral construction materials; (iv) alternative FF substitution scenarios in a future energy mix; and (v) alternative study periods.

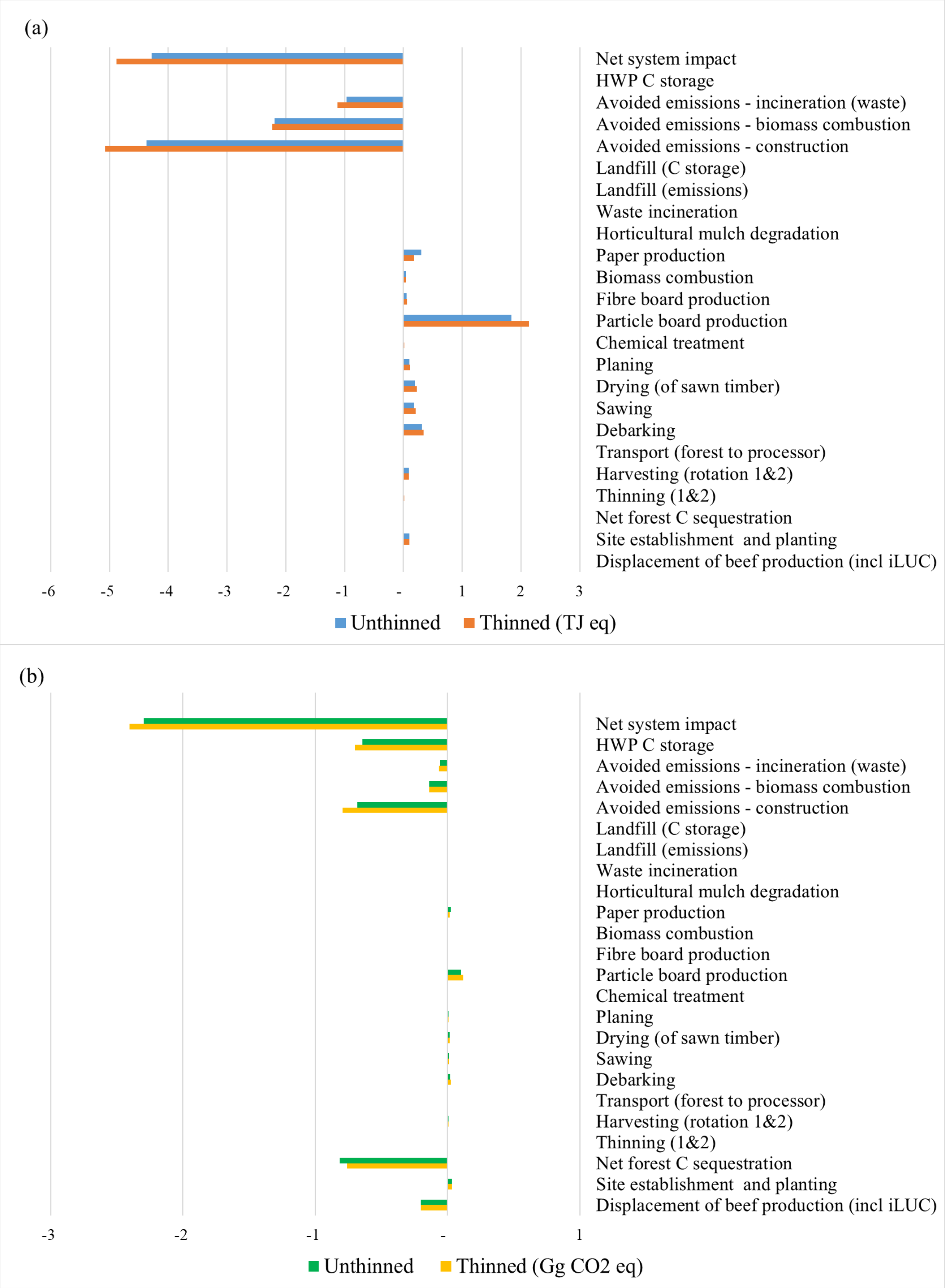

Figure 3. Life cycle assessment results for unthinned and thinned forest management systems (for scenario 1, displacement of beef to high intensity production, UK). Results expressed for (a) fossil resource depletion potential (TJ eq) and (b) global warming potential (Gg CO_2 eq).

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Life cycle assessment of rammed earth made using alkaline activated industrial by-products

Meek A H[1], Elchalakani M[1]

[1] School of Civil, Environmental and Mining Engineering, University of Western Australia, M051, 35 Stirling Highway, Crawley, 6009, Western Australia, Australia

alexandra.meek@research.uwa.edu.au

Abstract. Given increasing environmental concerns, lower energy building materials are being developed to reduce greenhouse gas emissions. The ancient technique rammed earth has been combined with modern industrial waste products to both reduce greenhouse gas emissions and reduce waste. The new rammed earth mixes have been developed using alkaline activation (sodium hydroxide) of industrial by-products: fly ash, ground granulated blast furnace slag and silica fume. This paper explores the 'cradle-to-gate' life cycle assessment, assessing global warming potential of these rammed earth materials, considering acquisition of raw or recycled materials and processing to final product of residential building envelope. These are compared with commonly used building envelope materials, brick veneer and cavity brickwork, and the more common rammed earth variety, cement-stabilised rammed earth. Results show that greenhouse gas emission savings can be made using these rammed earth mixes compared to the control building materials while achieving comparable or better material properties. Greenhouse gas emissions associated with the building envelope materials are reduced by more than half or one third when compared to cavity brickwork or brick veneer respectively. Following testing of the waste products in surplus in a given area, the same process could be followed for any geographic location.

1. Introduction

Globally, buildings account for a significant portion of total energy use throughout the full life cycle, from raw material acquisition and processing, through the operation stage and finally, at end of life. Although in Australia per capita building sector energy use has been declining, population increases will result in absolute growth over time [1]. As such, buildings are an important area where greenhouse gas emissions (GHGE) reductions could be made. Average house sizes have been increasing and, as improvement are made in the operational energy stage, energy spent on the structure (known as embodied energy) becomes a higher portion of total emissions [2].

Further to GHGE, the building industry uses around 30-50% of raw materials and is responsible for approximately 40% of landfill waste in OECD member countries [3,4]. These statistics highlight the importance of repurposing waste both to reduce virgin material use and to reduce landfill waste.

Rammed earth (RE) is an environmentally friendly building material when made using traditional methods; natural inclusions such as clay and straw were used as binders [5,6]. However, the more modern versions of RE are 'stabilised,' incorporating more energy intensive materials; in the last century it has become more common to add stabilisers such as lime, bitumen and cement, with 5-10 wt.% cement becoming the most common [7,8]. While improving material properties, cement addition significantly reduces environmental benefits. The cement industry is responsible for 6% of annual GHGE with around one tonne of CO_2 emitted per tonne of clinker produced, an intermediate product in cement production [9,10]. New RE mixes have been developed by the authors replacing cement with industrial by-products to lower GHGE associated with embodied energy of buildings and reuse waste.

Life cycle assessment (LCA) is being increasingly used to determine environmental impacts of any product or process. In the context of embodied energy in the building industry, LCA aids better material selection or can be used to identify problem areas and improve processes to reduce GHGE. In this study, LCA is used to determine GHGE associated with embodied energy of the newly developed RE mixes as well as the more common version cement-stabilised RE. The aim of the study is to determine potential benefits from a global warming perspective of using the RE mixes made with industrial by-products compared to more common building envelope materials.

2. Materials and methodology

2.1. Rammed earth materials

RE mixes being assessed are listed in Table 1. The mix most commonly used in Western Australia (WA), crushed limestone (CL) stabilised with cement, is used as a control mix. The second mix, CL_AA, replaces the cement with alkaline activated aluminosilicate materials, mostly industrial by-products. The third mix replaces the CL with recycled brick and concrete (RBC). The industrial by-products used are fly ash, ground granulated blast furnace slag (GGBFS) and silica fume. A by-product of coal combustion, it is estimated there are 225 million tonnes of fly ash currently stockpiled in Australia [11]. GGBFS is a by-product of iron and steel production. It is popular as a supplementary cementitious material (SCM) used by the concrete industry. The GGBFS produced in Australia is fully or largely used by the concrete industry with more imported [12]. Silica fume is produced as a by-product during silicon metal and alloys production and is supplied to the market by primary manufacturers based in Bunbury, WA. It is also used as a SCM by the concrete industry. Kaolin clay is available commercially. NaOH was prepared as a 12M solution. Additional water was then added to each mix to reach the optimum moisture content, determined according to AS 1289.5.2.1—2003 [13].

Table 1. RE mix designs.

Mix	UCS (MPa)	Mix components (%)								
		CL	RBC	Kaolin	Fly ash	GGBFS	Silica fume	Cement	NaOH pellets	Water
CL_C	11.1	81.5	-	-	-	-	-	8.2	-	10.3
CL_AA	19.8	73.0	-	3.7	7.3	3.7	2.9	-	1.65	7.8
RBC_AA	24.1	-	73.0	3.7	7.3	3.7	2.9	-	1.65	7.8

2.2. Sustainability analysis goal and scope

This LCA is completed in accordance with ISO 14044:2006(E) [14] and EN 15804:2012+A1:2013 [15] specifically for coproduction methodology. Results could be used by government in development of sustainable building policies, designers and builders, and to assist the general public when making material choices while building their own homes. The LCA has been completed as a 'cradle-to-gate' approach, incorporating material acquisition through to production of the final product, an external wall of a residential structure. Two common residential building envelopes were selected as controls to compare with the RE wall designs: brick veneer (BV) and cavity brick (CB). Brick veneer is the most common residential construction type around Australia while cavity brick is still commonly used in WA.

The functional unit (FU) considered is one vertical square meter of an external load-bearing wall. Envelope walls have been designed to meet requirements of Australia's climate zones 4-6, in which around 70% of the population resides [16]. To meet Australia's National Construction Code 2016 (NCC) 'Deemed-to-Satisfy' Provisions, two options are available: a house may meet the required Energy Rating for a particular climate zone using house energy rating software or Elemental Provisions may be satisfied [17]. Building envelope construction types assessed in this study have been designed to meet Energy Efficiency Elemental Provisions. In climate zones 4-6, high mass materials (>220 kg/m^2) such as cavity brick and RE can be used without additional insulation so long as certain other requisites are met, e.g. glazing and shading requirements. If not high density, external walls must meet minimum R2.4 in climate zones 4 (hot dry summer, warm winter) and 5 (warm temperate) and R2.8 in climate zone 6 (mild temperate). For the purposes of this study, this is achieved using various thicknesses of glasswool insulation (GWI) with a density of 40 kg/m^3. Details of each envelope design are shown in Figure 1. Bricks were modelled as 110 mm commons, average of Midland Brick cored commons and Austral Bricks Standard 76.

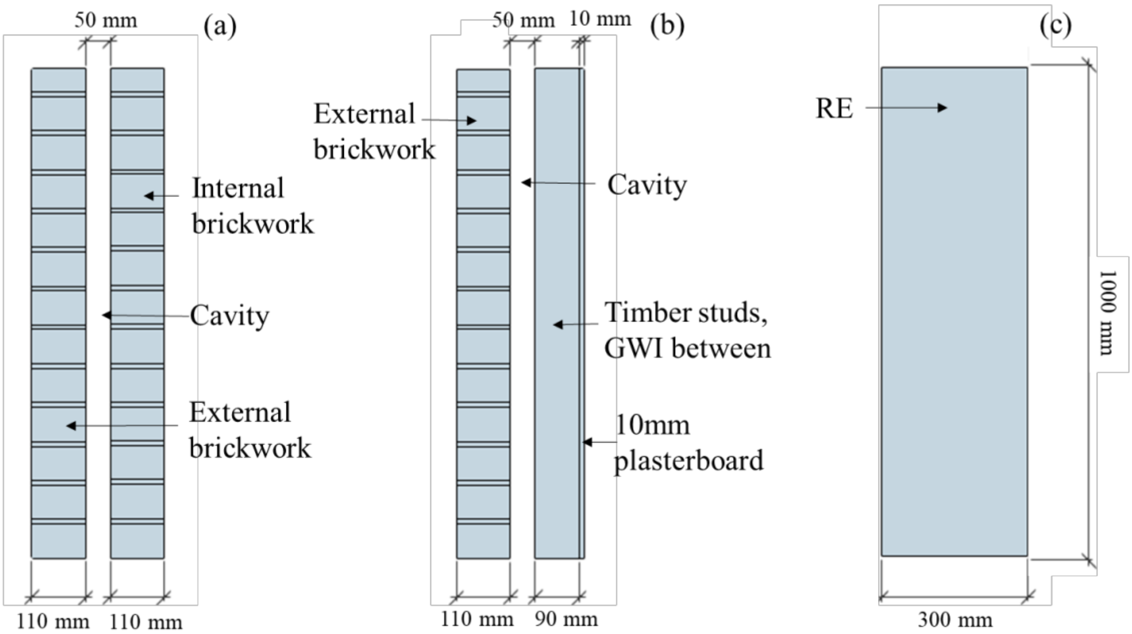

Figure 1: Cross-section of building envelope construction types; (a) cavity brick, (b) brick veneer, (c) rammed earth.

The boundary of the system studied is shown in Figure 2. Transport from plant to site has been excluded in the initial results as it is reasonably consistent regardless of material. A sensitivity study is conducted comparing different site locations. Construction energy has been excluded as it was found to negligible for RE in a previous study [18]. For consistency, brick veneer and cavity brick construction energies were also excluded. Operation stage was excluded in this assessment as thermal testing of the materials in question has not yet been completed.

The inventory is modelled based on EN 15804:2012+A1:2013 [15] which is predominantly an attributional approach. A cut-off system model is used meaning by-products were available burden-free at the primary production location. Transport and any processing required to prepare the by-product for the secondary material market is included. At end-of-life, the materials may be able to be recycled as aggregate however this stage has been excluded due to the uncertainty associated with long lifespan of a residential house, as the material properties at end of life are not known. Recycled content of materials has been included in the inputs to the model.

OpenLCA v1.7.2 software [19] using the AusLCI database v2.8 where possible [20] and Ecoinvent v3.4 where AusLCI data was unavailable [21] were used. Recycled brick and concrete were conservatively both included as recycled concrete aggregate. Brick's lower density would demand lower crushing energy. The environmental indicator category considered was global warming potential over 100 years (GWP100), developed by the Intergovernmental Panel for Climate Change [22]. This category measures emissions over a 100-year time period of any greenhouse gas, using CO_2 as an equivalence measure.

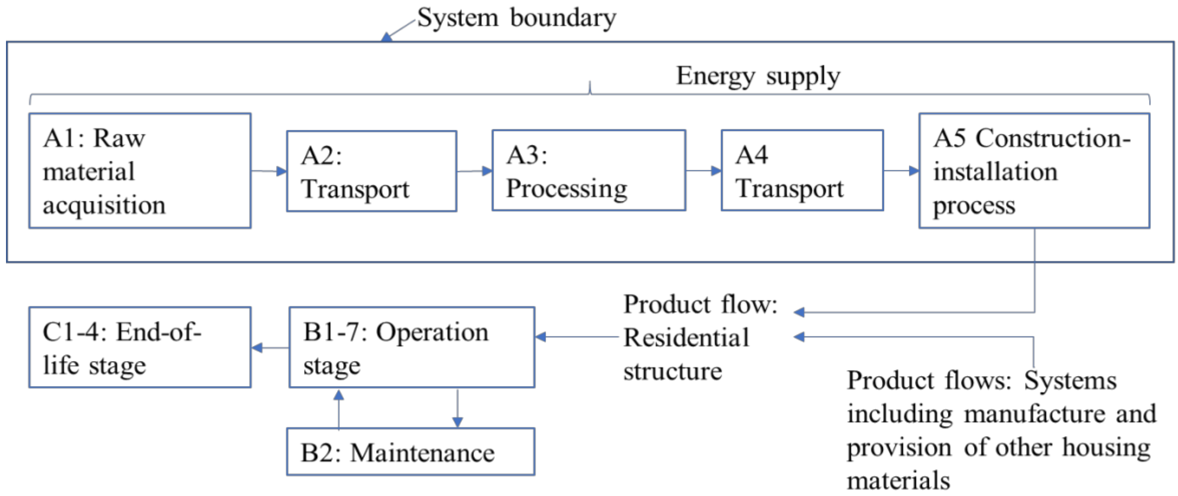

Figure 2: System boundary of RE LCA study, modules A1-5

3. Results and discussion

Figure 3 shows GWP100 (kg CO_{2eq}) for each material as a percentage of cavity brick emissions. These are a baseline measurement for each material/construction type: only required elements are included, e.g. bricks are unrendered/painted. Additional GWI required for brick veneer to meet R2.8 in climate zone 6 is shown separately to the GWI included to meet R2.4 in climate zones 4 and 5: the impact of additional insulation is minor compared to the total. For the three control materials, brick veneer, cavity brick and CL_C, the calcination process causes the vast majority of GHGE. For brick veneer and cavity brick, it is heating the kiln to fire the bricks that is responsible for GHGE whereas for cement production it is heating the kiln but also the inherent CO_2 released during clinker production, an intermediate product in production of cement:

$$CaCO_3 + \text{heat} \rightarrow CaO + CO_2 \text{ [23].} \qquad (1)$$

As calcination is not required for any of the components of RE mixes that include industrial by-products, this significant emission step is avoided. Inclusions for by-products were any processing required to render the by-product useable for its purpose as the secondary material, e.g. grinding of blast furnace slag, plus transport from the primary producer to a metropolitan storage location.

Just over 50% of CL_AA and RBC_AA emissions are directly related to NaOH production. Bricks used for residential construction are typically specified to have a characteristic compressive strength of 12 MPa. CL_C has been designed to match this strength requirement. However, the newly developed mixes currently have varied 28-day UCS strengths, as marked on the Figure 3 secondary axis: CL_AA and RBC_AA are both significantly stronger than required, averaging 19.8 MPa and 24.1 MPa respectively. While it is known that strengths achieved by CSRE are directly related to cement content [24], future work by the authors will determine if this same relationship applies to these mixes. Given the contribution of NaOH to overall GWP, it is nevertheless reasonable to assume that materials with a smaller proportion NaOH, will have lower environmental impacts.

Based on the current mix, CL_AA, replacing cement with NaOH and industrial by-products, GWP is 60% lower than cavity brick and 40% lower than brick veneer. For the control RE mix, CL_C, GWP is 37% lower than cavity brick but only 8% lower than brick veneer due to the high emissions associated with cement production. This highlights that RE does not necessarily have significantly lower environmental impacts than 'business-as-usual' construction types but that this is highly dependent on stabiliser selection.

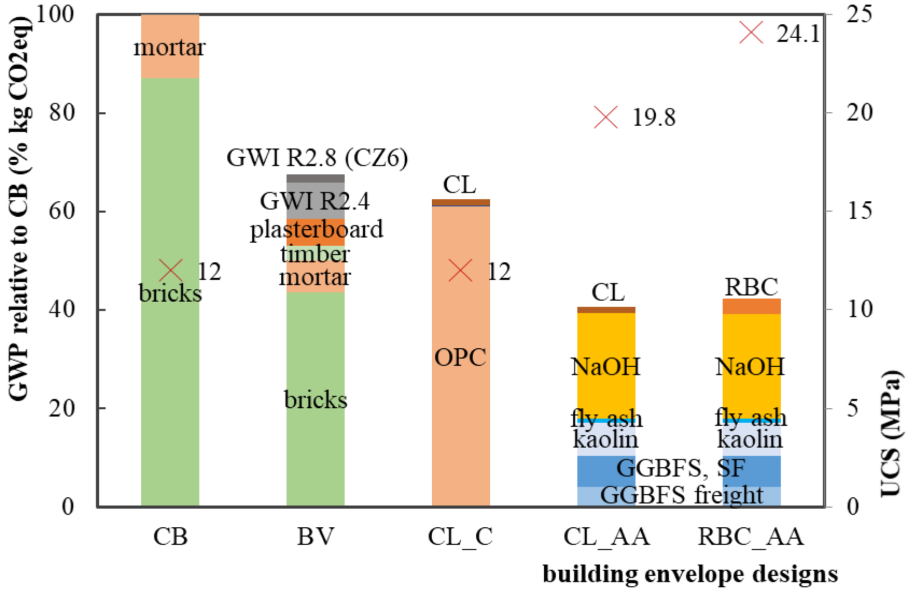

Figure 3: LCA results for environmental indicator category IPCC GWP for 1 m² of vertical external wall meeting insulation requirements for Australia's Climate Zones 4-6, system environment modules A1-3 only

Further to stabiliser selection, the base 'earth' component of a mix can also vary GWP of the final material. When comparing the two mixes CL_AA and RBC_AA, all components and proportions are identical other than base earth component. CL has low GWP as it is abundant around Perth, meaning transport distances are minimal, and it is a low density material so processing energy required is low. RBC, on the other hand, requires additional transport from demolition sites to processing locations, more varied sorting compared to the virgin CL, and additional processing energy as it is a higher density material. These factors result in a higher GWP for the fully recycled base earth compared to the virgin material for the same material mass. However, it should be noted that for the same mix proportions, RBC_AA has higher strength than CL_AA. Therefore, to achieve a given strength, less stabiliser should be required. As stabiliser contributes a much greater portion of the material's total GWP than earth, this will result in lower overall GWP. An additional benefit of using RBC over CL is its support of reusing waste materials to reduce use of virgin materials and reduce landfill, an OECD priority [3].

Another factor to consider in conducting LCA of RE is site location and transport requirements. Results of a sensitivity analysis addressing different transport requirements are shown in Figure 4. Two site locations are considered, 1) Perth metropolitan and 2) Kalgoorlie, a regional city 600km east of Perth. Two transport options are considered for Site 2:

i) all stabiliser materials transported from Perth, local material used as 'earth' component,
ii) all stabiliser and base earth materials transported from Perth.

It should be noted that, separate to these transport calculations, relevant freight to Perth metropolitan has already been included, e.g. fly ash includes 200 km transport in a 40T truck from coal plant location and GGBFS includes a portion of ship freight to account for imported material. GWP associated with material acquisition and production through to intermediate location in Perth metropolitan of RBC_AA materials are shown in Figure 4 to highlight impact of transport relative to total material impact.

Site 1 conservatively assumes a delivery location of 50 km in metropolitan Perth for all materials, based on location of material storage and processing locations around Perth. When stabiliser materials (NaOH and aluminosilicates) are transported from Perth to the site in Kalgoorlie, this adds 3.6 kg CO_{2eq} or 10% in the case of this mix for the FU of 1 m^2 vertical wall. If all materials, including base earth material, are transported from Perth, transport impacts increase significantly due to the mass of the earth component. In the case of RBC_AA, transport adds a further 60% on top of the material impacts considering a site within Perth. Local earth material in a regional location such as Kalgoorlie could include a local virgin material or local recycled materials so long as the location has the capacity to process the materials e.g. to crush recycled brick. Any local soil would require testing to establish whether it was appropriate to be used as a RE base. This potential to use local materials for the bulk of wall mass increases the benefit of these RE mixes relative to more standard building materials if components of these require transport to regional locations.

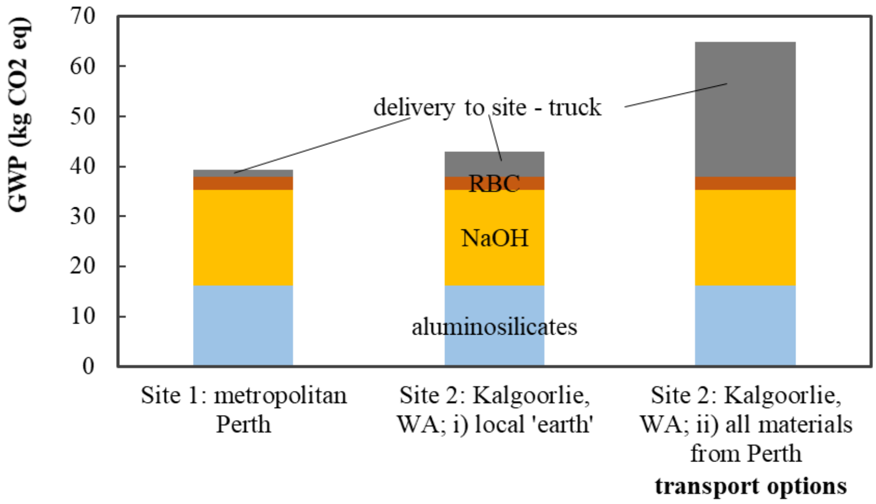

Figure 4: Varying site location and/or delivery requirements, mix: RBC_AA

4. Conclusions

The aim of this paper was to assess GWP of RE materials using LCA and determine whether use of these materials may provide a benefit over use of more common building materials. Results show that use of RE mixes stabilised with aluminosilicate by-products and NaOH would reduce GWP by 60% compared to cavity brick for the same unit of external wall and by 40% compared to brick veneer.

The newly developed alkaline activated RE mixes have a GWP 30-40% lower than the current most common RE variety in WA, CL_C, highlighting the benefits of using alternatives to cement in RE construction. Nevertheless, given the most prevalent construction type in Perth, WA is cavity brick, RE stabilised with cement is still a significantly better alternative in terms of reducing GHGE.

If the construction site is in a regional location, maintaining the benefit of using any RE mix is contingent on ability to use local materials, virgin or recycled, as the base 'earth' component. The high mass of base material required means GHGE emissions associated with long transport distances are high. Where possible, use of recycled materials as the base material has the benefit of supporting waste reuse, a current government and OECD priority.

Valuable further work would include thermal analyses of the mixes studied here as well as others to determine variability according to mix design, i.e. to what degree thermal properties are controlled by variables such as wall thickness and density rather than exact components and proportions. Thermal testing, i.e. determination of resistance to heat flow (R-value), would allow for comparison of GWP based on FU having identical R-values as well as wall designs meeting the current NCC requirements. Air quality tests of indoor environments created by these materials would also be beneficial. Lastly, analysis of materials at end-of-life would better enable understanding of capacity for reuse and/or recycling. This data could then be used for a more complete LCA of the full life cycle.

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Butt-joint bonding of timber as a key technology for point-supported, biaxial load bearing flat slabs made of cross-laminated timber

Zoellig S[1], Muster M[2], Themessl A[3]
[1] Timber Structures 3.0 AG, Thun, CH
[2] ETH Zurich, Chair of Structural Engineering - Timber Structures, Zurich, CH
[3] Bern University of Applied Sciences for Architecture, Wood and Civil Engineering (BFH), Biel, CH

stefan.zoellig@ts3.biz

Abstract. An efficient butt-joint bonding technology allows to build new types of timber structures. Under the name Timber Structures 3.0 a connection has been developed which connects timber elements with an end-grain to end-grain butt joint bonding. Therefore, it is now possible to build continuous, point supported flat slabs in cross laminated timber (CLT). Multiple CLT slabs are connected rigidly together and are only supported by columns. Some major challenges had to be solved in terms of bending strength of the glued connection and shear resistance of the part of the slab above the column. The research in both topics is successful and more projects were built in the last two years using this technology. Starting point was a real scale structure at ETH Zurich, followed by a working platform for a timber construction company and finally four three storey residential buildings. The research team is continuing to optimize the different elements of this innovative technology and will soon provide engineers with guidelines to design their own biaxial, point supported timber flat slabs.

1. Introduction

The research project “Wooden slabs in commercial and industrial buildings” has made huge progress since it was started in 2016 [1]. The goal of the research project is to build skeleton structures with flat slabs in timber. Therefore, a biaxial, point supported cross-laminated timber flat slab was developed. As CLT slabs are limited to approximately 20 m length and 3.4 m width a rigid connection is necessary. This key technology, the butt joint bonding of timber, has proven it’s applicability in the last two years. The research team from BFH Biel, ETH Zurich, Timber Structures 3.0, Timbatec, Henkel & Cie., and Schilliger Holz have increased the knowledge about all parts of a biaxial, point supported CLT flat slab. With microscopic analysis the important parameters of the bonded butt joint were revealed and therefore the reliability could be increased. At the same time the implementation of the bonding process into the construction process was improved. Besides the rigid connection of the CLT slabs, transmitting the forces from the slab into the columns is the second crucial part. In 2012 tests at ETH Zurich showed that beech plywood plates can resist high bending moments and shear forces. To lower the cost of construction the same investigations were made with CLT and reinforced CLT plates. This investigation showed that CLT slabs can also withstand high forces. The combination of the gained knowledge led to interesting projects which were accomplished in the last two years.

2. Evolution of timber structures

To explain the actual innovation of this project and the created possibilities in timber construction, we must take a step back. For centuries trunks and beams have been used to build houses. Trees were cut down, branches removed, debarked and sawn to beams and planks to construct buildings. In the 20th century, trees were sawn into boards, dried, planed and glued to glulam or more recently to CLT. With these products a structural beam can be larger, longer and more homogenous than a tree. This development is illustrated in Figures 1 and 2.

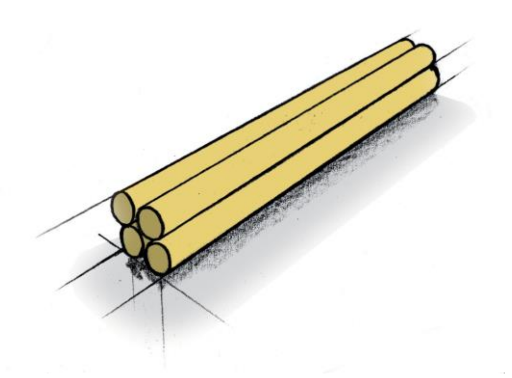

Figure 1. Timber Structures 1.0: Trunks and beams

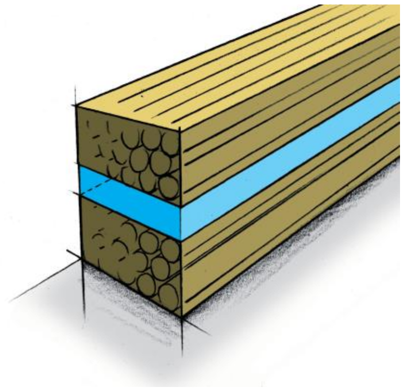

Figure 2. Timber Structures 2.0: Glulam and CLT

The current development illustrated in Figure 3 allows the butt joint bonding of fibres and therefore leads to the 3rd generation in timber construction called Timber Structures 3.0. The rigid connection of several CLT slabs allows new types of timber constructions. Figure 4 shows a multi storey skeleton structure as it is possible to build when several CLT slabs are connected rigidly to a single flat slab.

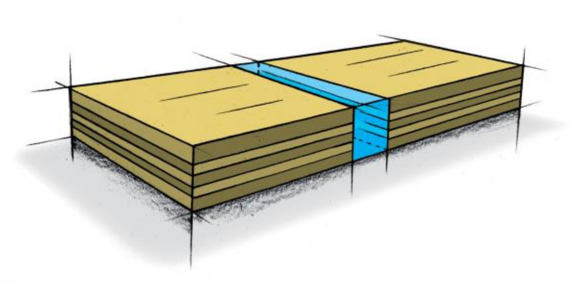

Figure 3. Timber Structures 3.0: Butt joint bonding technology

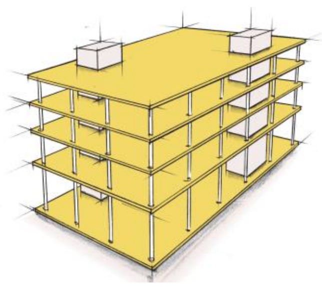

Figure 4. Typical skeleton structure

3. Environmental impact

Replacing building materials with high energy demands for production is a major challenge to achieve a sustainable built environment. Timber constructions have made remarkable progress in the last ten years. In Switzerland, 7.5% of the new built structures were made in timber in 2017. This share almost doubled since 2015. Not only an increased share of buildings is being built in timber, but also the volume of this buildings has increased by 25% over the last 15 years [2]. In the field of residential buildings, timber construction has established itself. In office and business buildings timber construction struggles to provide adequate solutions so far. The here presented technology could increase the current share of only 0.7% of newly built timber office and business buildings per year in Switzerland [2] and replace energy-intensive materials like steel and concrete.

4. Recent research

4.1. Structural system

The structural system shown in Figure 4 is divided into four structural elements. The first element is the rigid connection between the CLT slabs. This connection has to resist bending moments and shear forces. The current status of research is presented in chapter 4.3. The second element is the part of the slab around the column. This element has to lead high shear forces into the column, transfer vertical loads from upper storeys to the next column and at the same time resist high bending moments. The conducted research of this element is presented in the following chapter. The third element is the CLT slab band spanning from column to column. The fourth element is the part of the slab lying between the CLT bands. This element mainly has to resist small biaxial bending moments and therefore does not necessarily have to be a massive timber element such as CLT. Elements three and four are not part of this paper, as they are of lower interest than elements one and two.

4.2. Slab to column connection

Point supported slabs are mostly used for office or industry buildings. For such structures a column grid of 6 - 8 m is required and live loads of 300 - 500 kg/m^2 have to be considered. From this background several scenarios arise with punching loads varying from 380 kN up to 1050 kN. In 2012, Lorenzo Boccadoro tested the punching behaviour of six real scale plates at ETH Zurich [3]. The tested plates had dimensions of 2.5 m by 2.5 m and were 24 cm, 32 cm and 40 cm thick. The plates had a central opening with a diameter of 30 cm. Three of these plates were made of beech plywood and three were made of a combination of beech plywood and spruce boards. The load carrying capacity of all the plates was higher than the required resistance.

To improve the cost efficiency of the flat slab, CLT plates were tested by Marcel Muster in 2017 [4]. CLT plates with dimensions of 2.1 m by 2.1 m, as illustrated in Figure 5, were chosen to be tested. From the elements shown, six specimens were assembled. The basic element was always a six-layered 18 cm thick CLT plate. Two plates consisted of CLT only with opening diameters of 20 cm and 30 cm respectively. On one plate an additional load distribution ring made of beech plywood was placed (Figure 3 bottom left side). Another plate was tested with glued on beech plywood plates on both sides (Figure 3 top right) and finally two plates consisted of both a placed-on load distribution ring and glued on beech plywood plates.

A special feature in the CLT slab is an opening on top of the column as it can be seen in Figure 5. This opening is necessary to lead vertical loads from upper storeys through the slab without subjecting the CLT slab to stresses perpendicular to grain. This necessity on the other hand leads to a great challenge within this research process: at the point where the highest bending moments occur, a part of the slab is missing.

In Figure 6, the load-displacement behaviour of the tested plates is shown. Specimens 1 to 3 did not have any reinforcement plates. Specimen 3 had an additional set on load distribution ring made of beech plywood placed on the hydraulic jack and therefore a higher ultimate load. Specimen 1 with the black dotted line showed early deformations due to the narrow support area which led to a crushing of the timber perpendicular to grain.

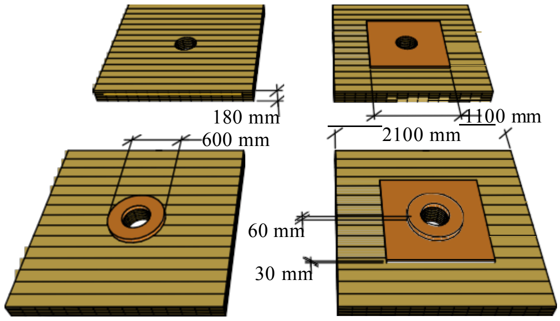

Figure 5. Tested plates

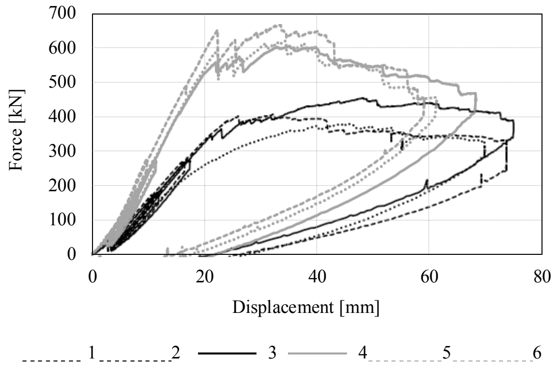

Figure 6. Load-displacement punching tests

The punching tests showed that the chosen slabs are able to transfer high shear forces into the column and can resist high bending moments. With an increase of the thickness of the slab it is also possible to fulfil the requirements defined earlier. In the following table the characteristics of the tested slab, the thickness and the ultimate loads are listed. Specimens F240, F320, F400 were tested by Lorenzo Boccadoro in 2012 [3]. These compositions could be used in situations with higher live loads than 5 kN/m^2.

Table 1. Performed punching tests

Specimen	Ultimate Load	Composition	Opening	Support
1	380 kN	18 cm CLT	D = 30 cm	D = 38 cm
2	408 kN	18 cm CLT	D = 20 cm	D = 40 cm
3	455 kN	18 cm CLT	D = 30 cm	D = 52 cm
4	605 kN	18 cm CLT + 2x3 cm beech plywood	D = 20 cm	D = 40 cm
5	620 kN	18 cm CLT + 2x3 cm beech plywood	D = 30 cm	D = 52 cm
6	666 kN	18 cm CLT + 2x3 cm beech plywood	D = 20 cm	D = 52 cm
F240	1350 kN	24 cm beech plywood	D = 30 cm	D = 55 cm
F320	2257 kN	32 cm beech plywood	D = 30 cm	D = 55 cm
F400	3138 kN	40 cm beech plywood	D = 30 cm	D = 55 cm

4.3. Butt joint bonding

To connect the slab elements rigidly together, various methods were evaluated between 2009 and 2012. Only a bonded butt joint technology can fulfil the broad requirements. So far, no certified adhesive exists on the market for directly bonded butt joints. Purbond AG, part of the Henkel Group, has developed a 2-component polyurethane adhesive which can be used for the required purpose. In the first development stage, various geometries of bonded joints were examined. The simplest geometry to be produced was the butt joint, but also different profiles as v-rabbets and finger joints were examined [5]. In various experimental tests it was studied which thickness of joints could be filled considering different conditions such as different temperatures or joint widths. More than 1’000 tensile tests on lamellas in 24 series have been carried out [[5],[6],[7],[8],[9],[10],[11]]. From these tests, important conditions and requirements for quality assurance were established. Füllemann [6] further examined different influences on building site: minimum joint thickness, temperature, moisture content, soiling with oil or dust, movement and vibrations and different types of pre-treatment of the connecting end-grain faces. Lehmann [11] finally determined by seven series of tests with totally over 250 test specimens statistically reliable strength values for the tensile and bending strength of a bonded butt joint in CLT plates. The tests allowed further a better understanding of the influence of moisture changes and the effects of long-term stresses on the bending strength of the bonded butt joint. The bending strength was determined in four-point bending tests illustrated in Figure 7 with variations of the thickness of CLT, wood moisture and load duration applied with springs as shown in Figure 8.

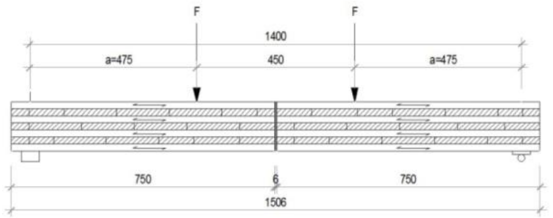

Figure 7. Four-point bending tests on butt joint bonded CLT-beams.

Figure 8. Long-term bending tests on butt joint bonded CLT-beams.

The results of this study showed a consistent good quality of the bonded butt joint. Through this progress, characteristic bending strengths from 15.6 N/mm^2 to 20.7 N/mm^2 were achieved depending on the wood moisture content and the load duration. These values were higher than all strength values reached before.

To reduce the appearance of bubbles in the glue line different techniques were tested most recently [12]. On the one hand, the roughness of the surface seemed to have an influence which was controlled by sanding the surface. On the other hand, different methods to seal the grains were developed and tested. Tensile strength test results showed that there was a considerable increase of mean tensile strength when combining sanding with roughness P 100 and applying a pre-treatment to the of end-grain surface. By sanding the end-grain surface, the intensity of bubbles occurred was reduced to a maximum of 10% of the complete fracture surface area. Latest results of tensile strength tests on butt joint bonded boards with improved adhesive formulation show a characteristic tensile strength higher than 15 N/mm^2. As tensile tests always show lower values than bending tests, an increase in bending strength can be expected. Specimens of this series show partly ripped out wood fibres. To examine that, broken specimens were rejoined with fluorescent PVAC adhesive and examined under the UV-light microscope. This is shown in Figure 9 [12]. The actual rupture line is visible through the fluorescent PVAC adhesive and the numbers indicate ripped out fibres (1), adhesive (2) and wood (3).

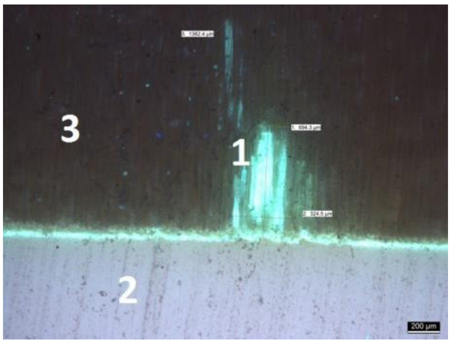

Figure 9. UV-light microscopy picture of broken and rejoined tensile specimen

As research is continuing, even higher strengths of the butt joint bonding are expected. Further research is also done in the process of how to implement the TS3 system the most economical way, meaning e.g. the conservation of the pre-treated surface and on-site construction processes. As in timber structures often serviceability or in other words deformation and vibration are governing a design, the achieved bending strength of the bonded butt joint are already sufficient to build biaxial, point supported flat slabs with a column grid up to 8 m by 8 m.

5. Proof of concept

In the last two years several projects were built with the bonded butt joint technology. In the following, three selected projects are presented.

5.1. Real scale, long term test ETH Zurich

The first real scale structure with a bonded butt joint was built at ETH Zurich in April 2017. Four 26 cm thick and 3 m by 3 m large CLT plates were glued together creating a corner supported 6 m by 6 m slab. The slab was subjected to a distributed load of total 96 kN representing a permanent load in an office building. A roof protected the slab from heavy rain. Since 2017 the slab has been exposed to moisture and temperature changes and also rain, as the roof was leaking several times. Nevertheless the slab showed no signs of weakness. Deformation measurements showed a creep factor of 1.3 after one and a half years. The slab was disassembled in April 2019 and will be reassembled at another place to continue the long-term experiment.

Figure 10. Real scale, long term test at ETH Zurich

5.2. Working platform Wangen b. Duebendorf

In spring 2017 the timber construction company Flueck Holzbau decided to build a new working platform in their factory. The platform was assembled out of three 13 m by 2.5 m large and 36 cm thick CLT slabs glued together along the long side. The slab is line supported on both sides over the 13 m. The slab is designed to withstand distributed loads up to 500 kg/m^2. To reinforce the slab and to avoid large deflections 14 steel bars were inserted into the slab and later post-tensioned. Three load cells were installed to monitor the behaviour of the post-tensioning.

Figure 11. Working plattform in use

Figure 12. Post-tensioned working plat-tform

5.3. Residential buildings Grossaffoltern

Four three storey residential buildings were built close to Biel in the second half of 2018. The floor plans are 12 m by 7 m rectangles with surrounding line supports and three, respectively four (in the left apartment of Figure 14) columns aligned in the centre of the slab. The flat slabs were built out of three and four 16 cm thick and 12 m by 2.5 m large CLT slabs glued together at the long sides.

Figure 13. Residential building

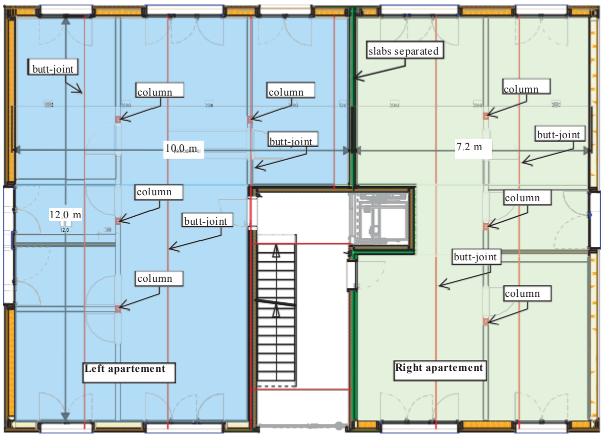

Figure 14. Layout of the CLT slabs

To validate the structural design of the biaxial, point supported slab ETH Zurich performed vibration measurements at different stages of construction. This measurements will help to op- timize future projects.

6. Outlook

The research about the slab to column connection is mostly finished. The next step will be the combination of the design guidelines to provide engineers a reliable and user-friendly design approach. To this design approach a guidance on improving the robustness of the CLT flat slab will be added as soon as the research about this topic is completed. The research about the bonded butt joint is continuing as there is still potential to increase both bending and tensile strength. Besides that, the research team is working on a European Technical Assessment (ETA) for the butt joint bonding.

7. Acknowledgement

The project is a collaboration of Timbatec AG, Timber Structures 3.0 AG, Schilliger Holz AG, Henkel & Cie. AG, ETH Zurich and BFH Biel. Gratefully acknowledged by the authors is the intense cooperation among the partners of this project, as well as Innosuisse, which is funding the ongoing project in large part.

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Environmental Product Declarations (EPDs) as a competitive parameter within sustainable buildings and building materials

Andersen S C[1, 2, 5], Larsen H F[1, 2], Raffnsøe L[3], Melvang C[4]

[1] EPD Danmark, Gregersensvej, DK-2630 Taastrup, Denmark
[2] Buildings & Environment, Danish Technological Institute, Gregersensvej, DK-2630 Taastrup, Denmark
[3] Green Building Council Denmark, Frederiksborggade 22, DK-1360 Copenhagen, Denmark
[4] MiljøForum Fyn Byggeri, Forskerparken 10, DK-5230 Odense, Denmark
[5] Corresponding author

sara@teknologisk.dk

Abstract. The demand for technical and verified documentation of buildings and building materials is growing, along with the increasing focus on sustainability in the built environment. However, despite a common wish to build sustainably, it is still found that EPDs and LCAs are not always similarly interpreted, leading to misunderstandings on how they should be used to quantify and verify sustainability along with being a competitive parameter when choosing materials.
To overcome this barrier this project seeks to discover:

1. How can EPDs be used as a competitive parameter within the sustainable built environment?
2. How can product specific EPDs, used as an input to building-level LCAs, help to quantify the concept of 'circular economy'?
3. How do some countries seem to succeed in introducing EPDs to industry while others only succeed to a lesser extent?

By involving the Danish building-industry's value-chain through qualitative interviews, workshops and reference groups, as well as by contacting EPD programme operators throughout Europe and USA, a mapping has been performed on the tendencies of how and to what extend EPDs are used to quantify and support material decision-making in buildings. Further, the drivers as to why EPDs are used in some countries is investigated along with suggestions on how to boost the development, use and integration of EPDs with the aim of quantifying and documenting sustainability in the built environment.

1. Introduction

Due to an increasing demand for sustainability in the built environment a natural need for documentation and transparency has evolved – both globally and locally in Denmark [1,2]. In Denmark, while the construction industry is actively seeking a development towards increased sustainability, authorities and the regulatory system are lagging behind and fail to provide a structured, holistic approach to this transition. Therefore, a part of the industry is starting to come up with various individual initiatives and strategies on how to move forward [3,4].

A Danish report from 2017: "Roadmap 2030 – Bygningers rolle I den grønne omstilling" [3] (which roughly translates into: Roadmap 2030 – The role of buildings in the green transition) touches on several matters and suggestions for actions to be taken within e.g. energy consumption, indoor climate and environmental aspects. Being managed by a Danish innovation network for sustainable construction, InnoBYG, the project included a broad variety of stakeholders within the built environment, covering NGOs, universities, consultants, engineers, architects etc.
One of the recommendations made within the environmental considerations was to improve and strengthen the documentation of materials and their impact on building environmental sustainability by performing Life Cycle Assessments (LCAs) that are based on the principles for Environmental Product Declarations (EPDs), and thus measuring embodied energy and environmental impacts. Additionally, they suggest an implementation of a voluntary sustainability classification system within the building regulations of Denmark.

However, despite a common wish to build sustainable, it is still found that EPDs and the underlying LCAs are not always similarly interpreted, leading to misunderstandings on how they should be used to quantify and verify sustainability along with being a competitive parameter when choosing materials.

In Denmark, while the interest in EPDs is rapidly increasing, as well as the number of new EPDs published every year, the total number of EPDs developed and verified so far at the Danish EPD Programme Operator (EPD Danmark) is still clearly in the low end, compared to other European and American EPD Programme Operators. Considering the infographic by Jane Anderson [5], see Figure 1, it is seen that the 'dominating' EPD programmes can be found in Germany, USA, France, Sweden and Norway, i.e. many of the neighbouring countries of Denmark. It is uncertain why this difference occurs.

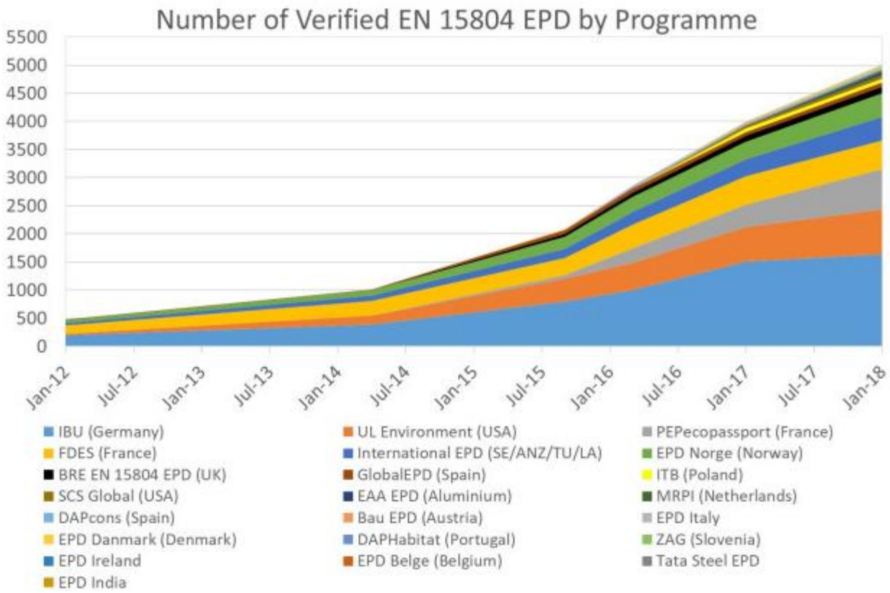

Figure 1. Infographic, showing the numbers of verified EPDs for construction products which align to EN15804 from 2012-2018. Reprinted by permission of Jane Anderson, ConstructionLCA Ltd.

This project aims at defining a consensus for the use and usability of EPDs and their underlying LCAs by gathering knowledge from the industry and provide real-life and practical examples of Danish value-chain stakeholders of the construction industry. Additionally, it is investigated why EPDs seem to be used to a greater extend in some countries and how this has occurred.
The three main questions worked with are thus:
1. How can EPDs be used as a competitive parameter within the sustainable built environment?

2. How can product specific EPDs, used as an input to building level LCAs, help to quantify the concept of ‘circular economy’?
3. How do some countries seem to succeed in introducing EPDs to industry while others only succeed to a lesser extent?

1.1. Literature

The main focus of the project was to investigate how EPDs are used by the Danish construction industry and value chain, through inclusion of stakeholders. However, to define a starting point of the study, a preliminary literature study was performed. The results are shown below.

A study considering some of the aspects in question was done by the Green Building Council in Iceland (IGBC) and a Nordic project group, consisting of Norway, Sweden, Iceland and Finland [6]. The project conducted two surveys, representing stakeholder groups of respectively building owners/consultants/contractors and producers/providers of building products, in the summer of 2015. The report points at the lack of market demand as one of the main obstacles for the use of EPDs. The study found that the first group of respondents (building owners, consultants and contractors) did want fairly more information on environmental impacts of building materials. Other obstacles, beside lack of market demands, were pointed out, such as lack of knowledge about the documentation, high costs and lack of synchronisation of EPDs. This is agreed upon, when considering the second group of respondents in the study by IGBC (material manufacturers).

Ibáñez-Forés et al. (2016) [7] who investigated the barriers towards use and implementation of EPDs in the construction industry, confirmed the findings of the above study by IGBC. Identified barriers included a general lack of knowledge about EPD programs and content of EPDs, the cost of developing the LCA (i.e. the basis for the EPD), lack of international standardisation, and the fact that the content of EPDs can be hard to read for non-specialists [7]. Among the advantages mentioned by Ibáñez-Forés et al. (2016) are the possibility for manufacturers to communicate verified environmental information objectively, thereby also proving their interest in transparency, improve their corporate image, and achieving better knowledge of production processes [7,8]. The latter was additionally observed through the fact that 90% of the manufacturers having an EPD of their product were also enrolled in a voluntary environmental management system [7].

Similar incentives were identified by Passer et al. (2015) [9]. The main advantage identified by the authors was that EPDs are recognised as a feasible format for communication of environmental claims, requirements and demands, facilitating their export market development [9].

In general, main drivers for EPDs have in several studies/mappings been mentioned to be building certification schemes [6,8–11], e.g. HQE, Green Star, LEED, BREEAM and DGNB, being some of the most well-known and applied schemes – some of them having national editions to allow for country-specific aspects to be taken into account.
Many of these certification systems have included either direct (EPD) or indirect (building-LCA) requirements in their guidelines and criteria [8], for example:

- LEED has criteria within their ‘Materials & Resources’ category, that assign credits when applying LCA to prove building life-cycle impact reductions and when using materials which hold an EPD [12].
- BREEAM also allocates credits for criteria about life cycle impacts through the use of LCA and EPDs in the materials section. However, the weighting differs across national editions of the certification scheme, e.g. considering the international, UK and Norwegian editions [13–15].
- DGNB has national editions in some countries, thus the specific criteria may differ from country to country. The Danish version of DGNB contains criteria for both inclusion of EPDs and LCA, weighting respectively 1,5% and 13,5% (considering LCA for both environmental impact

categories and primary energy, representing respectively 7,9% and 5,6%) of the total score [16]. Considering the German DGNB, 'only' LCAs are credited, weighting 9,5% of the total score [17].

Other incentives to develop EPDs mentioned by the literature are Green Public Procurement (GPPs) plans, which are voluntary tools that aim at stimulating the market demand for 'greener decisions' [18]. The voluntary EU-GPP for '*Office Building Design, Construction and* Management' [19], prescribes mandatory LCA-based criteria [18] which can be based on EPDs of main building elements. However, as mentioned in Ibáñez-Forés et al. (2016), the incentives from governmental instances are quite low [7].

A study performed in 2015 by Passer et al. [9] reviewed and discussed the experiences with EPDs in European countries in the past 5-10 years. The review was based on an EPD workshop which was held prior to SB13 Graz conference and reviews the European status of the use and application of EPDs. Alongside a list of current (as per 2015) EPD programmes, authors looked into what is done specifically in five European countries (Austria, Belgium, Germany, France and Switzerland – however the latter not having an official EPD programme) and how EPDs are used, developed and applied. While all five countries follow the European standard for EPDs EN15804 as well as ISO14025, some of them have additional requirements and legislations, incentivising the use of EPDs. An example is Belgium, where the Royal Decree on Environmental Messages [20] imposes modules A4, C and D as obligatory as of 2017 [9], in addition to those already prescribed by EN15804 (A1-A3). In France, the EPD programme (INIES) combines Environmental and Health product declaration (EHPD, in French FDES) [9]. Additionally, the French national appendix for EN15804 set up requirements to include toxicity and ecotoxicity along with sanitary and comfort requirements, in order to conform with existing national requirements/standards. As of 2014 a further decree prescribes that manufacturers wishing to make environmental claims about their product need to support their claims through a cradle-to-grave EPD [9].

According to Sariola and Ilomäki (2016) [21], the Finnish EPD programme (RTS EPD) has set out additional requirements to the included LCA modules for an EPD, namely that modules A4, C1-C4 and D need to be included [21].

1.2. EPDs in Denmark

The programme operator for EPDs in Denmark is EPD Danmark. Currently there are more than 30 EPDs registered, covering 80+ products.

While the largest incentive for EPDs in Denmark is building certification, and specifically the Danish version of the German building certification scheme, DGNB, other incentives are actions from public instances, such as municipalities (e.g. Aalborg [22] and Copenhagen [23]) or partnerships where various public instances commits to follow a Green Public Procurement having outlined a Green purchasing method.

While Denmark does not have any direct requirements or legislation about the use of LCA and EPDs, the construction sector is willing to improve and drive sustainability further. One of the initiatives is a voluntary add-on to the Danish building code, to classify buildings according to their overall sustainability level [4]. The system, which has been proposed and recommended by the construction industry itself, does not have a clearly defined format yet. However, one of the suggested parameters is the development of building LCAs, which should preferably be based on EPDs.

2. Method

Apart from the preliminary literature study, the project aimed to seek answers through stakeholders and implementation of real-life practice. This has been done through qualitative interviews, workshops and meetings with a reference group. Furthermore, the aspect of discovering as to why other programme operators seem to meet a greater demand for EPDs than experienced in Denmark, the project group has interviewed EPD programme operators throughout Europe and USA, certification bodies and Danish consultancy companies working internationally.

2.1. Qualitative interviews

The qualitative interviews where performed by setting up a list of questions specific for each interviewed group along the value-chain: consultants (architects and engineers), contractors, builders, manufacturers, public authorities and technical organisations (i.e. programme operators and certification bodies).

Due to the natural focus of the project on the building materials and competitivity effects as a consequence of the use of EPDs, the main group of interviewees were found within the manufacturers of building materials, as illustrated in Figure 2.

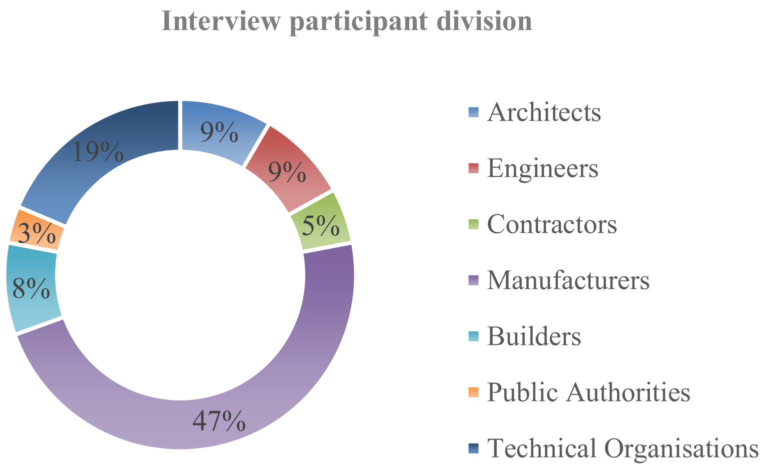

Figure 2. Interview participant division

The method was not strictly scientific, due to a limited number of participants (~60), however it does give an indication of the obstacles and opinions about EPDs and constitute a valuable starting point for further discussion at workshops.

2.2. Workshops

Throughout the project period, two workshops were held, where the building industry was invited across the value-chain. The topics of the workshops were respectively:

- EPDs as a competitive parameter
- Circularity in the built environment and documentation (with a focus on whether and how EPDs might be used)

As the invitation for the workshops were public, a broad spectre of participants showed up to discuss the given topic – some of them had previous experience with EPDs and some were new to the topic, wanting to expand their knowledge.

The workshops were used to discuss and analyse the qualitative interviews, extrapolate common tendencies, and investigate the underlying hypotheses. Additionally, guest-speakers provided their perspectives to the questions asked and gave input for further discussion to qualify the output.

2.3. Reference groups
Reference groups were used to provide opinions and guidelines to the questions asked in the project, along with supporting development of, and discussing, preliminary results before their publication.

2.4. Format of results
The main project outcome was a booklet of real-life examples (published in spring 2019 by EPD Danmark) referring to the Danish construction sector, explaining how and why EPDs should be used.

The results in this project cannot be divided into results found from one of the individual investigation methods, as the discussions were iterative and summed up all thoughts and angles found throughout. The results (which correspond to the content of the booklet) are presented in the following section, including the identified tendencies and a discussion on how to improve the understanding and increase the use of EPDs as a documentation for environmental sustainability in the built environment.

3. Results & Discussion

As the project put up three main questions to be investigated, the results are presented coherently. However, as mentioned earlier, the answers and conclusions mix, which is why the discussions will overlap in between the project questions.

3.1. EPDs as a competitive parameter
An initially observed tendency showed that many stakeholders throughout the value-chain of the Danish construction industry did not find EPDs to be a competitive parameter. However, when putting up a hypothesis on this initial finding, arguments against this were made, summing up the value of getting an EPD depends on the definitions of value.

When added value and increase in competitiveness was defined as a 10% increase in the producers' customers portfolio, it was a common conclusion that EPDs could not be considered to have *direct* value. However, several stakeholders recognised the value of having EPDs when considering:

- The knowledge obtained by the manufacturer about a product, when utilising the LCA lying behind an EPD.
- The willingness from the manufacturer's side to be transparent about their products and processes, and their impacts on the environment.

Other mentioned that the value and ability to use an EPD as a competitive factor was dependent on the type of customer for the specific product. There was broad agreement about the fact that EPDs are not highly rated by general customers as much as other parameters, such as price, aesthetics and durability. However, if aiming to sell and distribute materials and products for larger construction projects (e.g. tenders from public authorities and large investment companies), there was a clear increase in the demand for documentation – especially for sustainability claims.

This again supports the perception that EPDs themselves are not the 'value', however the knowledge obtained about the product, through an LCA, and the willingness to be transparent about the product were. The EPD is thus 'only' the document that sums up the facts.
Thus, an EPD cannot provide value to the 'unknowing' and 'unenlightened' customers, as they do not have the tools to utilise the potential behind the EPD.

However, even though arguments in favour of EPDs and their possibilities appeared, there is still a cold fact that only front-runners have, and use, the EPDs. Recurring reasons for this were identified as the cost of developing an EPD, lack of a requesting market when looking at tenders and a general lack of knowledge.

While the cost of getting an EPD might not be easy to reduce, due to the elaborate work going into developing the LCA at its basis (even though recent development within digitalisation and automation might shift this), issues about lack of demand and knowledge can be offset – and this might in the end also affect the cost of developing EPDs.

At current, the main, and virtually the only, driver for EPDs is building certification schemes. This lack of demand often leads to the industry pointing fingers at each other. The manufacturers keep repeating that they do not see a reason for getting EPDs for their products if the builders do not request them in e.g. tenders. On the other hand, builders say they cannot see a reason for demanding them, as there are not enough EPDs to accommodate this demand in tenders. Thus, there is a need for all stakeholders in the building industry to move simultaneously, as they all demand sustainability, but no-one appears to really move. Some stakeholders also point to the authorities when discussing who needs to make the move. This can be either authorities themselves, who put out requirements in their own tenders (as they often own large projects), or to legislate on the industry, e.g. the previously mentioned sustainability classification that the Danish construction industry suggested to be introduced in the Danish construction code, similar to the existing (and successful) operational energy classification regulations. Future implementation of the 7th basic requirement (BRCW7) of the Construction Products Regulation (CPR) regarding sustainable use of resources and related to the CE marking and Declaration of Performance (DoP) may increase the demand for LCA data on building products substantially.

Considering the lack of knowledge about EPDs and implied also the view on cost of EPDs, there is a clear need for more and better information about the groundwork, e.g. guidance on how to read an EPD or a general informative campaign on the added value gained through the LCA, which is the backbone of the ‘bought’ EPD.

3.2. EPDs as input to quantifying ‘Circular economy’

The increasing focus on resources and ‘circular economy’ in Denmark [24] has led to initiating a discussion on how to quantify these concepts and the potential of using EPDs for this purpose.

While there was a general consensus about that fact that EPDs do not provide any specific information about circular economy, several participants throughout the project mentioned that EPDs might be used in building-level LCAs. This could have a significant effect with respect to circular economy, if the EPDs include the LCA phases about End of Life (EoL, C1-C4) and potential for Recycling (D). These phases may enable a verified and quantified knowledge about EoL and resource management.

A recurring issue was however how to define the LCA phases C and D. While the intentions (increased documentation and transparent quantification) are seen as positive, several stakeholders, throughout the project, questioned the assumptions for EoL and recycling potential scenarios and the accuracy of the relevant data.

Well aware that this issue is part of a broader discussion throughout the industry and also the LCA communities (researchers, practitioners), the project group and the stakeholders recognised that we have at the current state little or no knowledge at all on how we will handle building demolition in 50-100 years (if not even longer) and how materials will be treated. It is therefore only possible to base the LCA phases C and D on today’s know-how and practice, which is a significant limitation. It is difficult to say whether this will hold true, however we reasonably expect that today’s ‘standards’ will be conservative compared to what will be possible in the future. In general, there was common agreement, that documenting something and making necessary assumptions, although uncertain is better than ignoring these phases. In the coming revised version of EN 15804 (expected to come into force this summer, 2019) the inclusion of the phases C and D is mandatory (due to adaption to the EC PEF scheme, i.e. EU Single Market for Green Products).

The discussion focused also on the current practice for modelling EoL and regulatory challenges regarding waste handling were pointed out, calling out for authorities to take actions and lead the industry. Considering clear differences in e.g. cost of landfilling vs. recycling/reuse, regional waste management fees and the fact that manpower for selective demolition and proper dismantling for recycling is more expensive than new materials, the incentives to 'choose circular' are not necessarily supported, according to the Danish construction industry.

3.3. Use and demand of EPDs outside Danish borders

One of the research questions driving the project was why the amount of EPDs registered and used in Denmark was significantly lower than in neighbouring countries. An important consideration, which represents part of the answer, was made by several manufacturers. While they acknowledged that not many EPDs are registered by EPD Danmark, the Danish EPD Programme operator, compared to other countries, more EPDs exist from Danish manufacturers. For various reason these may just not be registered at EPD Danmark – some argue due to a large export market for which reason they've placed their EPDs where their buyers are, other already worked with environmental documentation even before EPD Danmark was established in 2014, for which reason their EPD is placed with other programme operators.

The lack of registered EPDs by EPD Danmark might thus support the argument discussed earlier, about a lack of incentive driven by a demand in the Danish construction industry, whereas countries like Germany, Norway and the UK have had better success in creating incentive – e.g. public procurement, regulation, building certification schemes and knowledge and requirements of documentation about environmental claims.

4. Conclusion and recommendations

The current project investigated the conditions for and the use of EPDs within the Danish construction industry. The project results confirm that most conditions and obstacles found in studies conducted between 2015 and 2018 still account as barriers. The most dominating ones include lack of demand from the authorities and builders, expenses for the LCA/EPD and lack of knowledge about how to document sustainability in the built environment. These barriers need to be addressed in order to strengthen the competitive power of EPDs within the Danish building sector.

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Roles of the reference service life (RSL) of buildings and the RSL of building components in the environmental impacts of buildings

Potrč Obrecht T[1], Kunič R[2], Jordan S[1], Legat A[1]

[1] Slovenian National Building and Civil Engineering Institute
[2] University of Ljubljana, Faculty of Civil and Geodetic Engineering

tajda.obrecht@zag.si

Abstract. The Life Cycle Assessment of a building is a complex analysis that also involves the use of the predicted Reference Service Life (RSL) of the building components and materials, as well as the predicted RSL of the whole building. The RSL values of individual materials and building components can be obtained from different sources and are not exactly comparable. In the present study, the influence of selected RLS values on an LCA assessment was evaluated. Three different RSL databases were used as the sources of the data to estimate the environmental impacts of selected building components (internal wooden door and external finishing coat). Two scenarios were presented. In the first scenario a building component can be reused in another building, while in the second scenario the reuse of the building component is not possible. The study showed that dependent on the selected RSL database, the results can differ by up to a factor of five. Therefore, it is very important to describe clearly the maintenance scenarios for a building in order to have a reliable comparison of the results of LCA assessments.

1. Introduction

It is estimated that buildings account for 30–40% of energy use and greenhouse-gas emissions [1,2]. The EU has been focusing on reducing energy use and, consequently, the environmental impact of the use phase of buildings. As a result of these measures, the ratio between energy use and the embodied energy of a building and its components has drastically changed: the embodied energy of the building has become more significant [3]. Therefore, it is important to assess the environmental impacts during the whole life cycle of a building, including the phases of producing the materials and components, the process of constructing the building, the operation and the decomposition. A Life Cycle Assessment (LCA) is a method used to evaluate the potential environmental impacts during the whole life cycle of a product and this method is also increasingly being used to evaluate the environmental impacts of complex products, such as buildings. The methodology is outlined in the ISO 14040 series of standards [4].

LCA studies consider the service life of the building and its components; therefore, their lifetimes need to be known as a reference service life (RSL). The building's RSL is defined as the period during which a building is in use. The building itself, however, has a very long RSL, usually longer than the individual components. In addition, the RSL of the component can vary greatly from one component to another. But the most important point is that the RSL values for the same buildings or components can vary depending on the database they originate from [5].

The RSL of a building component is influenced by many parameters, among them the indoor and outdoor environments, the predicted maintenance, the design of the product, etc. [6–8]. Different approaches can be used to estimate the RSL of a building's component and the building itself. In the study of Grant et al. [7] three main approaches to predict the RSL of a component were identified.

- First, the principles of structural engineering can be used to estimate the structural integrity and the fatigue of materials in accordance with the physical loading, the ongoing chemical reactions, and the degradation over time.
- Secondly, the factor method offers different factors that are used to modify the reference service life of a component (RSLC) to calculate an estimated service life of the component (ESLC). The method is declared in ISO Standard 15686-1 and includes factors for the quality of components (factor A), the design level (factor B), the work-execution level (factor C), the indoor environment (factor D), the outdoor environment (factor E), the in-use conditions (factor F), and the maintenance level (factor G):
-

  ESLC = RSLC × Factor A × Factor B × Factor C × Factor D × Factor E × Factor F × Factor G

- The third option is the use of empirical data. This method is seen as very accurate, but at the same time the acquisition of empirical data is very costly and time consuming.

The RSL of a component that is determined using one of the above-described methods can be acquired from different sources [9]:

- individual EPDs (cradle to gate, or cradle to grave);
- client requirements and current practices;
- product and component manufacturers' information;
- existing applicable standards such as ISO 15686-1, -2, -7 and -8;
- conventional service life in a national context or within an LCA software package for buildings.

There are also other sources that can be used to determine the RSL of building components and products:

- publicly available, national or commercial databases;
- research-group publications and initiatives;
- scientific publications.

The Eeb Guide states that in an LCA analysis the RSL of the component has an influence on several aspects of the life cycle of the building [9]. The RSL of the building influences the length of the use phase and thereby the impacts connected with the operational energy and water use as well as the maintenance. A lot of LCA studies are not paying enough attention to the maintenance scenarios of building components, although according to EN 15978, which divides the life cycle of the building into different stages (Fig. 1), various maintenance scenarios should be included in the life cycle of the building, i.e., B2 - maintenance; B3 - repair; B4 - refurbishment and B5 - replacement. According to EN 15978 the module B2- maintenance applies to planned actions and should include preventive and regular maintenance operations as well as cleaning operations. Maintenance scenarios should be provided along with a product's RSL according to EN 15804. The scenario B3 - repair encompasses all the actions, including corrective, responsive or reactive treatments of a construction product and the replacement of a broken component or part because of damage (replacement of a whole element should be assigned to B4 - replacement). B4 - replacement covers the replacement of a complete construction element [EN 15804], including the impacts on the production and installation of a new (and identical) construction element. The B5 - refurbishment module is applied when the connected actions of modules B2, B3 and B4, for a significant part of the building or a whole section of the building, are carried out.

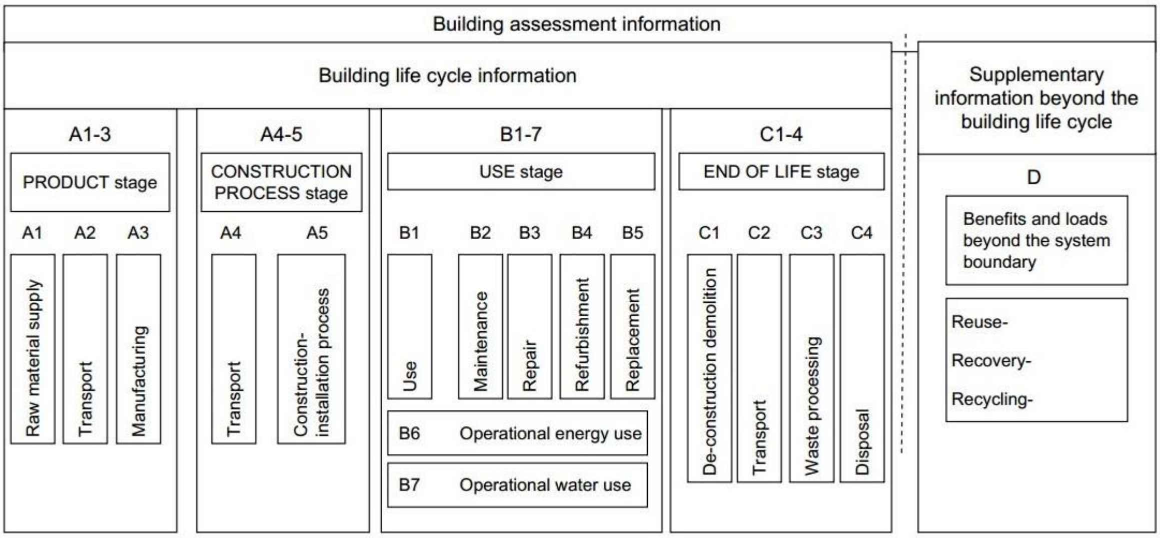

Figure 1. Building's LCA stages according to EN 15978.

A building's RSL has a significant influence on the LCA results related to the use stage of the building. Firstly, the RSL of the whole building influences the energy use of the building. In the case of a long RSL for a building, the amount of energy needed to operate the building can be much higher than in the case of a shorter RSL (modules B6 and B7). Secondly, the RSL of a building influences the results for the energy needed to maintain the building, since it affects the maintenance and the number of replacements of individual components (modules B2, B3, B4 and B5). And vice versa, the lengths of the RSLs of the components affect the number of their replacements over the entire lifetime of the building. However, it often happens that the end of the RSL of a building and the end of the RSL of the last replacement of the component under consideration do not coincide. If the RSL of the component exceeds the RSL of the building and if the component is still intact, it can be reused in another building (Figure 2). In this case the environmental impact of this last replacement can be divided between the life cycle of the first and the second buildings.

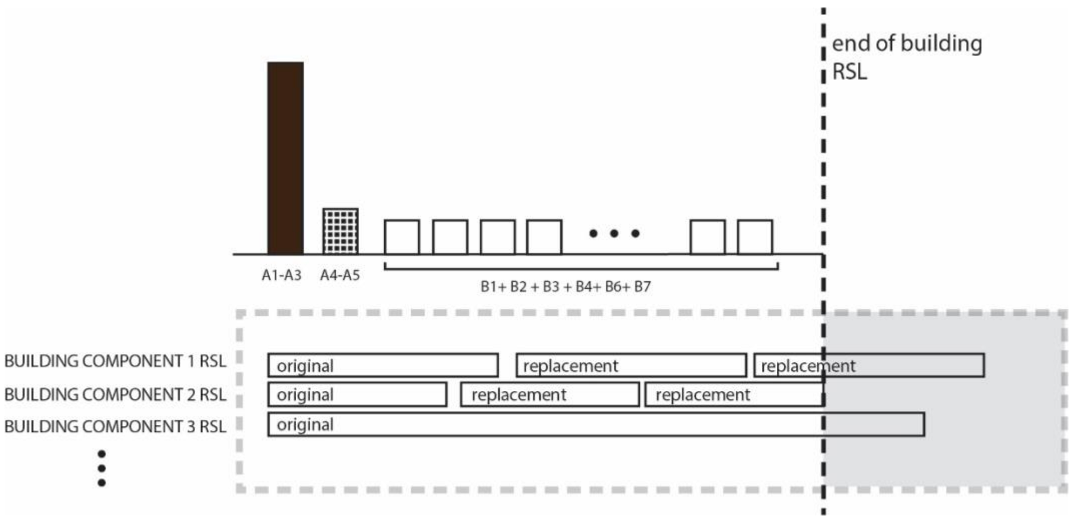

Figure 2. Residual RSLs of individual building components after the end of the building's RSL (marked grey)

Grant et al. [6,7] showed that LCA studies are not using uniform RSL values for the calculation of environmental impacts. They demonstrated that different predictions for the RSLs of building components and maintenance scenarios directly influence the environmental impacts of a building with an RSL of 50 years. In their study they compared the impact of the replacement phase for different building components in five RSL databases that are mainly present in the US market. The results can vary from 4 % to 25 % depending on the impact category. For an easier comparison of LCA studies it is very important that appropriate data about the use stage of the building's components and materials is provided, including information about their service lives and the maintenance scenarios. The RSL values of the building's components should be provided along with a maintenance scenario, as required by EN 15804. The LCA analysis should also take into account the decline in the performance of the building's products and components because this also has an influence on other aspects of the use stage (e.g., a lower performance of the heating system could result in a higher energy consumption), but this is almost never performed in practice.

The aim of the presented study is to show the role and importance of the length of the RSL of a building and its individual components in the calculation of the environmental impacts of the building. In the first part of the study the sources of the RSL values from different EU countries are described and compared. The study shows whether the RSL data is acquired from a standard or from legislation or is determined by the national method for LCA. In the second part of the study a comparison between the RSLs taken from three databases for buildings and building components is made, with the aim to clarify to what extent different RSL values in two scenarios of a possible product's reuse can influence the results of an LCA study.

2. RSLs of buildings and building components

2.1 RSL regulations in European countries

In order to carry out LCA studies, EU countries use data sources of various origins for determining the RSLs for buildings and their components. In general, the countries have developed their own databases, which are often based on the current standards, such as ISO 15686 or SIA 2032. The RSL values in Austria, for instance, are obtained from a document that is issued by the government; in Switzerland there is a standard, while the RSL in Slovenia is determined by legislation. In the case of Belgium and the Czech Republic the RSL database is included in the national LCA method.

Table 1 presents the sources of the RSLs for building materials and components in some European countries. The listed databases are mainly used for LCA calculations; although some can also be helpful for other analytical procedures (e.g., life cycle cost analysis).

Table 1. RSL regulation in European countries

Country	RSL Source for building components	Standard, legislation or part of the national assessment method	RSL of the building defined in relation to the main structural material	RSL of the building defined in relation to the building's use
Austria	Nutzungsdauerkatalog baulicher Anlagen und Anlagenteile 2012 [10]	Legislation	no	no
Belgium	Durées de vie dans MMG2017/TOTEM [11]	National assessment method	yes	no

Czech	SBToolCZE [12]	National assessment method	yes	no
Germany	Nutzungsdauern von Bauteilen für Lebenszyklusanalysen nach Bewertungssystem Nachhaltiges Bauen (BNB) [13]	National assessment method	no	no
Slovenia	Pravilnik o standardih vzdrževanja stanovanjskih stavb in stanovanj [14]	Legislation	yes	no
Spain	Documento Básico SE Seguridad structural [15]	Legislation	no	no
Switzerland	SIA 2032 [16]	Standard	no	no

Table 1 also provides information about whether there is a link between the RSL of a building according to its main construction material (fourth column) and between the RSL of a building and the use of the building (the last column). To illustrate this, the RSL value of wooden buildings in Slovenia is for 50 years, while this data for masonry buildings is for 90 years. It is clear that in the above-listed databases there is no distinction whatsoever between the RSLs of buildings according to their use (last column). Nevertheless, there are certain building-certification schemes, for instance DGNB, where the RSLs of buildings depend on the building type (e.g., office building, residential building) [10].

When calculating the environmental impacts, it is essential to differentiate between the building components that can be further reused in the same form either in the renovation of the same building or can be used in a second building and the building components that cannot be further used, although they have not reached their full RSL at the time of the building's demolition (Fig.2). For example, if a roof tile is still functional, it can easily be reused on a second building. On the other hand, it is impossible to reuse external wall finishes, even if they have not reached the full RSL at the time of the building's demolition. In the first case the environmental impacts can be divided between the two buildings, and in the second case the whole burden is assigned to only one building.

Table 2, below, shows the RSL data for building components from Slovenian's legislation, the Austrian catalogue (Nutzungsdaurekatalog) and the European Organisation for Technical Assessment (EOTA) technical guidelines.

Table 2. RSL for the building components of Slovenia, Austria and the EOTA

Building elements	**Slovenia**	**Austria**	**EOTA**
Foundations	90	60	100
External walls (above ground)	80	100	100
External door	50	30	25
Windows	50	30	25
Internal wall construction (supporting)	80	100	50
Partition wall (non-supporting)	50	30	25
Internal door	**50**	**30**	**25**
Floors (structural)	80	50	50
Ceilings	80	80	100
Roof structural construction	70	60	50

Stairs and ramps (structural)	50	70	50
Water system	40	N/D	25
Sewage system	40	N/D	50
Electrical system	40	N/D	25
Heating system (heat producer)	20	N/D	25
Heating system (heat distribution)	25	N/D	25
Ventilation system	20	N/D	25
External finishing coat	**40**	**30**	**25**
External thermal insulation (compact facade)	30	N/D	25
Roof cladding - inclined roof	30	N/D	25
Internal finishes (walls, floors)	30	30	10

2.2 Comparison of the environmental impacts of building components calculated with different RSL databases

In the continuation of this study a comparison of the environmental impacts determined based on different RSLs is presented. The environmental impacts were calculated for two building components with specific scenarios, an external finishing coat and an internal door. Each calculation was performed for three databases (Slovenia, Austria and the EOTA) in which the RSL for the building and the components under consideration differ considerably. The RSL data for both components, the finishing coat and internal door, are shown in Table 2 (marked bold). The environmental impacts were calculated with the data for the GWP impact category, taken from the Oekobaudat database [11] (Table 3).

Table 3. Oekobaudat data for the GWP impact category, used in this study

Internal wooden door (1pcs)

Indicator	Unit	Provision of raw materials A1	Transport A2	Production A3	Transport C2	Waste treatment C3	Elimination C4	Recycling potential D
GWP	kgCO(2)-Eq	-43,8	1,19	28	0,0792	101	2,6	-40,1

External finishing coat (1 kg)

Indicator	Unit	Production A1-A3	Transport A4	Installation A5	Elimination C4	Recycling potential D
GWP	kgCO(2)-Eq	1,22	0,199	0,0289	0,0112	-0,0193

For the purpose of the comparison, the study included two scenarios. The first scenario is related to the building component, the internal wooden door, which can be reused in a second building. The calculated environmental impacts of the replaced door can therefore be divided between the life cycles of both buildings. At the end of the second scenario (decomposition of the building) the building component, the external finishing coat, is destroyed. Consequently, it cannot be reused in the same form in another building, so the whole environmental burden of the finishing coat falls on the first building. The RSL of the whole building in our case study was 90 years for Slovenia, 100 years for Austria and 100 years for the EOTA database.

The internal wooden door

Within the RSL of the building the internal wooden door must be replaced several times, since the RSL of the door is much shorter than that of the building. The RSLs for the internal wooden door considered were 50 years for Slovenia, 30 years for Austria and 25 years, as proposed by the EOTA (Table 2). The needed replacements are as follows: one time according to the data for Slovenia, and three times according to the data for Austria and the EOTA.

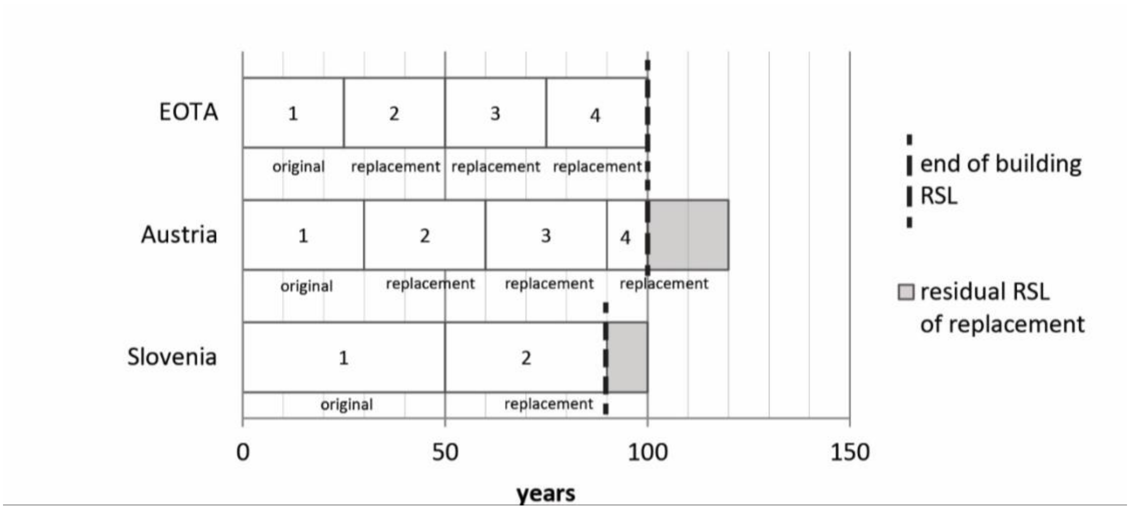

Figure 3. Internal door replacements in the RSL of the building according to the selected RSL databases

In the case of Austria and Slovenia the RSL of the last replaced internal wooden door exceeds the RSL of the building. So only the part of the production phase (A phase according to EN 15978) is assigned to the life cycle of the first building, while the rest (C3, C4 and D phases according to EN 15978) should be assigned to the LCA of the new building where the material will be subsequently used.

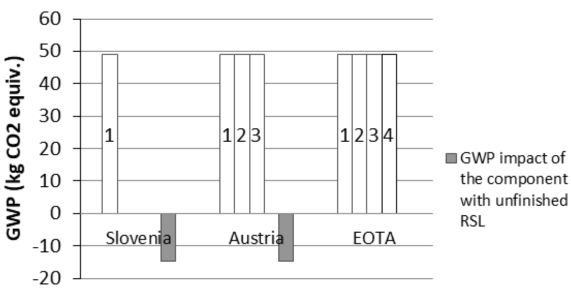

Figure 4. GWP emissions of each internal door (original + replacements) during the RSL of the building

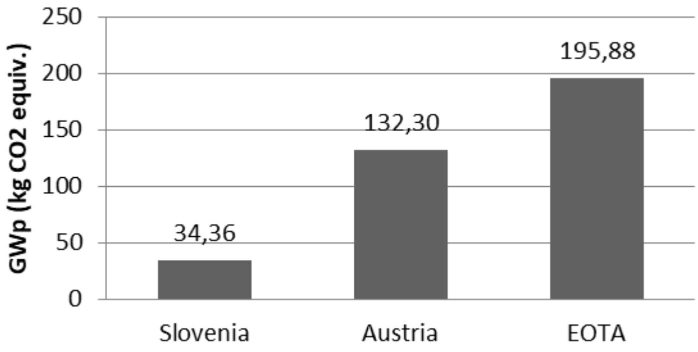

Figure 5. Total GWP emissions for an internal door (original + replacements) during the RSL of the building according the selected RSL databases

The production phase for the internal door has an impact of -14,61 kgCO2equiv., the end-of-life phase 103,6 kgCO2equiv and the D phase has an impact of -40,1 kgCO2equiv. In the case of Slovenia, the impact of the original door (the sum of all the phases) and the production phase of the replacement door are summed together. According to Austria's RSL database the impact of the original door, the impact of the first two replacements (all life cycle phases) and the production phase of the third replacement are summed. For the EOTA the total impact of the original and the total impact of all three replacements are summed.

The calculation shows that the results can differ by up to a factor of five (Fig. 4 and Fig. 5). The gap between the results is further emphasized by the fact that the internal door is made of wood, which is considered as a carbon sink. This means that the benefits of the carbon sequestration are attributed to the first building, as a positive impact on the environment (Fig. 4), while the environmental burden of wood disposal is assigned to the second building.

External finishing coat

An external finishing coat is a type of product that is virtually impossible to disassemble in such a way that it can be reused. Therefore, it is anticipated that although this product has not reached its full RSL it has to be disposed of at the end of the RSL of the building. The entire burden of the external finishing coat, even if it is still functional, needs to be ascribed to the first building.

Again, the RSL of the building in our case study was 90 years for Slovenia, 100 years for Austria and 100 year for the EOTA database. The RSL for the external finishing coat was 40 years in Slovenia, 30 years in Austria and 25 years as proposed in the EOTA (Table 2).

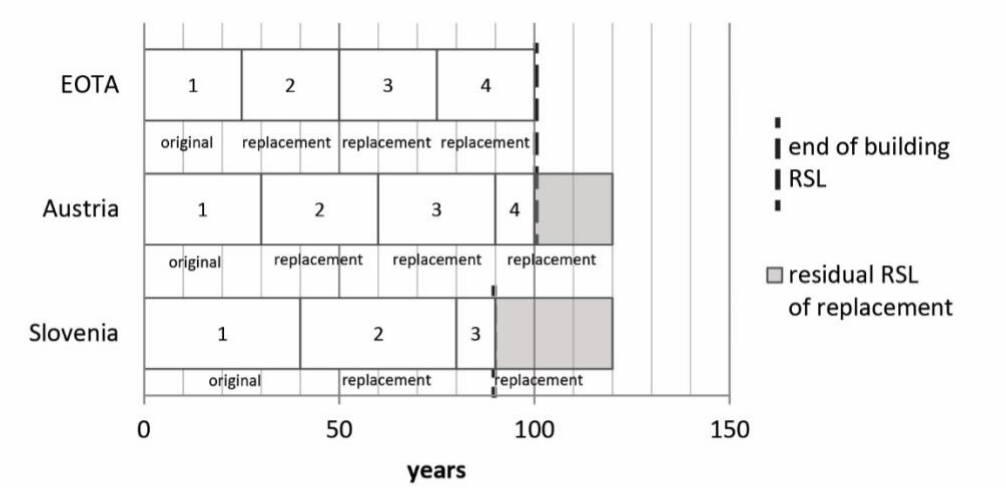

Figure 6 Finishing-coat replacements in the RSL of the building according to the selected RSL databases

Also, the external finishing coat must be replaced several times within the RSL of the building: two times according to the Slovenian data and three times according to the data from Austria and the EOTA. It is clear (Figure 6) that in the case of Austria and Slovenia the RSL of the external finishing coat exceeds the RSL of the building. Nevertheless, the whole environmental burden of the last replacement of the component must be assigned to the building.

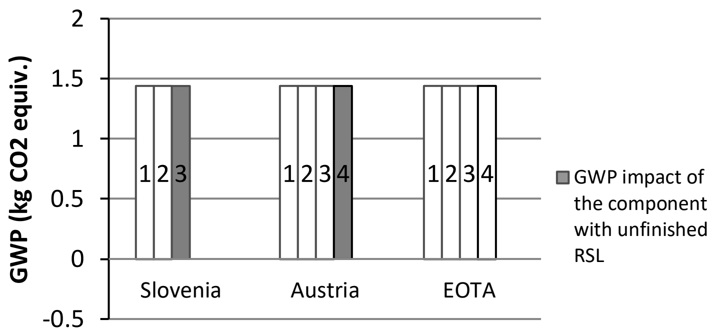

Figure 7. GWP emissions of each kg of finishing coat (original + replacements) during the RSL of the building

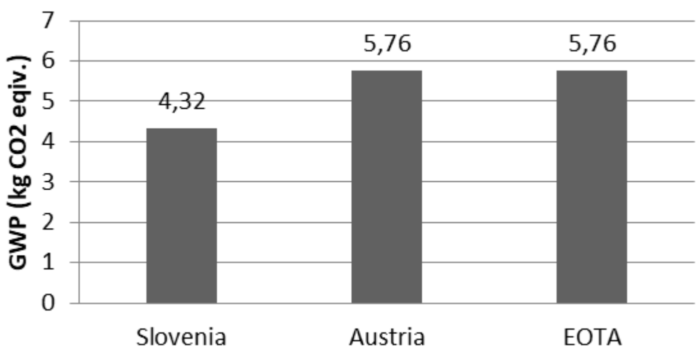

Figure 8. Total GWP emissions for 1 kg of finishing coat (original + replacements) during the RSL of the building according to the selected RSL databases

The production phase for 1 kg of finishing coat has an impact of 1.448 kgCO2equiv., the end-of-life phase 0.011 kgCO2equiv and the D phase has an impact of -0.019 kgCO2equiv. According to the Slovenian RSL database two replacements are needed (the environmental impact of all the life cycle phases is calculated). In the case of Austria and the EOTA the environmental impact of the whole life cycle of 1 kg of finishing coat is calculated four times (original + three replacements).

The GWP emissions caused by 1 kg of external finishing coat are the same when calculated with the Austrian or the EOTA RSL data, despite the fact that the RSLs of the finishing coats are 30 and 25 years. In both cases three replacements of the coating in the RSL of the building are required (Fig 7). In Slovenia the RSL of the external finishing coat is longer and only two replacements of the external finishing coat are needed; consequently, the GWP emissions of the latter are lower (Fig 7).

3. Conclusions

This study confirms that the reference service life (RSL) of a building and its components can have a significant influence on the results of the LCA analysis of a building. Therefore, for ensuring a reliable comparison between analyses it is extremely important that the RSL data in European databases are reasonably harmonized and clearly presented.

The results of the analysis showed that the calculation scenario at the end of the RSL of a building must be consistent with the actual handling of the components when the building is decomposed. In an ideal scenario, multiple RSLs of building components and the RSL of a building would end simultaneously. In reality this is very rare: the environmental impacts of the component strongly depend on the reuse scenario in terms of whether they should be attributed only to the life cycle of the first building or the next one, in which it is reused as well. This case study confirms that the scenarios for the reuse of individual components must also be methodologically consistent.

The influence of building components' RSLs was analysed with just two examples. It was shown that due to the selected European RSL databases and the predicted scenarios the results of the environmental impacts in a life cycle of a building can differ by up to a factor of five. In real buildings there are hundreds of components, so the influence of various reuse scenarios on the overall LCA analysis results can be even more significant.

RSL values of the individual materials, building components and buildings can be selected from many sources and are not completely comparable. It was found that the RSL sources in the European context are usually linked to different kinds of national legislation, but the background for their definition is not exactly known. Some countries have a uniform RSL for all the buildings, while others (including Slovenia) have RSL values that are mainly related to the type of building material (brick, concrete, wood, steel). There are some cases where the RSL values primarily depend on the use of the buildings. It is obvious that further research based on European data and subsequent comparisons of the results are needed to define reliable RSL values for specific individual materials and building components as well as for buildings.

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Economic valuation of life cycle environmental impacts of construction products - A critical analysis

Durão V[1], Silvestre J D[1], Mateus R[2], De Brito J[1]

[1] CERIS, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
[2] CTAC, University of Minho, Department of Civil Engineering, Guimarães, Portugal

vera.durao@tecnico.ulisboa.pt

Abstract. The aim of this paper is to identify existing methods for economic valuation or monetisation of life cycle environmental impacts and to assess its applicability in the broad European context. Although environmental awareness is more and more important in several industrial sectors, including the construction sector, easy to understand data are still missing for professionals to assess and manage impacts related to the whole life cycle of a building. Life Cycle Assessment (LCA) is one of the most commonly accepted methodologies to calculate potential life cycle environmental impacts of a product or service. However, the results of such method, even when published in an Environmental Product Declaration, meant for business to business communication, are not always comparable or easily understandable by non-practitioners. Economic valuation or monetisation of LCA results is a weighting step that can make it easier for non-practitioners to use LCA results to support decision-making. From the several monetisation methods analysed, it is discussed the one that is most suitable for use when LCA results already exist. It is concluded that further work is needed to improve such weighting methods or develop a common one that can be representative at a broader geographical level (for instance, Europe-wide).

1. Introduction

Environmental degradation, such as climate change or resource scarcity, are increasing due to human activity. Population concentration in urban areas and fast urbanization are also aspects with the potential to impact society. Despite its importance in economic and social aspects (namely, accounting for 6% of the global Gross Domestic Product (GDP), providing millions of jobs, and the social service of providing housing), the construction sector is the largest global consumer of raw materials, and responsible for 25-40% of the world's total carbon emissions [1].

To enable Architecture, Engineering and Construction (AEC) professionals, decision-makers and investors throughout the EU to consider impacts related to the whole life-cycle of a building, empirical-based, reliable, transparent and comparable data are needed, based on clear indicators of the building performance [2]. Life Cycle Assessment (LCA) is a commonly accepted and well-established methodological tool. It applies life cycle thinking, quantitatively, to the environmental analysis of activities related to processes or products [3]. However, to apply the Sustainability concept to buildings based on its three pillars (environmental, social and economic), other tools must also be used. Currently, several European standards, developed by the Technical Committee (TC) 350 of the European Committee for Standardization (CEN) (TC350/CEN), are published concerning the evaluation of construction works performance in all these three pillars [4–7]. Both TC350/CEN and ISO have also developed standards concerning the communication of environmental impacts through Environmental Product Declarations (EPD), that aim at providing AEC professionals with LCA information on construction materials [8, 9].

In what concerns LCA application within the building sector, as a strategy to reduce environmental impacts, it is often identified as complicated and time-consuming. Moreover, most of the impact assessment methods commonly used result in a set of environmental categories that are not easily understandable or interpretable [10]. This conclusion can be obtained from the analysis of the list of parameters and environmental information specified for a Type III Environmental label - EPD [9]:

- Parameters describing environmental impacts (7 impact categories);
- Parameters describing resource use (17 parameters);
- Environmental information describing output flows (4 parameters);
- Environmental information describing waste categories (3 parameters);
- Parameters describing pollutants emission from materials (3 parameters);

Taking this into account, for AEC professionals to use LCA more efficiently as a decision support tool, this information needs to be simplified, and monetisation is a solution for that. Currently, opinions diverge on the monetisation of environmental impacts, with a discussion on whether and how to value them [11]. This paper intends to identify existing monetisation approaches and methods for environmental impacts and their main pros and cons when applied to LCA results. More specifically, it intends to assess their application in the case that LCA results are available in the form of an EPD.

2. Material and Methods

The main method used for the development of this work was through a literature review.

Methods reviewed for this work include LCA and monetisation methods already developed, used and accepted by the scientific community.

3. The Life Cycle Assessment method

LCA is a structured, comprehensive and internationally standardised method (ISO 14040 series [12]). It allows the quantification of all relevant emissions, resources consumed and the related potential environmental and health impacts and resource depletion issues that are associated with any goods or services (“products”) (ISO, 2006). This is a complex and data-intensive methodology that considers the potential impacts of the whole life cycle of a product, from the extraction of resources, through production, use, and recycling, up to the disposal of remaining waste [13]. This method is an important tool applied to [12]:

- Identify “critical points” and respective opportunities to improve the environmental performance of products at several stages of their life cycle;
- Inform decision-makers in industry, government or non-governmental organizations in the search for more sustainable consumption and production (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign);
- Select relevant indicators of environmental performance, including measurement techniques;
- Marketing activities (e.g. implementing an eco-labelling scheme, making an environmental claim, or producing an environmental product declaration).

LCA methodology is standardized namely by ISO 14040 concerning Environmental management - Life cycle assessment - Principles and framework [12] and by ISO 14044 concerning Environmental management - Life cycle assessment - Requirements and Guidelines [14].

ISO 14040 describes the principles and framework for LCA, including its four main stages: the goal and scope definition of the LCA study, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, and the life cycle interpretation phase.

There are cases in which the aim of an LCA can be achieved by performing only the first two phases - it corresponds to an LCI study [15]. However, a complete LCA includes the evaluation of the environmental impacts associated with these inputs and outputs of the system (LCIA) and the interpretation of the results of the inventory and evaluation phases, taking into account the objectives of the study [14, 15]. Life cycle impact assessment is the stage of an LCA that allows understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system. ISO 14040/44 refers to several steps in the LCIA [12, 14], as described in the following paragraphs.

- Mandatory elements:
  - Selection of impact categories, category indicators and characterization models;
  - Classification: assignment of LCI results to the selected impact categories - each elementary flow from the inventory is assigned to the impact categories according to the substances' potential to contribute to different environmental problems (e.g., eutrophication, climate change); these impact categories may be endpoint (human health, resource depletion, later in the cause-effect order) or midpoint (climate change, land use; earlier in the cause-effect order);
  - Characterization: calculation of category indicator results - for each impact category several substances contribute with specific magnitudes.

To reduce all substances to a common equivalent unit, normalisation, equivalence factors or characterisation factors may be applied during this step (optional).

- Optional elements:
  - Normalization: calculating the magnitude of category indicator results relative to reference information, for instance, in reference to the average level of pollution produced by an average European citizen;
  - Grouping: sorting and possibly ranking of the impact categories;
  - Weighting: converting and possibly aggregating indicator results across impact categories using numerical factors based on value-choices;
  - Data quality analysis: better understanding the reliability of the collection of indicator results/the LCIA profile.

Thus, weighting is an optional element with two possible procedures, either to convert the indicator results or normalized results with selected weighting factors or to aggregate these converted indicator results or normalized results across impact categories. Weighting steps are based on value-choices and are not always objective [14]. This is the step that allows the monetisation of environmental impacts by attributing an economic value to the equivalent unit of the characterisation result of each impact category.

4. Monetisation approaches and existing methods

Monetisation expresses the relative importance of an impact category in monetary value. This value can be based on the costs associated with preventing or repairing damage (e.g. damage costs using market prices). Another example to monetise an impact category is to measure how people are willing to pay to prevent a given impact. These include expressed willingness (through interviews) or estimated willingness to pay through value attribution by the users or measurement of welfare losses, as well as political willingness to pay [16, 17]. These are applicable to both use and non-use values, i.e. the value that people derive from goods independently of any use, present or future, that they might make of those goods, in contrast with use values, which people derive from direct use of the good [16]. A summary of monetisation approaches is presented in Table 1.

Based on these approaches, several monetisation methods/weighting sets have been developed and are widely used for the weighting of environmental impacts resulting from LCA studies. The most relevant are listed in Table 2.

5. Discussion

The **Eco-costs** approach is a prevention-based monetisation method [18]. It translates the environmental impact into economic cost by measuring the cost of preventing a given amount of environmental burden [19]. Eco-costs provides monetary values for the following impact categories: acidification (from the LCIA method International Reference Life Cycle Data - ILCD): eutrophication and summer smog (from the LCIA method Recipe); ecotoxicity and human toxicity (from the LCIA method UseTox 2); fine dust (from the LCIA method RiskPol); and global warming (from the LCIA method of Integrated Pollution

Prevention and Control - IPPC). In addition, there is a set of eco-costs to characterize the 'midpoints' of resource depletion [18]:

- Eco-costs of abiotic depletion (metals, including rare earth, and fossil fuels);
- Eco-costs of land-use change (based on loss of biodiversity);
- Eco-costs of water (based on the midpoint Water Stress Indicator - WSI);
- Eco-costs of landfill.

Table 1. Monetary valuation approaches (adapted from [20]).

Approach	Description
Revealed willingness to pay	Market prices (damage costs: loss of production, loss of capital or added value)
	Revealed preference methods (productivity method and travel cost method)
	Hedonic pricing (combining market places of a good and the influence of environmental aspects on the user's willingness to pay)
Expressed willingness to pay	Stated preference methods (contingent valuation and choice modelling)
Imputed willingness to pay	Damage cost avoided method (e.g. restoration costs, remediation costs, defensive expenditures)
	Replacement cost method uses the cost of replacing an ecosystem or its services
	Substitute cost method uses the cost of providing substitutes for an ecosystem or its services
Political willingness to pay	Costs-to-reach-target
	Taxes
Avoidance costs	Estimation of the cost to limit some emissions or impacts to a chosen limit, based on a hypothetical situation and not on willingness to pay

Table 2. Identified monetisation methods and respective approach.

Method	Approach
Eco-costs	Revealed willingness to pay - Market prices (prevention prices)
Ecotax 2002	Political willingness to pay - Taxes
Ecovalue 08	Revealed willingness to pay - Market prices (added value) and imputed willingness to pay - Damage cost avoided method (defensive expenditures)
Environmental Prices	Revealed willingness to pay - Market prices (prevention prices)
Environmental Priorities Strategies in product design (EPS)	Imputed willingness to pay - Damage cost avoided method (defensive expenditures)
External costs of energy (ExternE)	Revealed willingness to pay - Market prices (added value)
LIME	Expressed willingness to pay - Stated preference methods
Social Cost of Carbon	Revealed willingness to pay - Market prices (damage costs: loss of welfare)
Stepwise 2006	Imputed willingness to pay - Damage cost avoided method (defensive expenditures)

Eco-costs refers to the environmental categories most often used in the environmental assessment of building materials and assemblies, which are compatible with the environmental information provided in EPDs [21, 22]. The marginal prevention costs at a midpoint level can be combined and expressed as "endpoints" in three groups, plus global warming as a separate group [18]:

- Eco-costs of human health = the sum of carcinogens, summer smog, and fine dust;
- Eco-costs of ecosystems = the sum of acidification, eutrophication, and ecotoxicity;
- Eco-costs of resource depletion = the sum of abiotic depletion, land-use, water, and landfill;
- Eco-costs of global warming = the sum of CO_2 and other greenhouse gases (GWP 100 table);
- Total eco-costs = the sum of human health, ecosystems, resource depletion and global warming.

Ecotax 2002 is a monetization approach based on the Swedish eco-taxes and fees on emissions and resource use. It assumes that political decisions reflect societal values of environmental impacts. This method also uses CML Baseline midpoint impact categories, which are compatible with the use of EPDs. In some cases, a tax or fee can be used directly as a weighting factor, for example, the taxation on CO_2 for global warming (CO_2 eq.). In other cases, weighting values are calculated based on existing taxes, for instance, taxes on nitrogen fertilizers are adapted to provide a weighting factor for eutrophication [23–25].

Ecovalue 08 builds on weighting factors that aggregate midpoints on a monetized endpoint impact. It is based on market valuations of resource depletion and individual Willingness To Pay (WTP) estimates for environmental quality. The characterisation method used for the midpoint impact categories is CML (Centre for Environmental Sciences - Leiden University) baseline [26]. This method is compatible with the use of EPDs as information sources for the environmental LCA results.

Environmental Prices expresses the willingness-to-pay for less environmental pollution in Euros per kilogram of pollutant [27], similarly to Eco-costs. It indicates the loss of economic welfare derived from each additional kilogram of the pollutant entering the environment and often coincides with external costs. Environmental prices distinguish on the environmental categories it values. Environmental Prices Handbook defines five endpoints [27]:

- Human health (morbidity, i.e. sickness and disease, and premature mortality);
- Ecosystem services (including agriculture);
- Buildings and materials (man-made capital);
- Resource availability;
- Wellbeing (aesthetic and ethical values).

Regarding midpoint categories, environmental prices closely follow the categories used in the ReCiPe method, add a nuisance-related category, and are not consistent with the information provided by EPDs. However, environmental prices are presented also at the pollutant level, allowing for the application of the method based on the inventory of the product/process assessed.

Environmental Priorities Strategies in product design (EPS) system [28] is one of the eldest (1991-1992) monetary valuation models developed to facilitate comparison of environmental impacts (mostly for product development). It calculates environmental costs using inventory data, characterization factors, and weighting factors (monetisation), reaching an endpoint result. The impact categories in the EPS method are identified within four areas of protection: human health, ecosystem production capacity, abiotic stock resources, and biodiversity. Damages to these safeguard subjects are monetised according to the willingness to pay (WTP) to avoid changes from the present state of the environment. Environmental aspects such as emissions of substances (e.g. CO_2, CO, NO_x, SO_x, etc.) or resources extraction (e.g. fossil fuels, minerals) are classified in each of the mentioned areas of protection. Weighting factors are defined for 15 impact categories, grouped in 4 main damage categories, as defined in the EPS 2000 method used for life cycle impact assessment, not consistent with the information provided by EPDs.

External costs of energy (ExternE) is a project funded by the European Commission, which started in 1995, intending to monetise socio-environmental damages caused by distinct energy carriers. ExternE makes a detailed and systematic assessment of the full cause-to-effect chain from burdens or emissions to environmental impacts and damages. The three safeguard subjects considered are public health, built environment, and ecosystem production capacity. Impacts are valued based on market prices or 'willingness to pay'. The two follow-up projects of ExternE are the New Element for the Assessment of

External Costs from Energy Technologies (NewExt) and the New Energy Externalities Developments for Sustainability (NEEDS). The aim of the former was to improve the assessment of externalities and that of the latter was to evaluate costs and benefits of energy policies and of future energy systems [25]. This method is also not compatible with the use of products' EPDs as input for the monetisation.

LIME, Life-cycle Impact Assessment Method based on Endpoint Modelling, is a Japanese project that aims at developing a database to assist industries in implementing reliable LCA studies in the characterization step. LIME considers 11 impact categories: urban air pollution, hazardous chemicals, eutrophication, global warming, ecotoxicity, acidification, ozone layer depletion, photochemical oxidant creation, land use, waste, and resource consumption. The monetisation is based on a survey conducted in 2004 (in Tokyo) and in 2012 (throughout Japan) to assess the WTP of the Japanese society to avoid damage on certain safeguard subjects (for example, human health or biodiversity). With the use of logit modelling, the weighting factors to aggregate midpoint categories were calculated estimating the environmental attitudes and preferences of the Japanese public. Based on the logit model, LIME provides two types of weighting factors: a dimensionless index; and an economic valuation. Both can be used on the results of different impact assessment methods for estimating monetary values [24, 25].

Stepwise 2006 [29] is a monetization method built on the results of LCIA method Ecoindicator99 [30], which provides results as physical scores for each of the three safeguard subjects: humans, ecosystems, and resources. These damage categories are redefined [29] so that they can be measured in: Quality Adjusted Life Years (QALYs - the amount an average person is willing to pay for an additional life year) for impacts on human well-being; in Biodiversity Adjusted Hectare Years (BAHYs) for impacts on ecosystems; and in monetary units for impacts on resource productivity. To aggregate these results, a monetary value is attributed to QALY and to BAHY and an exchange rate between BAHY's and QALY's is set, measuring impacts on resource productivity. Both valuations allow environmental impacts to be expressed in monetary values [29]. Considering that the LCIA method Ecoindicator99 is an endpoint method based on panel approach, there is already a high subjectivity of the results even before the monetisation step. However, currently, the STEPWISE method uses characterisation models from IMPACT2002+ v. 2.1 and the EDIP2003 methods, that are second-generation methods, building on previous work (Ecoindicator1999 and EDIP1997, respectively) [31]. Still, the format of environmental information provided by EPDs is not compatible with this method.

The Social Cost of Carbon (SCC) is a commonly employed metric of the expected economic damages from carbon dioxide (CO_2) emissions [32, 33]. SCC represents the economic cost associated with climate damage derived from the emission of an additional tonne of carbon dioxide (tCO_2). Considering that global warming potential, measured in $CO_{2eq.}$, is one of the indicators provided in EPDs, this valuation method may also be compatible with this source of information. It neglects, however, other important environmental impact categories declared in these declarations.

Table 3 presents some examples of the application of the identified monetisation methods. The examples chosen were those from the most recent years and, when available, including the application of the valuation methods to the construction sector.

6. Conclusions

Taking into account the economic and environmental relevance of the construction sector, there is a growing need to provide the AEC professionals with tools that support the improvement of its sustainability, namely in the environmental dimension. LCA is an important methodology for that. However, considering the complexity, and the information and time demand, of this methodology, it is understandable that it is not the focus of these professionals. Even the results of an LCA study as presented on EPDs (most common sources of LCA results for these professionals) are usually difficult to interpret and use. The weighting of these results in the form of monetisation of environmental impacts has the advantage of providing a single indicator in an objective unit, allowing professionals to evaluate and easily compare options while being aware of the magnitude of environmental impacts in each life cycle stage (in relation to market costs of a project).

Table 3. Examples of application of the identified methods.

Method	Reference and additional methods	Objective of the use of monetisation
Eco-costs	Scheepens *et al*, 2018 [34]	A combined analysis of cost, (market) value, and eco-burden was used to compare strategies of passive (insulation focused) and active (behaviour focused) end-users, by applying the methods of eco-costs/value ratio (EVR) and eco-efficient value creation. The analyses identified the economic and environmental payback and the likelihood for potential rebound effects.
	Mano *et al*, 2017 [35]	Incorporation of costs of the environmental impacts caused by energy generation and equipment construction in the heat exchanger networks (HEN) using the eco-costs methodology. The inclusion of indirect costs (externalities) in the optimization procedure was found to significantly affect the characteristics of the minimum cost design, the operational conditions and HEN topology.
	Carreras *et al*, 2016 [36]	Eco-costs method was used to translate the environmental impact of the building envelope into monetary units. This was incorporated into the economic performance assessment, to optimise the thermal insulation of a building envelope in different climate zones.
Ecotax 2002	Du *et al*, 2018 [37] (also Ecovalue 08)	Comparison of the environmental performance of two bridge types through the whole life cycle, based on eight selected cases in Sweden, applying Ecovalue08 and Ecotax02 methods to evaluate the environmental costs of each design option.
	Nguyen *et al*, 2016 [25] (also EPS and Stepwise 2006)	Calculation of the environmental externalities of electricity from renewable (e.g. biomass) and from non-renewable sources (e.g. coal, oil, and gas), comparing three monetization methods, the EPS 2000, the Stepwise 2006, and the Ecotax.
Ecovalue 08 (also Stepwise 2006)	Huysegoms *et al*, 2018 [24]	Application of different monetization methods of LCA study results to the assessment of the site remediation of a former gas plant. Implementing monetized LCA results in social cost-benefit analysis (CBA) allowed for a more detailed overview and valuation of the secondary environmental effects.
Environmental Prices	Huysegoms *et al*, 2019 [38]	Application of the environmental prices method to incorporate LCA in Social CBA in the comparison of remediation alternatives for a dry-cleaning facility.
ExternE	Entler *et al*, 2018 [39]	Ex-ante economic analysis of a fusion power plant in terms of the cost of electricity. It includes the external costs of energy based on the OECD statistical data and on the EU ExternE project results.
	Jochem *et al*, 2016 [40]	Comparison of the main external cost components for electric vehicles and internal combustion engine vehicles, based on the ExternE method.
LIME	Yamasaki *et al*, 2019 [41]	Incorporation of life cycle impact assessment (LCIA) into the calculation of environmental loads for administrative divisions applying monetisation method LIME-3.
Social Cost of Carbon		Investigation of the cost-effectiveness and environmental impacts of a green roof in an educational building of the University of Florida. Environmental costs were integrated using Global Warming Potential (GWP) measure to determine the social cost of carbon.

In this work, it was possible to identify several monetisation methods. However, taking into account standards for the development of EPDs, Eco-costs, Ecovalue 2008, Ecotax 2002 and Social Cost of Carbon are the most suitable ones, because they are based on CML baseline midpoint impact categories, declared in EPDs. Moreover, the first two were the methods for which case studies were found related to the construction sector. However, they do not show broad geographic representability, since they are both strongly influenced by the Swedish framework (in terms of existing taxes and of the valuation of environmental impacts).

From this work, it is possible to conclude there is a need for further development/improvement of monetisation sets or methods, in order to obtain larger consensus and representability. Considering the efforts for the democratisation of the use of LCA and the communication of its results, it would be important to develop a monetisation method that can be Europe-wide representative as well as easily applicable to the available information, for instance, EPDs or other standardised sources of LCA information. Moreover, standards and guidelines related to these communication tools could also include the option of weighting the LCA results through monetisation, providing the common user with an easier to interpret and more tangible information in what relates to the potential life cycle environmental impact of a product.

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VinylPlus® and the VinylPlus Product Label. Could the industry label be integrated into independent sustainability certification schemes?

Sevenster A[1], Stone V[2], Schratt H[3]

[1,2] Technical and Environmental Affairs Senior Managers, ECVM—European Council of Vinyl Manufacturers, Brussels (B)
[3] Secretary General, PlasticsEurope Austria, Vienna (A)

heinz.schratt@plasticseurope.org

Abstract. In building & construction (B&C), polymeric materials are being used for roofing and waterproofing membranes, coated fabrics ("textile architecture"), window profiles, electrical installation, flooring, pipes, etc. The most widely used plastic for such long-life applications in B&C is Vinyl (PVC). VinylPlus is the value chain's commitment for sustainable development. The voluntary commitment has a track record with publicly available progress reports, based on third party auditing and monitoring since 2001. More recently: After having substituted certain additives such as lead compounds, that had previously been used as stabilizers, and after abandoning mercury cell technology, VinylPlus is addressing further needs of the sustainability communities, e.g. by zooming in on additives and complementing standard LCA requirements. The VinylPlus voluntary commitment for sustainable development has been developing an additives sustainability footprint (ASF) and a set of criteria for its product label.
The scope and the current status of those tools will be presented and examples be given in order to document the relevance of those efforts. The information given is intended to fuel the discussion on how can / to which extent should those value chain commitments be integrated into existing sustainability.

1. Sustainability principles and assessment methodologies

The contemporary concept of sustainable development evolved progressively from growing awareness of the interdependence of social and economic progress with the supporting environment. Development of the concept culminated in 1987 with the UN's report Our Common Future (World Commission on Environment and Development, 1987), also known as the 'Brundtland Report'[1], which introduced the most widely recognised definition: "…development that meets the needs of the present without compromising the ability of future generations to meet their own needs". New or amended definitions of sustainable development have continued to proliferate, and regulatory instruments and management tools have increasingly sought to integrate the concept into operational norms.

The UN's consensual 17 Sustainable Development Goals (SDGs[2], United Nations, 2016) make a welcome addition to considering the limitations in the sustainable development narrative. The SDGs succeed in re-focusing attention on a linked set of human needs aimed at "Meeting citizens' aspirations for peace, prosperity, and wellbeing, and to preserve our planet"[3]. The SDGs have to be understood in a systemic context, addressing all goals as an inherently interconnected set. The SDGs also provide a framework for assessment of progress towards a more sustainable future. Such a framework avoids a company, value chain or other institution to fall into the trap of selecting just a few goals in a given sector[4].

A comprehensive review of sustainability assessment schemes is obviously impossible within the limited size of the present paper. We will therefore briefly mention a few particularly relevant for the construction industry and/or the VinylPlus sustainability programme.

1.1. Sustainability assessment methodologies relevant for VinylPlus

In view of the wide use of vinyl products in construction applications, it is worthwhile mentioning the most widely used building rating systems in Europe such as the Leadership in Energy and Environmental Design (LEED) developed by the U.S. Green Building Council (USGBC)[5], BREEAM (the Building Research Establishment Environmental Assessment Method)[6] and the rating system developed by the German Sustainable Building Council (DGNB)[7].

Those methodologies focus essentially on the sustainability of entire buildings—but not to the same extent on the sustainable production of individual building elements. Unless there are established sustainability labels, e.g. FSC for timber, on the elements and materials level the predominant schemes build on the ecological characterization of products.

The analysis of upcoming and/or commercially less relevant sustainability rating systems is not within the scope of this paper.

The Cradle to Cradle methodology[8] (C2C) has its own set of aspirational principles and terminology, which is sometimes presented as an alternative model to sustainability and a foundation for the circular economy. Its essential reliance on chemical hazard of substances, embodied in its Banned List of Chemicals, does not however consider impacts during product use, nor the contribution of chemicals to product functionality.

Transitioning to a sustainable society is obviously a complex endeavour, requiring, e.g., extensive coordinated collaboration across disciplines and sectors. How can humanity hope to succeed with this without having a unifying and operational definition of sustainability, and a systematic approach to planning and acting for the fulfilment of it? In response to this problem, a consensus process aiming at developing such a definition and approach began in Sweden in the early 1990s and the result is now widely known as the Framework for Strategic Sustainable Development (FSSD). This scrutiny also involves a kind of modelling where scientists study contemporary sustainability issues and test whether they are all covered, and can be clustered under the different sustainability principles. Forecasting and backcasting represent two major approaches to support planning and decision making. Forecasting is often used in attempts to predict and solve problems but is not appropriate when planning for long term and novel goals in complex systems and when the dominating trends are themselves a main part of the problem[9]. For such planning endeavours, backcasting is a more appropriate approach[10]. Backcasting begins by defining the vision, and then asks: what shall we do today and subsequently to get there?

This was one of the main reasons why the European PVC industry called on the expertise of The Natural Step (TNS). TNS approach[11] relies on the backcasting approach and is based on four basic rules defining success (sustainability principles). According to these principles, in a sustainability society, nature is not subject to systematically increasing concentrations of substances from the earth's crust, concentrations of substances produced by society, and degradation of physical means. In that society, there are no structural obstacles to people's health, influence, competence, impartiality and meaning.

2. VinylPlus's approach to sustainable development

"The sustainable use of (sustainable) chemicals aims at providing socially necessary products while minimizing resource consumption, reducing substance losses and controlling exposures by corporate, design oriented, organizational and technical means and at the same time enhancing healthy workplaces and fair social conditions."[12]

Already in 2000 the entire European PVC industry value chain—resin manufacturers, converters and additive producers —launched the voluntary commitment Vinyl 2010. This 10-year programme marked a leap in the PVC industry's journey towards sustainability. Despite a financial crisis and a much-enlarged target area due to the addition of EU member states, all goals were met and in some instances even exceeded.

Building on the achievements of Vinyl 2010, the partners decided to launch a new 10-year voluntary commitment, VinylPlus, undersigned in June 2011[13]. First, a fundamental assessment of the sustainability aspects of PVC was conducted and it became logical to involve The Natural Step since the NGO also has a clear vision of a sustainable society and a history of working with PVC-related issues. As a ‘critical friend’ of the industry, TNS became involved in laying out the basic principles. The VinylPlus programme builds on The Natural Step’s well-recognized science-based framework System Conditions for a Sustainable Society. For PVC, five challenges were identified that form the core of VinylPlus:

- #1 Controlled loop management, with an ambitious target of recycling 800,000 tons of PVC waste per year by 2020.
- #2 Organo-Chlorine Emissions, addressing concerns about to the undesired release of chlorinated organic substances from the whole life cycle of PVC to avoid any systematic increase of any concentrations in nature.
- #3 Sustainable Use of Additives: An essential component of PVC products, additives should also be used in sustainable way in order to secure alignment with the TNS sustainability principles.
- #4 Sustainable Energy & Climate Stability, which entails minimising climate impacts through the reduction of energy and raw material consumption.
- #5 Sustainability Awareness by which VinylPlus commits to building sustainability awareness across the value chain, including stakeholders inside and outside the industry. Its targets include, but are not limited to, developing a VinylPlus Product Label, and promoting VinylPlus’ sustainability principles to the audiences outside EU28.

In addition, the VinylPlus programme took over from the earlier Vinyl 2010 operational features ensuring transparency and accountability:

- An independent monitoring committee with representatives of the European Parliament and Commission, trade unions, retailers and consumer organisations oversees its progress[14].
- VinylPlus publishes every year a progress report which is independently audited and verified[15].

The VinylPlus programme plays a role in the overall progress towards sustainability by contributing to many of the 17 goals identified by the UN Sustainable Development Goals, in particular by minimizing impacts, while contributing to economic growth with suitable products for infrastructure and smarter cities (SDGs 7, 8, 9, 11, 12, 13, 17)[16]. It is also worth mentioning that VinylPlus has been a member of the Green Industry Platform since 2013, a global partnership led by the United Nations Industrial Development Organization (UNIDO) and the UN Environment Platform Programme (UNEP).

3. The VinylPlus Product Label

The development of a VinylPlus Product Label was one of the key targets of VinylPlus Challenge #5. The VinylPlus Product Label is a multi-criteria, third-party sustainability certification scheme. As other schemes[17], it has been created with the intent to shift the market preference towards the supply and demand of products with superior sustainability performance. Manufacturers of certified products can communicate these certifications to the downstream actors via a product label. For the buyers of such products, such label provides a simple way to convey information helping to select the products with best sustainability performance.

Voluntary certification schemes can be described and analysed using the tripartite standard regime framework developed by Busch[18,19]. In this framework, a scheme is characterized in three dimensions by Governance, Standard and Certification.

Governance tells how the scheme is owned and managed, how the auditors are accredited, how the engagement with stakeholders is organized, and how the scheme's activities and performance are communicated. All these elements drive the scheme's **legitimacy**.

The VinylPlus Product Label scheme is owned by VinylPlus but is operated and developed together with the Building Research Establishment (BRE) and TNS. As both organizations are independent from the vinyl industry, the scheme can be considered as a multi stakeholder initiative. As an important part of requirements are taken from the BES 6001 standard created by BRE, the third party audits have been run so far by BRE. With the recent recognition of the scheme by Accredia, the Italian accreditation body, and the expected recognition of the scheme by the 35 other members of the European cooperation for accreditation (EA), the audits will be run in a near future by properly trained auditors from ISO 17065 certification bodies specifically accredited for the scheme by government bodies. Auditors for many of the other environmental or sustainability schemes are certified by the scheme owner[20]. Criteria revisions and developments of the VinylPlus label are open to all relevant stakeholders through a procedure available on the website of the scheme[21]. All activities related to the scheme can be consulted at any time and any one on this website.

The second dimension of the framework is **Standard**, which describes the set of requirements and criteria that are set in the scheme. These elements directly impact the **effectiveness** of the scheme.

The VinylPlus Product Label scheme includes 18 requirements. 11 requirements are based on the VinylPlus challenges defined by TNS, based on a science-based definition of sustainability. They cover topics like recycling and building controlled loops, using the PVC resin and additives sustainably, committing to energy efficiency and internally and externally communicating to raise sustainability awareness. The other requirements are taken from BES 6001, the Framework Standard Responsible Sourcing developed by BRE[22].

Responsible sourcing of construction products offers a way to improve the implementation and traceability of sustainability objectives throughout the project supply-chain[23]. BES 6001 scheme is more comprehensive than chains of custody schemes such as Forest Stewardship Council or managerial systems such as ISO 14001[24]. BES 6001 includes a series of organisational management, supply chain management and environmental and social requirements; it covers legal compliance, management systems, traceability and more specific aspects such as waste management, transport impacts and life-cycle assessment. For each of the 18 requirements, a set of specific criteria is defined against which achievement can be scored; there is each time a threshold level of achievement which acts as a barrier to entry.

The third dimension of the framework is **Certification,** which describes the audit and certification processes and procedures. These elements impact the **efficiency** of the scheme.

By making use of the documents available on the website, any manufacturer of a PVC construction product can first determine if its product could be appropriate for certification. If this self-test reveals that threshold levels have been achieved for all requirements, the applying organisation sends its application online. VinylPlus then does a first conformity check and acknowledges reception of the application.

The audit is then prepared together with the auditor selected by the applicant among trained and accredited auditors. Once all the requested information has been gathered by the applicant, the auditor undertakes a pre-assessment. If this pre-assessment is positive, an on-site audit is performed by the auditor to collect additional pieces of evidence of conformity.

A detailed performance report is then prepared by the auditor. If required evidence is missing, the applicant has one year to fill any conformity gap. After all evidence has been gathered, the performance report is verified by BRE and additional inputs from the applicant may be requested. Once verified, the report is transmitted to VinylPlus. If the audit process is successful, VinylPlus grants a label certificate valid for 2 years. After this period, the certification needs to be renewed following the same process.

As of end of February 2019, 33 PVC window profiles manufactured in 11 manufacturing sites in 10 European countries have been certified[25]. The scheme is now being open to all PVC building and constructions products as defined in the EU Construction Products Regulation[26].

Figure 1. The visual design of the VinylPlus Product Label is protected as an internationally registered trademark of VinylPlus®. The mark consists of the stylized blue word "VINYL" in the middle of a green outlined teardrop-shaped leaf design and the stylized white wording "VERIFIED" in the middle of a green banner design.

4. The Additives Sustainability Footprint

The VinylPlus Challenge #3 recognises the sustainable use of additives as a key challenge. Sustainable use should not only account for the intrinsic properties of additive substances but also considers the risks and positive benefits within the full societal life cycle context of the PVC articles into which they are incorporated, based on the TNS science-based definition of sustainability.

Existing schemes for assessment of chemical sustainability differ significantly in definitions of objective, interpretation and scope. Many such schemes concentrate on intrinsic chemical properties and particularly potential hazard[27]. Regulatory mechanisms and management tools such as the REACH Regulation predominantly focus on hazard reduction or elimination. Risk assessment integrates hazard with potential exposure[28].

Both approaches—hazard and risk—fail to account for wider sustainability issues related to sourcing, production and application of chemicals, their interaction with products within which they may be used and their fate at or beyond end-of-life. Life Cycle Assessment (LCA) measures some of these aspects, using well-established environmental impact categories such as global warming potential, eutrophication, different aspects of ecotoxicity and ozone-forming potential[29]. Yet, models used to assess life cycle impact differ from each other in basic principles, scope and outcomes, potentially omitting impacts of chemical emissions and making different approaches hard to reconcile[30]. Lack of social considerations in conventional LCA has been acknowledged as a deficiency, and the SETAC/UNEP Social Life Cycle Assessment model is working to include social impacts as a more useful tool in progress towards sustainable development[31].

The European Commission is developing a Product Environmental Footprint (PEF) methodology for potential application to all products on the European market[32]. It remains unclear when or if this methodology will be used or be applied to any important PVC construction products (e.g. window profiles).

The Additive Sustainability Footprint (ASF) tool has been developed by VinylPlus since none of the REACH, LCAs, and PEFs initiatives, taken alone, can account for the roles and behaviours of the additives as functional constituents of complex products. None of these initiatives accounts for the wider context of sustainability as articulated by the TNS System Conditions. None accounts for positive benefits arising from the functional contributions of additives, enabling articles to address the meeting of human needs on a potentially sustainable basis.

The ASF uses the Sustainability Life Cycle Assessment (SLCA) approach developed by TNS (Lundholm et al., 2008[33] and 2011[34]). This life cycle assessment methodology implements the TNS FSSD within the ISO 1404X-compliant LCA methods[35]. SLCA addresses strategic pathways towards full sustainability based on the FSSD, rather than focusing on specific known problems[36]. SLCA has been applied in various operational contexts, including for example to paints[37].

The ASF development follows the ten-step SLCA approach consistent with established LCA protocols:

1. **Setting goal and scope** establishes vision and meaning about the sustainable use of additives. The agreed vision statement wording based on TNS criteria was:
    - Additives are sustainably produced using materials that are responsibly sourced.
    - Additives support the sustainable management of PVC products (e.g. safe and recyclable).
    - The functional benefits of additives enable PVC products to support sustainable development (e.g. meeting the UN Sustainable Goals)

2. **Creating a shared definition of the sustainable product system** entails agreement on success criteria for sustainable use of additives across each of the life cycle stages based on TNS sustainability principles;
3. **Setting system boundaries** establishes de minimis additive concentrations and other aspects of the life cycle such as aligning with assumptions in the published EPD and other protocols used by the industry, as well as agreement on guiding principles;
4. **Inventory analysis** collects information relevant to addressing the social and environmental criteria covered by questions in Step 6;
5. **Sustainability assessment** uses TNS System Conditions to assess sustainability strengths and weaknesses;
6. **Identify key impact areas** entails answering sustainability-relevant questions for each combination of TNS System Condition and life cycle stage;
7. **Brainstorm possible solutions** considers options to address 'sustainability hotspots' highlighted in Step 6;
8. **Prioritise solutions** prioritises optimal solutions to address 'sustainability hotspots';
9. **Create an innovation roadmap** entails taking innovations through to measurable actions; and
10. **Measure and report progress** includes as a useful output a summary 'Snapshot report' comprising a description that an ASF has been performed, an explanation of the process of the study, a link to further contact and other information, verification by those behind the study, and the insights and recommendations that arose from the process.

A pilot implementation of the method to the additives of a generic PVC window profile has demonstrated that the ASF method is workable, robustly founded on science-based sustainability principles, makes use of pre-existing assessments in addition to novel social and environmental criteria comprising a broader picture of necessary conditions of sustainability, and takes account of multiple dimensions associated with the sustainable use of additives throughout the full societal life cycle of the articles into which they are incorporated.

Development is ongoing to develop an online version of the ASF tool now the basic protocols are tested, with auto-filling of generic information for some implementations of ASF, making assessment easier, quicker and cheaper. The online tool can also serve as a vehicle for publishing outcomes whilst protecting commercially sensitive inputs.

5. Conclusion, outlook and vision

The unique value chain approach of VinylPlus, its wide range of targets to enhance the sustainability of PVC, and the concrete tools it has developed, such as its product label and additives sustainability footprint, are mentioned by policy makers as a kind of role model. For example, an EU Commission director stated that "VinylPlus can be considered as a frontrunner for the circular economy"[38].

It is particularly this toolbox, that positions VinylPlus as a valuable partner for stakeholders developing and implementing policies aiming at a more sustainable European industry, especially the construction industry.

In a nutshell, the VinylPlus Product Label is a document of responsible sourcing of feedstock—e.g. no mercury cell technology used; it is a proof of the absence/substitution of certain additives—such as lead compounds that had previously been used as stabilizers; and last but not least the Vinyl Plus Product Label stands for controlled loop and traceability—in order to guarantee the highest possible recycling level after decades of a product's useful service life.

The instruments of product label and additives sustainability footprint AFS allow for an easy discrimination between material grades and consequently of product sustainability levels. The label should thus be considered for direct integration into existing and future building sustainability schemes.

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PolyStyreneLoop – The circular economy in action

Demacsek C[1], Tange L[2], Reichenecker A[2], Altnau G[3]

[1]Güteschutzgemeinschaft Polystyrol-Hartschaum, Brückenstraße 3, 2522 Oberwaltersdorf, Austria
[2]PolyStyreneLoop Cooperative, Frankrijkweg 10, 4538 BJ Terneuzen, Netherlands
[3]CreaCycle GmbH, Auf der Artwick 74, 41515 Grevenbroich, Germany

info@polystyreneloop.eu

Abstract. For decades polystyrene (PS) foam is known as an efficient insulation material in the building and construction environment. At the end of its very long useful life, the waste remains a valuable material source for a variety of products. However, the flame retardant HBCD, which has been used since the 1960s until 2017, is considered a pollutant and millions of tons of PS foam waste can no longer be regularly recycled.
PolyStyreneLoop is developing a solution with a physico-chemical recycling process, based on the CreaSolv® Technology. The applied technology turns PS foam waste into new high-quality raw material. During the recycling process, impurities, such as cement or other construction residues, as well as the imbedded flame retardant HBCD are safely removed. The HBCD is destroyed, while the valuable bromine component and polystyrene are recovered.
In 2019 an industrial scale demonstration plant (with the capability to handle 3.3 kt of PS insulation foam waste per year) will be built in the Netherlands. The plant is aimed at starting up by the end of 2019. Subsequently the technical, economic and environmental viability of this new recycling process will be assessed. When proven to be successful, the process will be further rolled out with additional commercial plants in other countries throughout Europe.

1. Introduction

Polystyrene (PS) foam is one of the most widely used insulation materials ensuring climate control and energy efficiency of buildings. Over the lifetime, the energy savings achieved during heating save a multiple of the fossil resources required for its production. However, in the sense of a modern, low-carbon, resource and energy-efficient economy every effort must be made to use all resources sparingly. That's exactly where PolyStyreneLoop starts. It is a new recycling process for polystyrene (PS) foam that can be used for both expanded polystyrene (EPS) and extruded polystyrene (XPS). For this purpose, a demonstration plant will be built in the Netherlands. The primary aim is to recycle insulation materials that contain the imbedded flame retardant HBCD (which is no longer used). As PolyStyreneLoop will start with the recycling of EPS, the focus will be placed on this material in the remainder of this article.

EPS is a lightweight, rigid, plastic foam insulation material consisting of 98 % air and 2 % polystyrene. It is typically used in External Thermal Insulation Composite Systems (ETICS) and for flat roof, perimeter or impact sound insulation. Builders often choose EPS, because it is cost-effective, durable and easy to install.

1.1. Global and European Regulations for HBCD

To meet national fire regulations Hexabromocyclododecane (HBCD) has been used in many European countries since the 1960s until 2017 as a flame retardant in insulation materials made of expanded polystyrene (EPS) and extruded polystyrene (XPS). In 2013 HBCD was brought under the Stockholm Convention regime due to its persistent, bioaccumulative and toxic properties as well as its potential for long-range transport and has been listed as a Persistent Organic Pollutant (POP) [1].

In Europe the provisions of the Stockholm Convention were implemented in Regulation (EC) No 850/2004 [2]. The concentration limits for HBCD in articles and waste were set in amendments to this regulation. HBCD in articles is allowed in concentrations equal to or below 100 mg/kg [3]. HBCD in waste is allowed in concentrations below 1,000 mg/kg [4].

The REACH regulation listed HBCD already in 2011 as a persistent, bioaccumulative and toxic substance [5] and prohibited it to be placed on the market or used after 21 August 2015. After this date HBCD could still be used for EPS until 21 August 2017 by companies granted with an authorisation under REACH. Since 1 January 2015, producers in e.g. Austria, Germany and Switzerland have converted to the new polymeric flame retardant pFR.

Table 1. Allowed HBCD concentrations.

HBCD concentration	Concentration limit for HBCD in products and waste	Legislation
≤ 100 ppm	Products placed on the market (unintentional trace contamination)	EC 2016/293
< 1,000 ppm	Recovery or disposal	EC 2016/460
≥ 1,000 ppm	Physico-chemical treatment (i.e. PolyStyreneLoop) or incineration	Basel Convention

1.2. Disposal of Construction EPS Waste today

One option of disposal is mechanical recycling, where EPS waste is ground into granulate. It might be added to thermal insulation panels for instance, but also serves as an aggregate for lightweight concrete, bound EPS ballastings [6] and insulating plaster, and acts as a pore inducer in the brick industry. This recycling process is possible for packaging EPS without HBCD and construction EPS with pFR, but not for old construction EPS with HBCD, as the concentration limit of 100 ppm for HBCD in the recycled product would be exceeded.

Another option is to use the calorific value of EPS in incineration plants and cement factories: 1 kg of waste saves 1.3 litres of valuable heating oil. The advantage of this process is that the requirements regarding cleanliness of the EPS waste are low. In a large-scale test in the Würzburg waste incineration plant [7] in 2013 it was proven that burning PS foam containing HBCD has no negative effects on the environment. The flame retardant HBCD is totally destroyed [8]. Even a proportion up to 30 percent by volume (or 2 wt%) of PS foam containing HBCD at the waste incineration changes nothing in terms of the composition of the end products such as slag, dust and filtration residues, owing to the high temperature applied. This means that old construction EPS waste containing HBCD can be burned in any state of the art municipal incineration plant [9].

In many European countries landfilling is not an option, because there are restrictions for waste with a high content of organic carbon (TOC). In this respect, EPS waste is no different from other insulation material waste of organic origin such as cork, wood fibre or hemp.

In 2017 the total EPS foam waste stream in Europe amounts to 527,000 tons. Of this, 98,600 tons come from the demolition of buildings [10]. This construction EPS waste stream will increase in the next decades and secures enough input for the future physico-chemical recycling.

1.3. EU Plastics Strategy

In December 2015, the Commission adopted an EU Action Plan for a “Circular Economy”. There, it identified plastics as a key priority and committed itself to ‘prepare a strategy addressing the challenges posed by plastics throughout the value chain and taking into account their entire life-cycle'. In 2017, the Commission confirmed it would focus on plastics production and use, and work towards the goal of ensuring that all plastic packaging is recyclable by 2030 [11].

1.4. EUMEPS EU Voluntary Pledge

The association "European Manufacturers of EPS" (EUMEPS) has submitted a voluntary pledge [12] on behalf of its members, as requested in Annex III of the EU Plastics Strategy, to indicate their recycling targets by 2025. Many companies in the value chain are already working to ensure that the EUMEPS pledge can be realised.

Table 2. Recycling targets of the EUMEPS EU Voluntary Pledge.

Object	Polymer	Baseline	Pledge	Quantities 2025 (estimates)		Quality	New Technologies involved
				Market	Recycle		
Insulated Packaging (e.g. fish boxes)	EPS	Conversio Study 2017	50 %	140,000	70,000	High quality EPS	Food grade quality potential (EPS SURE)
Protective Packaging (e.g. appliances)	EPS	Conversio Study 2017	50 %	230,000	115,000	Standard EPS	
Building Deconstruction	FR-EPS EPS	Estimated 2025 market	27 %	150,000	40,000	High quality EPS	PolyStreneLoop – HBCD removal and recycling of bromine. Chemical recycling.
New build and renovation	FR-EPS EPS	Conversio Study 2017	80 %	40,000	32,000	Standard EPS	
Civil Engineering New build and Deconstruction	EPS		90 %				
TOTAL			**46 %**	**560,000**	**257,000**		

FR = Flame Retarded

2. PolyStyreneLoop – Physico-chemical Recycling

A demonstration plant in Terneuzen, Netherlands, shall demonstrate the technical, economic and environmental feasibility of a physico-chemical recycling process. It is seen as an opportunity to roll out a system where PS foams containing HBCD can be handled as part of the circular economy.

2.1. Cooperative and its Members

PolyStyreneLoop is a cooperative, currently counting 66 members from 14 European countries from the whole polystyrene value chain. The cooperative was inaugurated on 6th of November 2017. Members and supporters include flame retardant producers, styrene and polystyrene producers, EPS and XPS producers, EPS converters, waste collectors, industry associations, recyclers and machinery manufacturers.

2.2. Financing – Funding Cooperative, LIFE Grant and Bank Loan

The total investment of the project is € 10.4 million. Of this, € 2.4 million were provided by membership fees and supporter contributions. Furthermore, PolyStyreneLoop received an EU initiated LIFE Subsidy program of € 2.7 million. The project is known under LIFE-PSLOOP (LIFE 16 ENV/NL/000271) and runs from 2017 till 2021 with the option of an extension, if requested by PolyStyreneLoop. For XPS recycling a regional additional funding of € 1 million has been received from the Province of Zeeland in the Netherlands. The remaining financing needs are covered by a bank loan.

2.3. CreaSolv® Technology and Bromine Recovery Unit (BRU)

The CreaSolv® Technology is a development of Fraunhofer Institute for Process Engineering and Packaging IVV in corporation with CreaCycle GmbH (CreaSolv® is a registered trademark of CreaCycle GmbH). Plastic wastes are selectively dissolved with a specific proprietary solvent formulation. The components of the CreaSolv® Formulation are fully REACH registered and not considered as hazardous according to the Globally Harmonized System (GHS). This dissolution is a physico-chemical separation process. It is a pre-treatment technology, which has the potential to recover plastic molecules and separate them from legislated additives (like HBCD) or other impurities.

The process consists of three steps [13]. Steps 1 and 2 are pre-treatment for step 3.

1. PS foam waste is dissolved in tanks containing a PS-specific liquid. The solid impurities (dirt, cement and the like) are separated through filtration and then incinerated.
2. Another liquid is added, which transforms the PS into a gel, while the additive (HBCD) stays in the remaining liquid. The PS gel is then separated from the process liquids. Once cleaned, this gel is transferred into granulated polymer and the liquid, together with the additive, is distilled and re-used in a closed loop; the additives remain as sludge.
3. Finally the HBCD additive within the sludge is destructed in a high temperature waste incineration. During the last step the elemental bromine is recovered and can be reused to produce new products (e.g. modern flame retardants), thereby closing the loop.

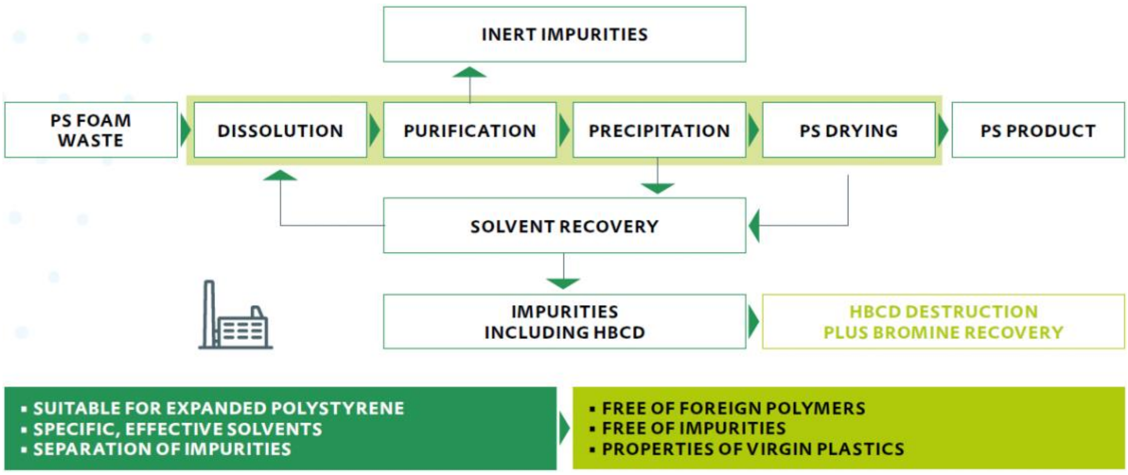

Figure 1. PolyStyreneLoop – CreaSolv® Technology and bromine recovery unit (BRU).

2.4. Technical Feasibility

The CreaSolv® Technology has been tested on laboratory scale and with PolyStyreneLoop it will be applied on demonstration scale for PS foams containing HBCD. The findings so far are that the characteristics of the recycled PS coming from PolyStyreneLoop are similar to virgin general purpose polystyrene (GPPS). The main difference is that PolyStyreneLoop GPPS recyclate is often dark, while virgin GPPS is clear. The dark colour of the recyclate comes from the carbon (graphite) that is present in part of the input material coming from new generation EPS insulation boards. As the PolyStyreneLoop project aims at closing the loop for EPS in the construction industry and the remaining graphite improves the insulating properties, less needs to be added to the raw material.

In order to utilise a CreaSolv® Plant, it is required that such a new technology be incorporated in the Basel Convention Technical Guidelines as an end-of-life (EOL) option alongside incineration. In May 2016 PolyStyreneLoop presented the CreaSolv® Technology at the Headquarters of the United Nations Environmental Programme (UNEP) in Nairobi, Kenya and got support from most global parties including many NGOs. At the 13th Meeting of the Basel Convention in Geneva in May 2017 it was finally agreed to include the individual process steps of the CreaSolv® Technology for the separation of polystyrene and HBCD as Best Available Technique (BAT) to treat PS foam waste with HBCD concentrations ≥ 1,000 ppm [14]. The guidelines are to be finalised and approved in May 2019.

2.5. Economic Feasibility

In the standard scenario, no costs for EPS waste have been set for the period 2020-2026. This stands in contrast to regulations in some countries, where it is already required to pay for the disposal of EPS waste (potential revenue upside). The forecasted sales prices have been set between the 2016-2018 sales prices of GPPS and styrene monomer. An input material conversion factor of 1.112 was taken into account. The cooperative expects that debt capital will be fully repaid in 2025.

In the worst case scenario, unlike the standard scenario, costs for the input materials occur. Although this is highly unlikely, the payback time for debt capital remains more or less unchanged.

2.6. Environmental Feasibility

TÜV Rheinland in cooperation with BASF performed a Life Cycle Assessment (LCA) [15] for the end of life treatment of EPS coming from deconstruction of External Thermal Insulation Composite Systems (ETICS). Two different end of life options for 1 ton of EPS were quantified and compared: incineration with energy recovery and the PolyStyreneLoop process. The data show that recovered polystyrene from the PolyStyreneLoop process has a 47 % lower global warming potential (GWP).

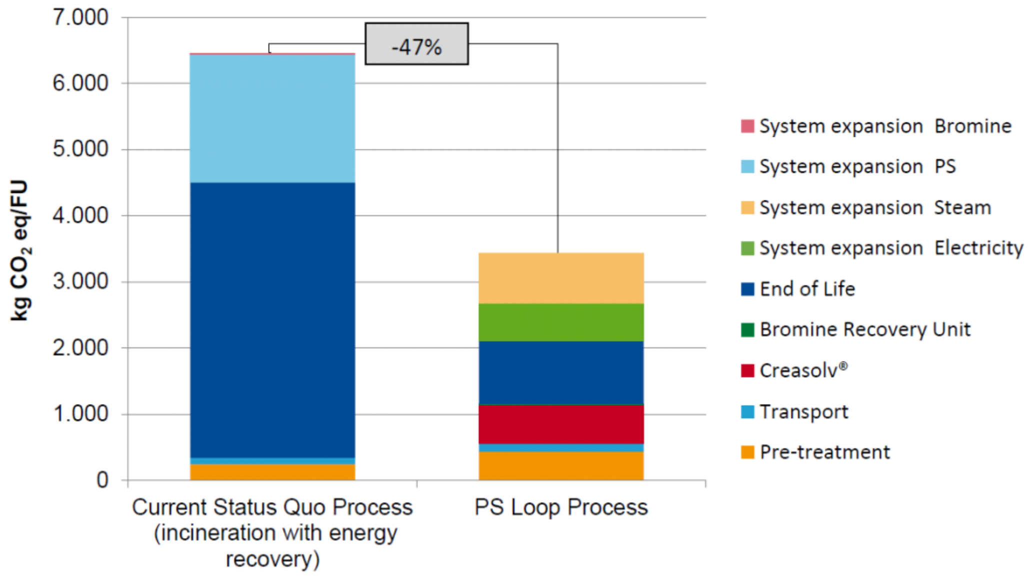

Figure 2. Climate Change in kg CO_2 eq/FU.

3. Waste Stream of Construction EPS Waste from Demolition Sites

Special attention has to be devoted to the waste stream to the PolyStyreneLoop demonstration plant, because the quality of the input material has an immediate effect on the quality of the output material. In addition, it is a crucial cost factor.

3.1. Collection and Pre-treatment

The material coming from demolition sites is collected and pre-treated by decentralized collection points, so-called HUBs. Most of the HUBs are managed by demolishers or recyclers with the necessary experience and network in the market. PolyStyreneLoop sources material only from certified HUBs. Making use of the cooperative model, only members of the cooperative can operate such a HUB.

PolyStyreneLoop requires certain input specifications regarding impurities of the material: HBCD content < 1.5 wt.%, water content ≤ 3 % and all other impurities ≤ 7 wt.% (PUR, mineral wool, cement, nails/iron and glue). Bituminous impurities are not allowed. As there are different applications for PS insulation such as ETICS or flat roofs with bituminous sheeting, the processes for deconstruction and waste treatment differ as well. A guideline for the collection and pre-treatment of PS foam waste is under preparation as part of the LIFE Grant requirements.

ETICS are widely used applications for the insulation of buildings. In Germany alone, it is estimated that between 1960 and 2012, 900 million m² of ETICS were installed of which, 80 % used EPS as insulation material. The complexity of the recycling of the EPS in ETICS lies in the fact that it is a composite of different materials such as adhesives, coating with reinforcing mesh and plaster. While the majority volume of ETICS is EPS, the insulation material itself only accounts for 10 % in terms of weight. Currently, Münster University of Applied Sciences and RWTH Aachen University are researching the necessary pre-treatment for ETICS for different utilisation processes such as PolyStyreneLoop. Through the crushing of ETICS with different stress loads, a selective pure EPS stream can be obtained. The universities are working on further optimizing the output through improved crushing. In a subsequent step, density-based sorting such as wind shifting can further concentrate the EPS fraction [16].

EPS Powerbrush [17] is a technology developed for cleaning EPS flat roof boards bond with bitumen sheets. At the demolition site the bitumen is removed by hand from the EPS boards. The bitumen is collected and follows a special recycling route. Then the EPS boards are stacked and transported to the pre-treatment plant. There the boards are sorted – to speed up the cleaning process – and fed to the EPS Powerbrush (maximum contamination 15 %). The outcome is clean EPS boards, free of bitumen, which can then be used for further recycling. The extracted impurities are finally burned. In 2014, the machine was already tested on a 6000 m² EPS flat roof.

Figure 3. EPS flat roof boards with bitumen leftovers before and after treatment [18].

3.2. Compaction

EPS is a lightweight material, because it consists of 98 % air, with a density of 11-30 kg/m³. This makes it easy to handle on a construction site, however to optimize transportation the material needs to be compacted after the pre-treatment. By compaction of the material to a density of 100-450 kg/m³ the volume is reduced by a factor 5-25.

The technology to compact EPS from demolition sites is already available and a number of manufacturers sell the necessary machinery. With mobile compactors HUBs can additionally offer the service to smaller recyclers or demolishers, which do not have the necessary machinery themselves. The temperature inside a screw compactor is a critical issue for EPS compaction, because the temperature of EPS rises during compacting. If the temperature of the material exceeds 90 °C, EPS can start to degrade. This is undesired for the quality of the polystyrene product and might lead to clogging in the screw mechanism.

XPS has a slightly higher density of 30-50 kg/m³, but may not be compacted (or even broken) without a deep cool unit, if it contains (H)CFCs, as these would otherwise be emitted.

3.3. Storage and Transportation to PolyStyreneLoop Demonstration Plant

EPS needs to be compacted into briquettes with a weight between 15 to 50 kg for better handling. The compacted briquettes are then either stored in Big Bags or stocked on pallets, wrapped in PE shrink foil. The wrapping prevents the material to become wet, if storage takes place outside, and avoids any loose material spread in the environment.

Once HUBs have collected, pre-treated, compacted and stored sufficient material, full truck loads are transported to the storage location in Terneuzen. In order to have enough feed-stock once the demonstration plant is operational, PolyStyreneLoop is already storing material from its certified HUBs.

3.4. Notification and Permits

The European Waste Shipment Regulation (EC) No 1013/2006 [19] establishes procedures and control regimes for the shipment of waste. If waste is transported across borders, a notification needs to be submitted to the authority of the place of origin by the transporting company. This requires notification (annex IA) and movement documents (annex IB). Each waste transporter is required to follow this notification procedure.

4. Future Developments

The PolyStyreneLoop demonstration plant is expected to run a test phase until 2021. In the meantime the technical, economic and environmental viability will be assessed. After successful results the concept is set to be gradually rolled-out to other locations throughout Europe coping with the upcoming volumes of PS foam waste in the following 10 years.

For XPS recycling a deep cool unit has to be installed for collecting the (H)CFC's under the Montreal Protocol.

5. Conclusions

The goal of PolyStyreneLoop is to build a plant for recycling polystyrene (PS) foam in Terneuzen, Netherlands. It shall demonstrate the safe destruction of HBCD while recycling the valuable resources polystyrene and bromine and thus closing two loops and contributing to a circular economy.

PolyStyreneLoop is a physico-chemical recycling process based on the CreaSolv® Technology. PS foam waste is dissolved and the polystyrene recovered. Subsequently, the remaining impurities including HBCD are destroyed and the bromine is recovered. This process has already been included in the UNEP Basel Convention Technical Guidelines as a best available recycling technology to handle HBCD waste. The financial plan of PolyStyreneLoop predicts a repayment of the debt capital within a few years. A Life Cycle Assessment by TÜV Rheinland certifies the environmental benefits of the PolyStyreneLoop process versus incineration.

Decisive for the success of the project will be the availability of the input material in sufficient quantity and quality. A guideline for the collection and pre-treatment of PS foam waste is under preparation. Corresponding demolition and pre-treatment techniques are already in place, further innovations are expected in the near future. In order to facilitate economic transportation, compaction of the foam waste is essential. Certified decentralized collection points (HUBs) will make sure that certain input specification will be fulfilled to ensure a smooth operation. For the transportation of waste containing HBCD across borders, a permit is required.

In 2019 the PolyStyreneLoop demonstration plant will be built. It is funded by companies from the entire PS foam value chain, and has also attracted the support of a European LIFE Grant. The plant shall be operational by the end of 2019. If the technical, economic and environmental viability will be as expected, the concept is set to be gradually rolled-out to other locations throughout Europe.

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Building Physics as a Tool for Development of New Components: Roof Window

Tywoniak J[1], Calta V[1], Staněk K[1], Novák J[1], Maierová L[1]

[1]Czech Technical University in Prague, University Centre for Energy Efficient Buildings, Třinecká 1024, CZ 273 43 Buštěhrad, Czech Republic

jan.tywoniak@fsv.cvut.cz

Abstract. Knowledge and instruments of building physics (calculation methods and measuring procedures) can be used as key tools and perspectives to develop new components for building envelopes. This paper illustrates this fact by presenting the successful development of a roof window fulfilling higher requirements on reduction of overall heat losses and avoiding the risk of water vapor condensation on surfaces at very low external temperatures (thermal transmittance below 0.7 W/m^{2}K in the first generation, close to 0.5 W/m^{2}K in the second one) and better daylight distribution for the interior. This is the result of a publicly supported project with an industrial partner: from a general idea through detailed analysis of thermal performance in geometrical and material alternatives up to construction, prototyping, and verification by measurements and certification. Building physics tools applied in the project are discussed here together with lessons learned which are important for technical design. An effective shading system equipped with PV elements for energy smart harvesting is mentioned in the conclusion.

1. Introduction

Roof windows are traditionally known as the weakest part of the building envelope concerning thermal transmittance. For this reason, they are not commonly accepted by designers of energy optimized buildings (passive house level etc.). Nevertheless, they should be used in some cases and the consequence due to increased heat transmission must be compensated in order to achieve the passive house criteria [1]. On the component level, there is a usual requirement for cold moderate climate not to exceed thermal transmittance of 0.8 W/(m^{2}K) by keeping the linear thermal transmittance due to connection to building envelope negligible. These values should be critically analyzed with respect to specific situations of roof windows in order to derive correct targets for new developments.

2. Comparison to vertical windows in the wall

By comparing roof windows with vertical windows in walls, the following significant differences can be found (see Fig.1, Fig.2):

- Heat transfer in the air cavities between glazing panes is larger due to increased heat convection caused by air movement (the more inclined the more significant.) Result: U value increased in the range of 0.1 – 0.2 W/(m^{2}K), relative to the whole window.

- Heat transfer in the connection of the window to the opaque part: In roof windows a very important problem arises from the geometrical situation (Fig.2). The external perimeter of the window is situated in the cold area of the roof. So, it is not possible to achieve the so called thermal-bridge free solution (see Fig.3). The result is expressed as linear thermal transmittance ψ [W/(m.K)] in the range of 0.05 – 0.03 W/(m.K) by optimized solution.
- Surface heat transfer coefficient h [W/(m^{2}K)] describing the heat transfer between internal surface of the window and surroundings varies. In the case of larger vertical windows one can expect the standard values across the area [2]. In smaller, inclined roof windows, additionally often influenced by heaters close by, the situation can be dramatically different: To be on the safe side from the energy perspective, the h-Value can be up to twice as high as the standard value. This is the preliminary result of our own in-situ experiments.
- The radiation heat exchange between the external surface and the (clear) sky [3] is higher for roof windows (e.g. multiplied by factor 1.5 for 45° sloped windows). This fact leads to an increase of the total external surface heat transfer coefficient.
- Passive solar gains in the rooms and risk of their overheating is primarily influenced by the orientation of the façade/roof, by the shading from external obstacles, by shading devices, and by the coefficient of the permeability of total solar radiation (solar factor) g [-] of glazing unit. The overall effect cannot be related to window quality itself. It depends on several other parameters of the (occupied) room, including thermal inertia, ventilation strategy and actual climatic data. Generally, there is a higher passive solar gain due to the inclination of roof windows. Moreover, efficient external shading such as venetian blinds are not applicable for roof windows.
- Specific effects can be observed in roof windows in summer conditions: The external air can be significantly warmer close to the roof surface (heated by the roof covering) compared to climatic data. This further increases the risk of the room overheating.

From the list above can be concluded that the actual desired U-value of roof windows for passive house quality must be lower compared to vertical windows. It should be 0.7 W/(m^{2}K) or less, ideally approaching 0.5 W/(m^{2}K). Simple parametric studies (Fig.3) have shown that the unavoidable heat transfer due to the thermal coupling of the window to the roof plays an important role, especially in energy optimized windows. Corresponding compensation must be found in other components of the building envelope.

For this reason it is recommendable to integrate the additional heat transfer due to thermal coupling in the (extended) thermal transmittance $U_{w,inst}$ to have a „full picture" in one value [4]:

$$U_{w,inst} = \frac{A_g . U_g + A_f . U_f + \Sigma(\psi_g . l_g) + \Sigma(\psi_w . l_w)}{A_g + A_f}$$

where the $\Sigma(\psi_w . l_w)$ describes the influence of installation. It is illustrated in Fig.2 for a hypothetical window of excellent quality: Assumed thermal transmittance of the glazing unit U_g 0.60 W/(m^{2}K), frame U_f 0.60 W/(m^{2}K), thermal bridges of glazing edge expressed by linear thermal transmittance ψ_g 0,03 W/(m.K), thermal bridge due to installation in the roof (ψ_w 0.05 W/(m.K), considering the reference window size 1.14 m x 1.40 m. It can be seen that for improvements of roof windows all parts are of a high importance: glazing, frame, installation method and overall geometry.

Summer situation should be analyzed carefully as well and new ways of effective sun-protection should be found.

- Requirements on U-value of the roof construction result in overall thickness approx. 400 mm and more. This can negatively influence the daylight quality due to very deep side lining. Therefore, the daylight distribution in rooms as the primary function of each window should be studied very carefully as well.

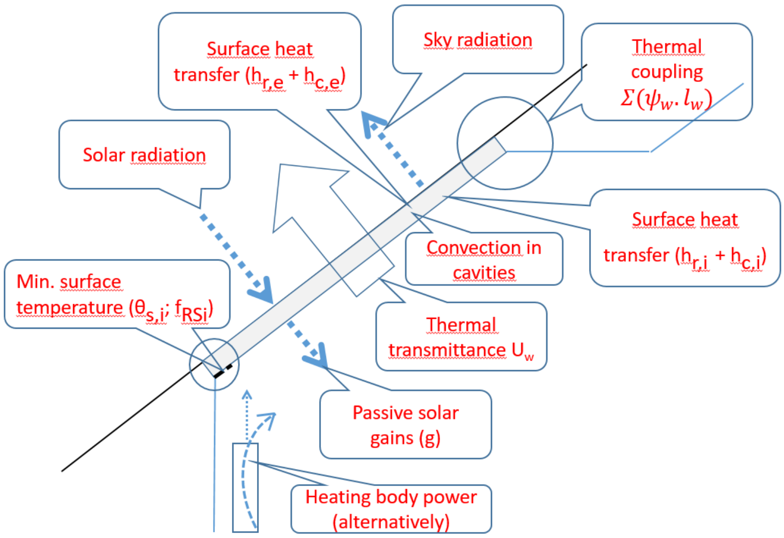

Figure 1. Significant thermal phenomena related to roof windows.

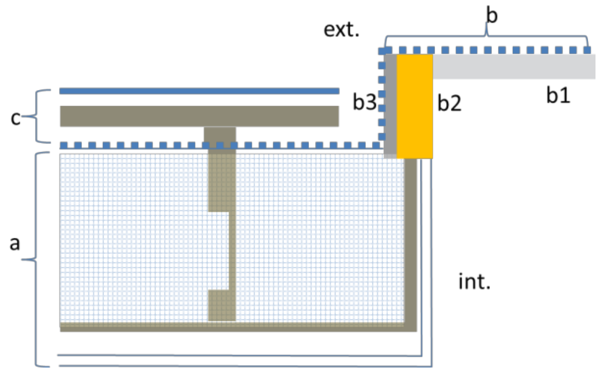

Figure 2. Schematic horizontal cross section of a typical position of roof window in a pitched roof. Dotted line represents the surfaces exposed to the exterior temperatures. (a typical pitched roof assembly (from interior): indoor gypsum board lining, OSB boards, thermal insulation, protective membrane open to water vapor diffusion), b roof window (simplified): b1 glazing unit, b2 frame and sash, b3 possible additional thermal insulating shield), c roof covering)

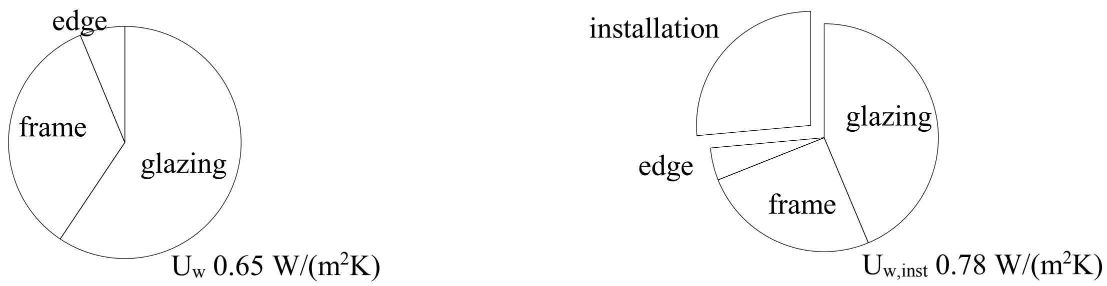

Figure 3. Result of a parametric study for (hypothetical) excellent roof window. Heat transfer (left), heat transfer including the effect of installation into roof (right) based on 2D calculations for all relevant cross sections.

3. Other technical and non-technical facts

Of course, not only building physics related phenomena should be studied before starting any development works. From the discussions with the experts (including unpublished results of questionnaire campaign) one can conclude following: a. total weight of the window should not increase, b. installation work on roof should not be more complicated, c. acceptable price increase of new, high performing product is approximately 10-20 %.

4. Methodology

Several steps were performed in order to support the development activities in close cooperation with our industrial partner:

a. Introductory parametric studies based on repeated 2D-heat conduction calculation [5,6]. Search for general relation among geometry of frames, position of glazing, material and construction. The quality of glazing unit and methods of installation in the roof were set as fixed.
b. The construction team selected a solution from parameters found in a), and a 2D-heat conduction calculation was used to check its plausibility, respecting the technological limitations. Some prototypes were built accordingly after.
c. Measurements in climatic double-chamber. Prototype installed in a fragment of roofing structure for studying surface temperatures on window and lining.
d. Detailed 2D-heat conduction calculation supporting fine-tuning in detailing of selected prototypes.
e. Declarative heat transfer calculations. Estimation of thermal transmittance (U-value) for standardized reference window size, estimation of temperature factor for evaluation of surface temperatures. Performed for promising alternatives and for two types of glazing units.
f. Simulation of daylighting in the room [7]. Study of influence of side lining geometry (perpendicular and slanted, "open" to the room).
g. Measurement of daylight distribution on a model of under roof space in the scale 1:4 under artificial sky. Alternatives for different side lining geometry were analyzed.
h. Catalogue of overall solution in interactive form. It serves for the selection of proper alternative including detailed solution of roof construction and joints window-roof considering type of construction, roofing and geometry.

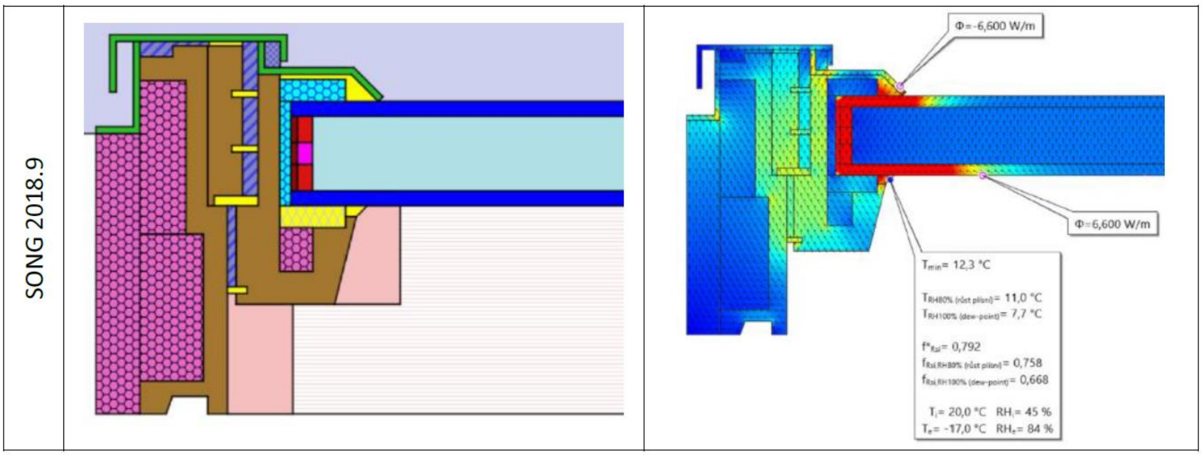

Figure 4. Example of analysis. Left: simplified geometry of a cross section. (Violet color corresponds to hardened polystyrene placed in the window frame, brown for wood, turquoise for aerogel stripes.). Glazing unit with two transparent foils. Right: Results of 2D-heat conduction calculation in HT-flux software.

5. Results

For the real technical solution, the following principles were applied:

a. Profiles made of hardened polystyrene (thermal conductivity 0.039 W/(m.K) are used here in combination with wood for increasing of thermal resistance of the frames in both directions, perpendicular and parallel to roof layer (Fig.4).

b. Glazing unit: Triple glazing with thermal transmittance 0.5 W/(m^{2}K) or special glazing having two transparent foils between glazed panes (glazing pane – air gap – foil – air gap – foil – air gap – glazing pane) with thermal transmittance 0.3 W/(m^{2}K) are applied alternatively.
c. No additional insulated mounted frames in the roof are used.
d. Surface temperature is safe: high enough to prevent the risk of condensation of water vapor, including all critical areas.
e. Smart detailing can be applied for even higher surface temperatures at the edges (use of aerogel stripes).
f. Slanted side linings are recommended in most cases in order to support better daylight distribution in rooms. Additional slightly increased heat transfer due to limited space for placing of the thermal insulation is neglectable.
g. Low emissivity coating at external surface of external glazing can be advantageous additionally.

Based on the results of standard calculations (reference size of window, vertical position, standard value of surface heat transfer) it can be concluded that U-value of 0.7 W/(m^{2}K) is feasible with our newly developed frame for usual triple glazing and near to 0.5 W/(m^{2}K) for glazing with two foils (with extra bonus of lower weight).

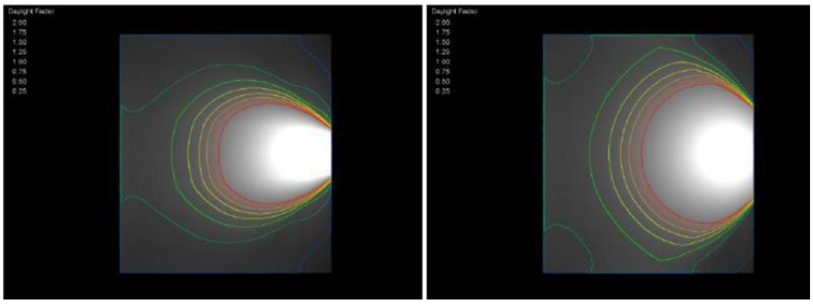

Figure 5. Results of daylight simulation [7] for a typical under roof room with one roof window centered. Side lining perpendicular (left), slanted (right). Isophotes in distance of 0.25 %.

Figure 6. Measurement of daylight distribution. Model 1:4 (left) of a typical small room equipped with one roof window in the center, swappable roof for testing of various side linings. Preparation in the artificial sky-laboratory (right)

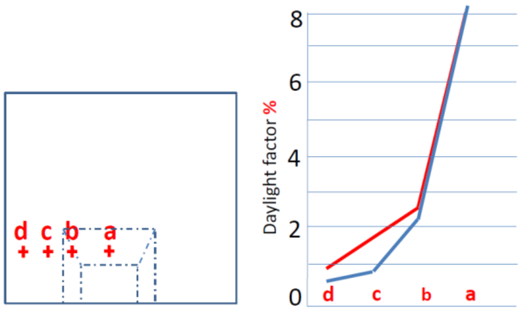

Figure 7. Key results of the measurement of daylight distribution. Left: Floor plan of a room with one roof window in the center with/without slanted side lining. Right: Daylight factor for perpendicular side lining (blue), for slanted side lining with 45° degree (red).

Figure 8. Figure shows the prototype presented at a building fair in September 2018.

6. Conclusion and outlook

In general, roof windows cover only a small area of the overall building envelope of each house. But their influence can be significant. During the project with the industrial partner a new generation of roof window was developed, including sub-variants. Technical information and construction detail can be found in an interactive catalogue [8], adjusted for different roof construction. Analyses using building physics tools played a key role in overall process. One prototype was tested on all obligatory parameters according to EN 14351-1 [9] in independent certification institution with very good results (thermal transmittance, airtightness, resistance against wind driven rain). The first product is ready to be placed on the market, but the development can continue.

We tested the possibility of further reduction of thermal transmittance to 0.4 W/(m^{2}K) level which seems to be possible through significant change of the frame construction using identical materials. On the other hand, we should keep in mind the additional heat transfer caused by thermal coupling to roof construction: In such case it will be in the same range as the window itself. Therefore, a future development should be focused on other phenomena, especially on reduction of overheating risk by keeping the daylight quality in interior.

Exterior shading system with integrated function for roof windows was designed (patent pending). Such system consists of a set of movable lamellae, partly covered by photovoltaics elements. The small amount of harvested energy is used preferably for fans supporting the air movement in the air cavity between shading and external surface of glazing and it is used for movement of lamellae as well. Such system can operate partly in autonomous mode or according to information from local control unit or superordinate control unit of the house.

Acknowledgment
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[6] software HTflux (https://www.htflux.com)

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Nomenclature

D daylight factor, %
U thermal transmittance, W/(m^{2}K)
g solar factor, dimensionless
h surface heat transfer coefficient, W/(m^{2}K)
l length, m
ψ linear thermal transmittance, W/(m.K)

indices

c convection, g glazing, e exterior, f frame, i interior, inst installed, r radiation, s, S surface,
R required, w window

Environmental performance of window systems in patient rooms: a case study in the Belgian context

Eisazadeh N[1], De Troyer F[1], Allacker K[1]

[1] Department of Architecture, KU Leuven, Kasteelpark Arenberg 1, 3001 Leuven, Belgium

nazanin.eisazadeh@kuleuven.be

Abstract. Hospitals produce high amounts of emissions due to their continuous operation, high flow of people, and intensive HVAC requirements. In order to reduce the environmental footprint of hospitals, it is crucial to improve energy performance while still maintaining a comfortable indoor environment for the occupants. Also to avoid high environmental burdens, it is important to understand the impact of building material selection from the full life cycle perspective. Window systems influence the energy loads and comfort in buildings and provide access to daylight and views. Therefore, windows contribute significantly to the energy consumption and indoor environmental quality of buildings and impact the well-being of occupants. The aim of this study is to determine the influence of various window system design configurations on the environmental performance of patient rooms in Belgium through life cycle assessment (LCA). The method is innovative as it combines dynamic energy simulations and daylight analysis and integrates these in the LCA study of the window systems. The influence of several components is investigated, such as the choice of glazing and shading system. The results are analysed and compared in terms of energy cost for heating, cooling, and lighting, daylighting performance and life cycle environmental impacts. A typical patient room from a hospital design in Belgium is used as a case study. Based on comparative analysis, the paper discusses potential window system design configurations that allow for energy efficient, daylit and environmentally-friendly patient rooms.

1. Introduction

Hospitals are large consumers of natural resources and energy due to their continuous operation, high flow of people, intensive HVAC demand and artificial lighting requirement. In order to reduce the environmental footprint of hospitals, it is crucial to moderate operational energy use through enhanced energy efficiency while still maintaining a comfortable indoor environment that supports the health and well-being of the occupants. So as to avoid high environmental burdens, it is important to understand the impact of building material choices from a full life cycle perspective. Window systems influence energy consumption and thermal/visual comfort in buildings and profoundly affect the indoor environmental quality by providing access to daylight and external view. Therefore, in order to reduce energy demands, emissions from energy use and the environmental burden associated with the choice of building materials, selecting the appropriate window system configuration is a fundamental part of the early design stage decisions and are difficult to change later on.

Literature review shows that only a limited number of studies address the environmental performance of window systems [1,2,3] and there appears to be no study focusing on combining dynamic energy simulations and daylight analysis and integrating these aspects in the LCA study of the window systems. There is hence a need for integrated performance analysis of window systems in patient rooms and this paper provides the first step towards this approach.

This paper presents an integrated approach for the LCA study of the window systems where the link between various window design parameters, and their combined effect on energy consumption, daylighting and environmental impacts are considered. The aim is to determine the influence of various window system configuration on the energy cost, life cycle environmental impact and daylighting in patient rooms. The effect of several components, including glazing type and shading device configuration is investigated. The various window system design alternatives are explored through parametric modelling. The key objective of this study is to identify window system configurations which balance the objectives of a daylit, comfortable and energy efficient patient room with the least environmental impact. The methodology combines dynamic energy simulations, daylight analysis and integrates these in the LCA study of the window systems. The methodology was applied to a typical patient room from a hospital design in Belgium.

2. Methodology

This paper investigates the effect of window system design on the life cycle environmental impact of the patient rooms. The alternative design options are evaluated in three steps. In a first step, the environmental impact study, the energy cost for heating, cooling, and daylight-linked artificial lighting and the daylighting performance of different window systems without any shading device are carried out. In the next step, various shading device configurations are added to the windows and the different design alternatives are evaluated based on environmental cost, energy cost and daylighting. After analysing and comparing the data for each glazing type, the design options with the least environmental and energy cost and higher access to daylight are identified. The final step provides a side-by-side comparison of the benchmark design (without shading) with the best performing selected design options with shading for each glazing type.

The patient room is modelled in Grasshopper [4], which is a plugin for Rhinoceros (3D modelling tool) [5]. Ladybug & Honeybee [6] components for Grasshopper are used to assign detailed patient room simulation parameters including construction types, materials and schedules to the model. Parametric simulations are performed using the Grasshopper plugin Colibri [7] and for the energy and daylighting analysis Ladybug & Honeybee are used to interface with the simulation engines EnergyPlus, Radiance and Daysim. The LCA was performed using the "MMG+_KU Leuven" tool which is an Excel-based tool developed at the research division of Architectural Engineering at KU Leuven in collaboration with VITO (Vlaamse Instelling Voor Technologisch Onderzoek) and BBRI (Belgian Building Research Institute).

2.1. Simulation model description

The patient room dimensions are 4.0 m x 6.0 m x 3.0 m (length x width x height) with 40% WWR (Window-to-Wall Ratio). The simulations only take into account the floor area occupied by the patient, the service area is excluded from the model (see Figure 1). In order to investigate the impact of glazing characteristics on the performance, six glazing types are considered. The double/triple glazing consists of 4 and/or 6 mm glass panes with 15 or 16 mm cavity (90% argon). The Berkeley lab WINDOW 7.6 software is used to determine the thermal and optical characteristics of the glazing. Table 1 lists the key properties of the glazing and Figure 2 shows the position of the coating within the glazing. The uncoated glazing acts as a benchmark for understanding the impact of the coating. Coated aluminium is the choice of material for shading devices. The patient room has one external wall (U-value = 0.22 W/m^{2}K) with a single window facing south; all other surfaces are assumed adiabatic. The patient room is located on the second floor and no external obstruction is taken into account. The simulation is performed with the EnergyPlus weather data for Brussels (latitude 50.90° N and longitude 4.53° E).

2.2. Energy analysis

EnergyPlus is used to calculate the annual energy use for heating, cooling and artificial lighting; taking into account the solar and thermal properties of the glazing with detailed layer by layer modelling of the glazing system. Daylight-linked lighting control is employed which incorporates a lighting schedule generated by Daysim software using Honeybee component for annual daylight simulation. The illumination threshold for activating lighting is 300 lux, as this value represents the illuminance necessary for simple examination and reading. The lighting sensor is placed at the patient's position to ensure sufficient light at this location.

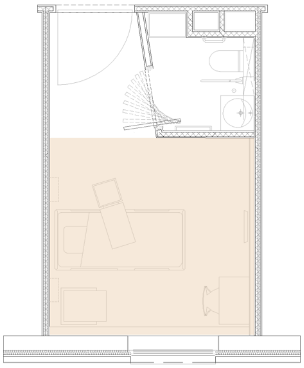

Figure 1. The patient room area taken into account for parametric model dimension

Table 1. Glazing characteristics

GLZ [Tvis/g-value]	Configuration	Coating features	U-value (W/m^{2}K)
GLZ1 [0.82/0.80]	4-16-4	No coating	2.50
GLZ2 [0.73/0.41]	4-16-4	Solar control + Thermal insulation	1.10
GLZ3 [0.61/0.31]	6-16-4	Solar control + Thermal insulation	1.10
GLZ4 [0.76/0.74]	4-15-4-15-4	No coating	1.70
GLZ5 [0.75/0.53]	4-15-4-15-4	Thermal insulation + High (light transmission + g-value)	0.60
GLZ6 [0.68/0.38]	4-15-4-15-4	Solar control + Thermal insulation	0.60

GLZ: Glazing Tvis: Visible transmittance Configuration: 4, 6 Glazing thickness (mm) - 15, 16 Cavity thickness (mm)

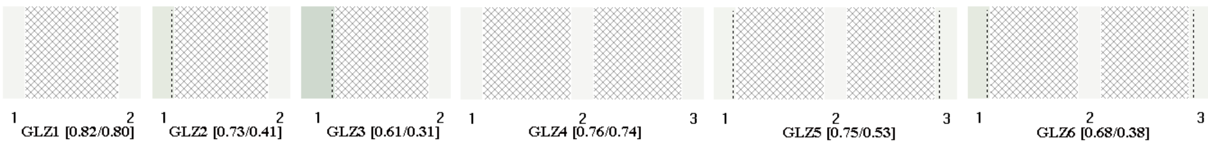

Figure 2. Coating position within glazing; 1- Outer glass pane
Dotted line: position of coating(s)

Space heating and cooling setpoint temperatures are assumed to be 21°C and 24°C respectively. Mechanical ventilation and infiltration are set to 2.00 (ac/h) and 0.20 (ac/h) respectively. These assumptions are in line with standards provided for patient rooms in Belgium. Mechanical ventilation is modelled with heating and cooling using the EnergyPlus Ideal loads system; the effects of heat recovery and economiser are included. In order to calculate the energy cost for heating a global system efficiency of 0.85 and for cooling a CoP (Coefficient of Performance) of 1.80 are considered. Natural gas (heating) and electricity (cooling and artificial lighting) prices (€/kWh) are based on the Belgian market prices of 2017; the price of electricity for one kWh is approximately four times the price per kWh of natural gas.

2.3. Daylight analysis

This study used climate-based daylight modelling which provides hourly daylight predictions for an average year derived from weather data. Honeybee is used to interface with the Radiance based daylighting analysis tool Daysim. The output from Daysim is a data file containing the annual illuminance/luminance values for the analysis points in the room.

UDI (Useful Daylight Illuminance) and sDA (spatial Daylight Autonomy) are used to assess the daylighting performance. The metric $sDA_{300/50\%}$ describes the percentage of an analysed area that meets the target illuminance of 300 lux for at least 50% of the annual occupied hours. This threshold also represents the "minimum" daylight provision value required by CEN daylighting standard (EN 17037: 2018) on the task plane during more than 50% of the daylight hours [8]. $UDI_{100\text{-}2000lux}$ determines when daylighting levels are within the range defined as useful for the occupants and $UDI_{>2000lux}$ presents the times when excessive levels of daylight could lead to visual discomfort [9]; This metric could also act as a proxy for detecting the likely appearance of glare. UDI metric describes the hourly varying daylight illuminances for the entire year at each of the calculation points [9].

The daylighting simulation is performed from 6 AM to 9 PM, as during this period of the day the patients need daylight/lighting. The task plane level is located 0.9 m above the ground (bed surface) with a grid of sensor points with a 0.3 m spacing, the reference point (sensor) location is selected based on the patients position in the room (see Figure 1). The walls, ceiling, floor and shading device reflectance are assumed to be 50%, 80%, 20% and 60% respectively.

2.4. LCA study

The "MMG+_KU Leuven" tool is based on the MMG method: the national method in Belgium to quantify the environmental performance of building elements. The LCIA (Life Cycle Impact Assessment) method applied in the MMG method combines the environmental impact indicators CEN and CEN+ [10]. The CEN indicators consist of seven environmental impact categories in line with the European standard and the CEN+ indicators include ten additional impact categories considered in Belgian legislation. For each impact category, the results are expressed as characterised results (equivalents) and as external environmental costs (monetary values, €). The environmental life cycle costs are calculated by multiplying the characterization values by a monetisation factor. This value represents the costs required to avoid, repair or compensate the damage caused by the environmental impacts [11]. Further details regarding this method can be found in De Nocker and De Backer [12].

The environmental impacts associated with each glazing type are assembled based on the data obtained from the AGC (Asahi Glass Co., Ltd) Glass Europe. The aluminium shading material is modelled via SimaPro and the environmental impacts are calculated. These inventory data are then further processed in MMG+_KU Leuven tool. In order to calculate and study the life cycle environmental impact of the patient rooms, the selected design options are modelled in the MMG+_KU Leuven tool (with and without shading device). In this study energy consumption data estimated via EnergyPlus is the basic input for the MMG+_KU Leuven tool.

3. Result and discussion

3.1. Step 1

In this step, for each glazing type the environmental impact, annual energy cost, $UDI_{100\text{-}2000lux}$, $UDI_{>2000lux}$ and $sDA_{300/50\%}$ are calculated without a shading device. The data obtained from this step acts as a benchmark for analysing the impact of shading devices on environmental performance. It should be noted that the criteria taken into account for evaluating the performance of the design options are environmental cost, energy cost, $sDA_{300/50\%}$>50% and UDI.

As can be seen in Figure 3, uncoated double and triple pane glazing (GLZ1 and GLZ4) show the highest energy and environmental cost due to higher heating and cooling loads. Moreover, triple pane GLZ6 which has a g-value of 0.38 and the lowest U-value among the glazing types shows the least energy and environmental cost; this is due to the lower heating and cooling loads. As for daylighting performance GLZ6 still maintains a sufficient level (58% sDA). The results show that there is ca. 18% difference between the sDA value for the highest (GLZ1) and lowest (GLZ3) light transmission glazing. However, GLZ3 has the highest $UDI_{100\text{-}2000lux}$ and lowest $UDI_{>2000lux}$ compared to the other glazing types which indicates higher access to useful daylighting levels and visual comfort.

3.2. Step 2

The second step consists of analysing different overhang and fixed horizontal louvres configurations for each glazing type. The parameters of the parametric analysis are shown in table 2. The shading device depth range is in accordance with the suns position for this latitude (peak sun angle is ca. 63°) and the height of the window. The shading devices are modelled without mounts and/or anchors. The performance criteria taken into account for evaluating the performance of the design alternatives are similar to the previous step. After adding the shading devices to the benchmark design and running the simulations it is evident that for some coated glazing a higher WWR (50%) is required due to the fact that the sDA$_{300/50\%}$>50% criterion is not met. However, for each glazing the design option without shading device still acts as a benchmark for that type of glazing.

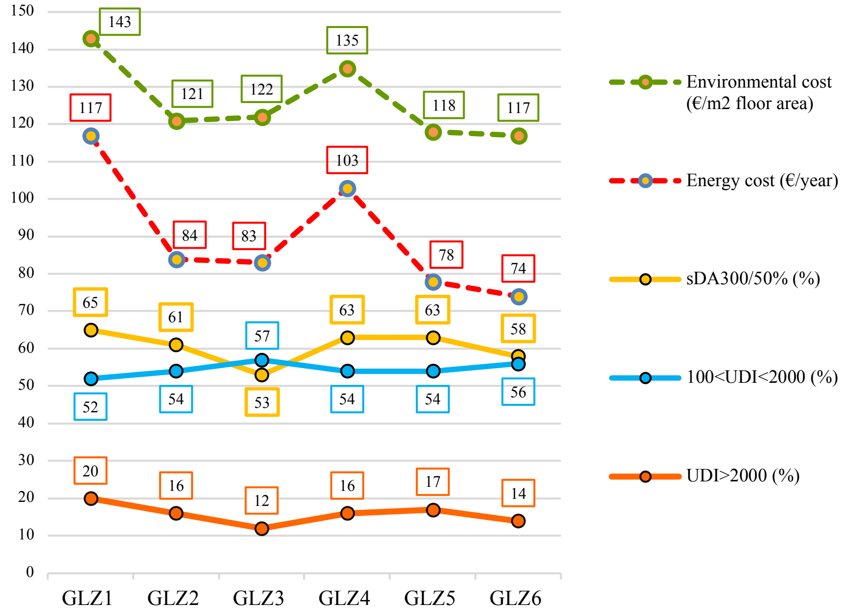

Figure 3. Benchmark designs performance without shading device (40% WWR – South orientation)

Table 2. Value of parametric variables

Variables	Minimum	Maximum	Step
Overhang depth	0.5 m	1.0 m	0.10 m
Slat depth	0.1 m	0.3 m	0.05 m
Number of slats	5	10	1

3.2.1. Overhang. In this stage for each glazing type, the design option with the least energy cost and sufficient daylight (sDA$_{300/50\%}$>50%) are selected; shown as highlighted grey cells in Figure 4. The results show that overhangs decrease sDA levels but still increase the useful daylighting levels and visual comfort (lower UDI$_{>2000lux}$) for all glazing types compared to the benchmark design even for coated glazing with higher WWR (50%). Moreover, the increase in window size for coated glazing designs results in slightly higher energy costs. In the next phase, the environmental cost of the selected design option for each glazing is calculated. As can be seen in Figure 5, the options with uncoated glazing (GLZ1 and GLZ4) and GLZ6 have the highest and lowest environmental costs respectively, similar to the previous step. The results show that the selected designs with coated glazing have higher environmental costs compared to the benchmark design, this is due to the increase in window size (50% WWR) which leads to higher quantities of overhang material and energy loads.

3.2.2. Fixed horizontal louvres. In the first phase after running energy and daylighting simulations for all glazing types the design options that meet sDA$_{300/50\%}$>50% criterion are identified and highlighted in a light grey tone as shown in Figure 6. The darker grey cells represent the slat depth which shows better energy and daylighting performance for the specified number of slats for each glazing type. The results show that the selected design options (darker grey cells) for each glazing type have fairly similar energy costs and the main difference between the options are the daylighting levels. In the second phase, the environmental performance of the selected design options for each glazing type are calculated and analysed, see Figure 7. The findings show the environmental impact of each design option is directly linked to the quantity of material used for the shading system. However, for designs with coated glazing the difference between the best and worst case scenario is ca. 2.5%. As for uncoated glazing design options the difference is less than 2%; this is due to lower operational energy use for cooling. The results indicate that the optimal shading device configuration differs based on the project goal i.e. in this study the goal is to have the least environmental and energy cost with sufficient daylighting levels and visual comfort. The black cells in Figure 6 show the best performing design option for each glazing type that fulfils this goal.

			No shading		0.5		0.6		0.7		0.8		0.9		1.0	
					Overhang Depth											
GLZ1 [0.82/0.80] 40% WWR	Energy cost	$sDA_{300/50\%}$	117	65	136	54	112	51	112	50	111	49	112	47	111	45
	$UDI_{100-2000lux}$	$UDI_{>2000lux}$	52	20	58	11	58	11	59	9	59	9	60	7	60	7
GLZ2 [0.73/0.41] 50% WWR	Energy cost	$sDA_{300/50\%}$	91	71	89	60	89	58	89	56	89	55	89	53	88	51
	$UDI_{100-2000lux}$	$UDI_{>2000lux}$	50	22	56	13	57	12	58	11	58	10	60	8	60	9
GLZ3 [0.61/0.31] 50% WWR	Energy cost	$sDA_{300/50\%}$	88	62	88	52	87	50	87	47	88	46	88	42	88	42
	$UDI_{100-2000lux}$	$UDI_{>2000lux}$	55	16	58	10	59	9	60	8	60	7	60	7	60	6
GLZ4 [0.76/0.74] 40% WWR	Energy cost	$sDA_{300/50\%}$	103	63	100	51	99	47	99	46	99	46	99	44	98	40
	$UDI_{100-2000lux}$	$UDI_{>2000lux}$	54	16	59	10	59	9	60	8	60	7	60	6	60	6
GLZ5 [0.75/0.53] 50% WWR	Energy cost	$sDA_{300/50\%}$	84	72	82	61	82	58	82	56	82	55	81	53	81	53
	$UDI_{100-2000lux}$	$UDI_{>2000lux}$	50	22	56	13	57	12	58	11	58	10	59	10	60	8
GLZ6 [0.68/0.38] 50% WWR	Energy cost	$sDA_{300/50\%}$	78	65	77	56	77	54	77	53	77	51	78	49	77	46
	$UDI_{100-2000lux}$	$UDI_{>2000lux}$	52	19	57	12	58	11	59	10	59	9	60	8	60	7

Figure 4. Energy and daylighting performance of the design options with overhang
Units: Energy cost (€/year) $sDA_{300/50\%}$ (%) $UDI_{100\text{-}2000lux}$ (%) $UDI_{>2000lux}$ (%)

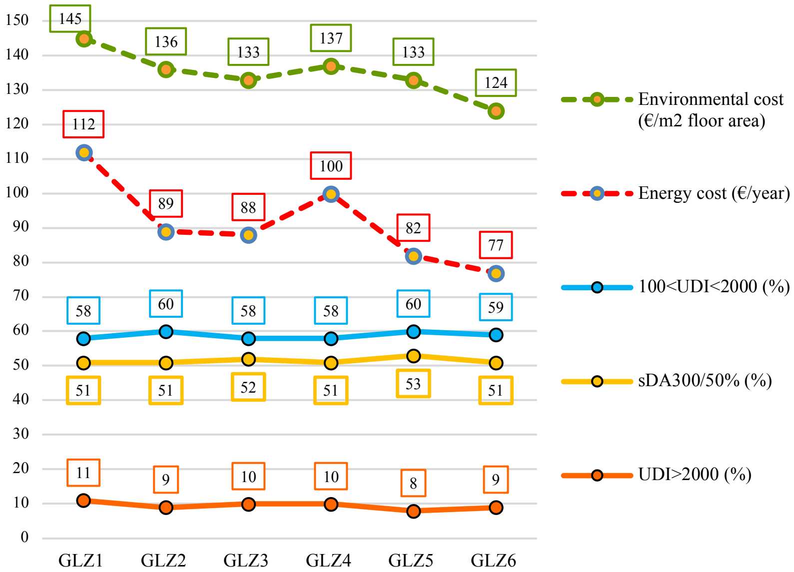

Figure 5. Selected design options performance with overhang

3.3. Step 3: Side-by-side comparison

Figure 8 and 9 show the side-by-side comparison of the benchmark design (without shading) and the optimal design options for each glazing type with shading devices. Figure 8 shows that the design options with fixed horizontal louvres have better performance in most analysed criteria compared to the other designs, except for higher environmental costs in some design options. This is due to the quantity of the material used for the shading system, which in some cases is slightly higher. Moreover, some design options with horizontal shades show lower sDA values (ca. 10% less in the most extreme case) compared to the benchmark design but still maintain a sufficient level ($sDA_{300/50\%}$>50%). The comparison also shows that fixed horizontal louvres reduce UDI>2000 lux values which could reduce the likely appearance of glare and increase visual comfort. The results, as can be seen in Figure 9, reveal that GLZ5 and GLZ6 design options show the least environmental impacts compared to the other glazing. This is mainly due to lower operational energy use for heating and cooling. As for GLZ5 design option with louvres this is also the result of smaller window size and less quantity of shading material.

GLZ1 [0.82/0.80] 40% WWR (DG)		N	Slat Depth 0.10		0.15		0.20		0.25		0.30	
Energy cost	$sDA_{300/50\%}$	5	109.7	62	106.8	61	104.5	60	102.9	58	101.7	59
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		55	15	56	14	57	12	59	10	60	8
Energy cost	$sDA_{300/50\%}$	6	108.9	62	105.1	61	102.1	60	101.2	56	101.2	51
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		56	14	56	13	57	13	58	11	61	6
Energy cost	$sDA_{300/50\%}$	7	107.5	64	103.8	62	101.6	60	101.6	54	101.4	45
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		56	14	57	12	58	10	61	6	62	4
Energy cost	$sDA_{300/50\%}$	8	106.3	63	103	61	102.1	58	102.8	51	102.1	40
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		56	14	57	12	60	8	60	6	62	4
Energy cost	$sDA_{300/50\%}$	9	105	62	101	60	101.4	54	100.9	44	102.7	35
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		57	13	58	11	61	6	61	5	61	4
Energy cost	$sDA_{300/50\%}$	10	103.8	63	101.3	59	101.5	49	101.1	40	102.3	32
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		57	13	59	9	62	4	63	3	62	1

GLZ4 [0.76/0.74] 40% WWR (TG)		N	Slat Depth 0.10		0.15		0.20		0.25		0.30	
Energy cost	$sDA_{300/50\%}$	5	96.9	61	94.1	59	92.3	58	90.2	56	89.2	52
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		56	13	57	12	59	10	59	9	61	6
Energy cost	$sDA_{300/50\%}$	6	95.5	60	92.3	57	90.8	57	88.8	53	88.6	47
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		56	14	57	12	59	9	60	8	61	6
Energy cost	$sDA_{300/50\%}$	7	94.6	60	90.8	58	88.6	55	90.6	44	88.4	43
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		57	12	58	11	59	9	62	4	62	4
Energy cost	$sDA_{300/50\%}$	8	93.2	58	91.1	56	88.7	51	90.7	43	90.3	35
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		56	13	59	10	60	8	60	6	62	3
Energy cost	$sDA_{300/50\%}$	9	91.5	61	88.1	54	88.0	44	89.0	38	90.2	28
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		56	13	58	10	60	7	60	5	59	3
Energy cost	$sDA_{300/50\%}$	10	90.5	60	88.2	54	88.4	42	88.8	31	89.8	28
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		56	13	59	9	62	4	63	2	63	1

GLZ2 [0.73/0.41] 50% WWR (DG)		N	Slat Depth 0.10		0.15		0.20		0.25		0.30	
Energy cost	$sDA_{300/50\%}$	5	87.1	71	84.9	69	83.7	67	83.8	65	82.2	65
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		54	17	54	17	56	14	58	10	59	10
Energy cost	$sDA_{300/50\%}$	6	86.9	69	84.5	69	82.7	65	82.2	63	81.3	61
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		55	15	55	15	56	13	58	11	59	9
Energy cost	$sDA_{300/50\%}$	7	85.4	68	83.4	69	81.3	67	81.1	60	81.0	58
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		54	17	56	14	57	13	59	10	60	8
Energy cost	$sDA_{300/50\%}$	8	85.4	70	82.9	69	82.1	65	81.9	62	82.0	52
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		55	15	56	13	59	9	60	7	62	5
Energy cost	$sDA_{300/50\%}$	9	83.5	70	81.5	70	80.9	65	81.3	59	82.1	47
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		54	17	57	12	59	9	61	6	63	3
Energy cost	$sDA_{300/50\%}$	10	82.8	69	80.3	67	81.2	60	81.1	49	83.8	40
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		55	15	56	13	61	6	62	6	63	2

GLZ5 [0.75/0.53] 40% WWR (TG)		N	Slat Depth 0.10		0.15		0.20		0.25		0.30	
Energy cost	$sDA_{300/50\%}$	5	75.5	58	73.3	58	72.4	56	70.8	54	69.7	51
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		57	12	58	12	59	10	60	8	61	7
Energy cost	$sDA_{300/50\%}$	6	74.0	59	71.7	58	71.2	54	69.7	49	70.0	47
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		56	14	57	12	59	10	60	8	61	6
Energy cost	$sDA_{300/50\%}$	7	73.6	58	71.5	56	70.3	54	70.5	49	71.3	38
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		57	12	58	11	60	8	62	5	62	4
Energy cost	$sDA_{300/50\%}$	8	72.9	60	71.3	55	71.2	48	70.7	40	73.1	33
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		57	12	58	10	60	7	60	6	61	3
Energy cost	$sDA_{300/50\%}$	9	71.5	59	69.4	56	71.0	44	70.2	38	71.8	27
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		57	13	59	10	60	5	61	5	60	4
Energy cost	$sDA_{300/50\%}$	10	70.8	60	69.4	50	70.6	40	72.8	33	72.6	25
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		57	12	60	8	62	4	62	1	62	1

GLZ3 [0.61/0.31] 50% WWR (DG)		N	Slat Depth 0.10		0.15		0.20		0.25		0.30	
Energy cost	$sDA_{300/50\%}$	5	85.4	61	83.9	58	83.1	56	82.3	55	82.4	54
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		56	13	57	12	59	10	60	8	62	5
Energy cost	$sDA_{300/50\%}$	6	84.8	61	83.2	58	82.3	56	81.4	49	82.2	47
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		57	13	58	11	59	10	60	8	61	5
Energy cost	$sDA_{300/50\%}$	7	84.3	60	83.0	56	81.7	54	80.5	48	81.6	40
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		57	12	58	11	60	8	60	7	60	6
Energy cost	$sDA_{300/50\%}$	8	83.7	60	82.5	56	81.3	51	84.7	40	82.9	38
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		57	13	58	10	60	7	60	4	62	3
Energy cost	$sDA_{300/50\%}$	9	82.8	60	81.5	54	81.4	47	81.8	36	83.6	29
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		57	12	60	8	61	6	62	4	62	2
Energy cost	$sDA_{300/50\%}$	10	83.2	59	80.4	53	81.2	45	84.2	36	84.5	28
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		59	10	59	10	62	5	62	2	62	1

GLZ6 [0.68/0.38] 50% WWR (TG)		N	Slat Depth 0.10		0.15		0.20		0.25		0.30	
Energy cost	$sDA_{300/50\%}$	5	75.6	65	73.7	65	72.6	63	71.4	60	71.1	58
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		56	14	56	14	57	13	58	11	59	9
Energy cost	$sDA_{300/50\%}$	6	74.7	65	72.9	63	72.5	61	71.0	58	71.0	54
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		55	15	56	14	58	11	58	11	60	7
Energy cost	$sDA_{300/50\%}$	7	74.1	65	71.8	62	71.2	60	70.8	56	71.6	51
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		56	14	56	13	58	11	60	8	61	6
Energy cost	$sDA_{300/50\%}$	8	73.6	66	71.4	62	71.3	60	71.5	54	73.8	43
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		56	14	57	13	60	8	61	7	62	3
Energy cost	$sDA_{300/50\%}$	9	72.7	65	71.0	62	70.4	60	71.3	45	72.4	41
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		56	14	58	10	61	7	62	5	63	2
Energy cost	$sDA_{300/50\%}$	10	71.7	64	71.0	60	70.1	53	71.8	42	72.0	35
$UDI_{100-2000lux}$	$UDI_{>2000lux}$		56	14	59	9	61	6	62	3	63	3

Figure 6. Performance of the design options with horizontal louvres
N: Number of slats Units: Energy cost (€/year) $sDA_{300/50\%}$ (%) $UDI_{100-2000lux}$ (%) $UDI_{>2000lux}$ (%)

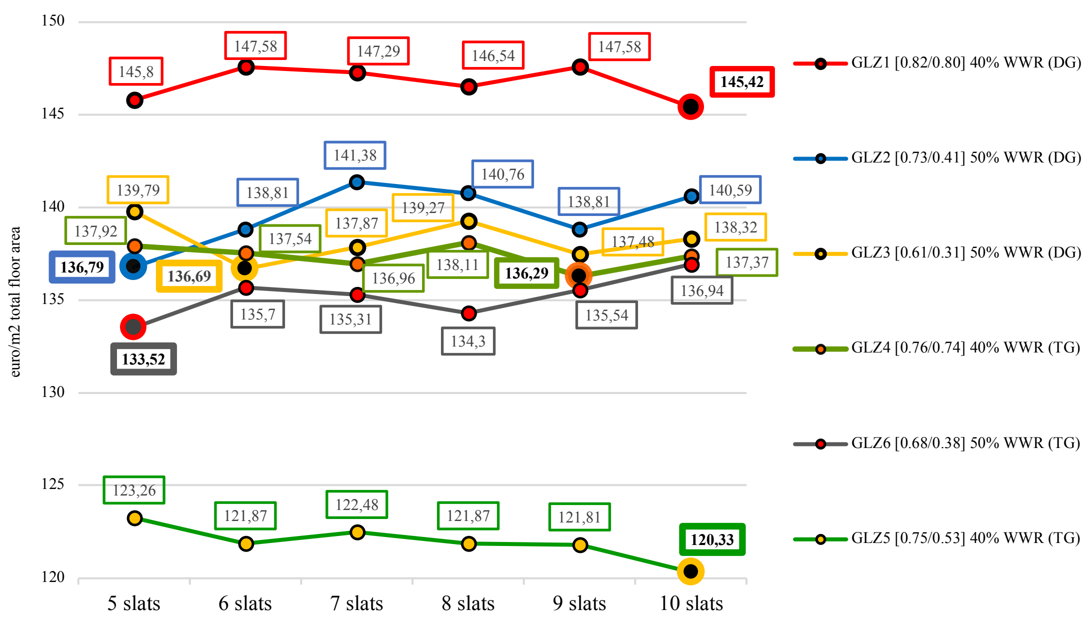

Figure 7. The environmental performance of the design options with horizontal louvres

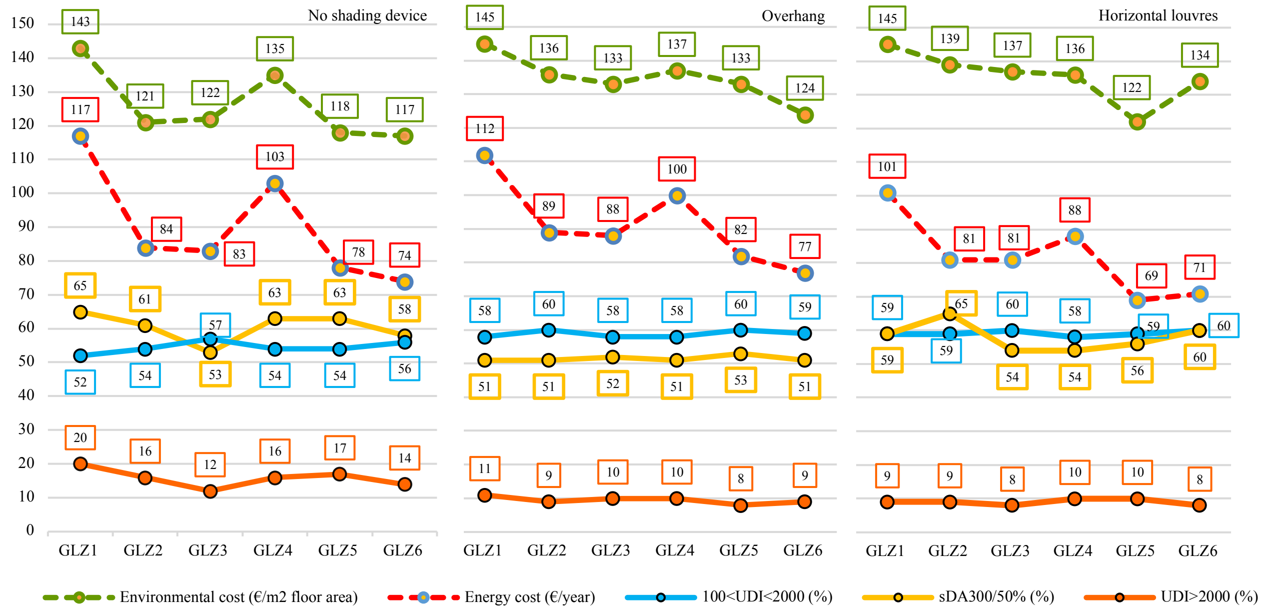

Figure 8. Side-by-side performance comparison of the benchmark designs (without shading) with the selected best performing design options with shading device

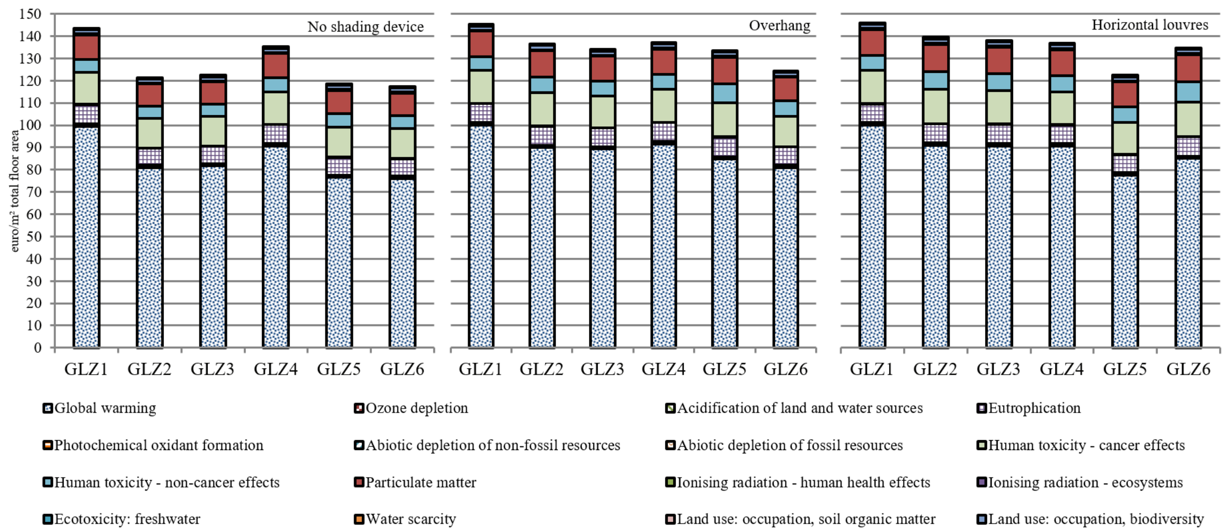

Figure 9. Side-by-side environmental performance comparison of the benchmark designs (without shading) with the selected best performing design options with shading device

4. Conclusion

The findings show that the glazing characteristics and the shading device configuration impact the design performance significantly and hence the selection and configuration of the window system design should be considered carefully during the early design process. The results highlight the fact that the window size and shading device configuration have a major impact on daylighting levels and visual comfort. This is especially important for patient rooms where adequate daylighting level is necessary and the patients have limited movement and generally are unable to adapt by moving around in the space. It is observed from the results that in the design options with shading, the main contributors to the environmental impacts are the window size and the quantity of material used for the shading system. The results show that design options with coated glazing have lower life cycle environmental impacts compared to options using non-coated glazing with similar conditions due to the reduction in energy use. The results also indicate that the most significant environmental impact indicators in all the design options are associated with global warming, particulate matter formation and human toxicity (cancer effects). This study shows that a comprehensive and integrated performance analysis approach is required to have a correct insight into the window system design performance. It can be concluded that a parametric study which considers the impact of window system design options (WWR, glazing characteristic, shading device, etc.) on various performance criteria (energy cost, environmental cost, sDA, UDI, etc.) can assist architects in understanding the cross effects. Thus, this approach can support the selection process of the most preferred window system design configuration based on the project objectives.

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Partially dynamic life cycle assessment of windows indicates potential thermal over-optimization

Horup L[1], Reymann M[1], Rørbech JT[2], Ryberg M[3], Birkved M[4]

[1] Section for Building Design, Department of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark
[2] VELUX Group, Hørsholm, Denmark
[3] Sustainability, Department of Technology, Management and Economics, Technical University of Denmark, Kgs. Lyngby, Denmark
[4] SDU Life Cycle Engineering, Department of Chemical Engineering, Biotechnology and Environmental Technology University of Southern Denmark, Campusvej 55, 5230 Odense-M, Denmark

morb@kbm.sdu.dk

Abstract. To reach the environmental goals set by EU, Energy Performance of Buildings Directive (EPBD) and national building regulations will demand reductions in building's energy consumption. Energy consumption goals for buildings are pursued through high thermal performance building components (HTPBC). Paradoxically, building regulations have no requirements regarding the embodied energy of buildings and components. To meet the requirements set by governments, HTPBCs in most cases require an increasing embodied energy (from insulation), assumed to be paid back during the service-life of HTPBCs. Accounting for decarbonization of the future energy supply, the expected payback might not be feasible in terms of total environmental footprint, since the future energy supplies are expected to be greener than the building's embodied energy. Using roof windows as a case study, we assess if strict demands for building's energy consumption, will lead to more sustainable buildings if all temporal variations in terms of global warming impacts across the service-life are taken into account. A comparison of double and tripple glazed windows reveals that the expected net energy savings obtained during the use phase are compromised by relatively higher impacts induced in the production stage. The case study indicates requirements of building's energy performance might compromise the overall sustainability of building component solutions, as the additional embodied energy required to produce triple glazed windows most likely will not be compensated for by saved operational energy, when taking into account the forecasted decarbonatization of the building energy future supply.

1. Introduction

Life Cycle Assessment (LCA) of building components can be used to select environmentally favourable building components. Many building components have service-lives in the order of decades and sometimes half centuries [1]. LCAs of such components are most often conducted in a formalised manner relying on standardized and traditional product system modelling principles assuming that the foreground and background systems of building components remain unaltered across the entire service-life of the building components, even in the case when the service-lives amount to 5-6 decades. For some building components serving solely ornamental purposes, lasting the entire service-life of the building and not demanding any replacement nor maintenance across the service-life of the entire building, the changes in the background and foreground systems of the product system will most likely only have moderate to low influence on the overall environmental performance of the component. The limited influence of the temporally dependent system changes on the environmental performance of such building components, stems from fact that the changes in the foreground and background systems only will affect processes taking place after installation which for the such "passive" building components is limited to disposal or rather End-of-Life (EoL) processes. On the other hand will the environmental performance of building components serving functional purposes (i.e. structural, thermal, light transmission etc. purposes), needing replacement(s), needing energy supply, demanding maintenance during the service-life of the building in which they are installed, to a much larger extent be influenced by temporal changes in the foreground and background systems. The reason for the much larger influence of temporal changes in foreground and background system on the last group of "active" components is caused by the fact the systems supplying these component e.g. energy supply systems, systems producing replacement components etc. will inevitably change over time most often becoming more resource and often (not always) also environmentally efficient meaning that the overall environmental performance of the building components most often improves if temporal changes are accounted for in LCAs of components. The fact that the LCA framework from early on was not envisioned to account for temporal system changes, makes accounting for temporal changes (obviously) quite tricky, since the most elementary parts on an LCA i.e. inventory data and product system modelling both are designed not to be able to account for temporal changes.

Irrespective of the obstacles encountered by life cycle assessors when attempting to conduct temporally dependent LCAs, a recent review introducing a much-needed terminology for temporally dependent LCAs (see Sohn et al., 2019), reveal that approximately a dozen temporally dependent LCAs have been conducted and published so far. The concept introducing review by Sohn et al. [2] further reveals that time dependency in LCA is not a single concept, but rather a concept that can be applied to all of the four ISO defined phases of an LCA, meaning that a fully dynamic (i.e. dynamic in all 4 LCA phases) LCA (a so-called DLCA – which is yet to be seen) will have to include a fully dynamic goal and scope definition, fully dynamic inventory, fully dynamic impact assessment and a fully dynamic interpretation phase. If not all stages of an LCA are made dynamic the outcome is what is referred to as "a partially Dynamic LCA" or rather pDLCA.

The term *dynamic* is a word that most often causes a lot of confusion, but which basically can be boiled down to one single modelling issue – time dependency. However, time dependency can as illustrated by Sohn and co-workers be introduced in LCAs using off-the-shelf software and data sources. Basically there are two types of time dependent LCAs: prospective and dynamic LCAs. Two fundamental points in time are needed in order to distinguish between the two types of time dependent LCAs: t_0 (the time the first activity in a product system takes place) and $t_{terminal}$ (the time where all activities in a product system ends). Depending on the number of (time) steps between t_0 and $t_{terminal}$ the difference between prospective and dynamic LCAs is revealed. If the number of time steps accounted for between t_0 and $t_{terminal}$ equals 1 then the assessment is referred to as a prospective LCA. On the other hand, if the number of time steps between t_0 and $t_{terminal}$ is larger than one 1 then the assessment is considered a (fully/partially) dynamic LCA.

In the study at hand we present comparative LCAs and pDLCAs (i.e. a novel form of LCA) of double and triple layered windows assessed as a building component both disregarding (i.e. LCA) and taking into account (i.e. pDLCA) carefully selected time dependent changes in the energy systems providing the necessary energy to heat the building in which the windows are installed and the systems that provides the energy needed to produce and dispose of the windows during the service-life of the building in which the windows are installed. The functional unit applied is hence "Allow daylight into a building, through a window with an area of 1.6m2 with a light transmittance of at least 0.7, placed in the roof of a residential building, at an angle of 45◦ for 40 years".

The purpose of conducting such an assessment is to illustrate how time dependent inventory changes in a building LCA may affect the results. Here we are merely illustrating how installation of a window (i.e. double or triple glazed Velux (2019a) [3] and Velux (2019b) [4] affects the environmental performance across the entire service-life of a single family when assessed in a conventional and dynamic LCA manner and hence a non-standardized form of LCA.

2. Method

For the assessment the attributional LCI modelling framework was be applied, in accordance with the ILCD recommendations for decision context C1 [5]. This study applies cut-off allocation, meaning that recycled materials are considered "burden-free", and only the impacts related to the recycling process and associated transportation are attributed to subsequent cycles of the service-life cycle of a product. However, the primary user does not benefit from producing the recyclable materials either [6].

Figure 1 presents the product system assessed along with the system boundaries of our study. In accordance with Figure 1, the analysis includes all life cycle stages from cradle to grave. The product systems compared include all processes which are required to provide the functions/service of the windows, including upstream stages (i.e. extraction and production of raw materials and manufacturing), the use stage and downstream stages (i.e. disposal and end-of-life).

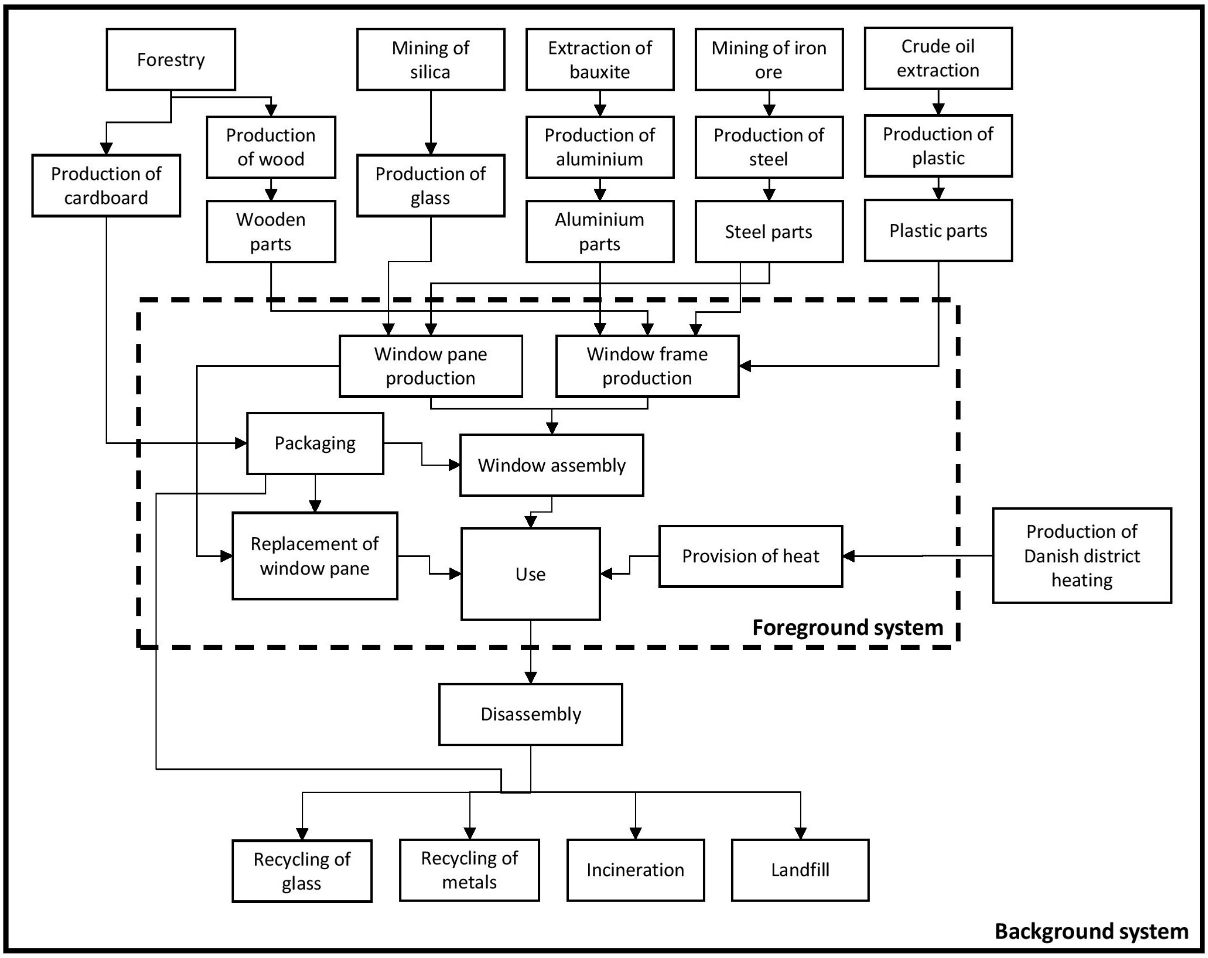

Figure 1: System boundaries representative for our case study of skylight windows. The dotted line delineates the foreground system which covers the production as well as the use of the windows. Arrows represents mass- as well as energy flows.

Upstream processes include extraction of resources, e.g. mining of metal ore, sawmill activities, extraction of crude oil and production of materials such as aluminium and wood profiles used in the production of the window pane and frame.

Assembled windows are after production transported to retailers and subsequently distributed to residential buildings. The use phase includes, in our case, replacement of the window pane and the sourcing of indoor heating compensating for heat loss/gain through the window (i.e. the systems is intended to include the thermal properties of/service provided by the windows). Maintenance (i.e. cleaning of the window is excluded in our assessment), as cleaning activities mainly depend on end-user preferences and hence subjective preferences. The EoL of the windows covers disassembly, transport to a waste receiving/processing facility, and terminal disposal of the materials. Steel and aluminium are assumed to be recycled. Glass from a demolition project often end up as landfill, as the recycling processes of window glass are both expensive and complicated [7]. Hence, here the disposal of glass is modelled as landfill. Wood is assumed to be incinerated while plastics and cardboard are disposed of through a combination of landfill and incineration processes.

Figure 2 depicts the temporal scope of the systems assessed. The skylight window is produced in year 0 (here 2018) and the panes replaced after 20 years (2038) in year 20, 70% of the pane packaging material is assumed to be used again. The disposal of the entire window (frame and window pane) takes place in year 40 (2058). The window has an estimated service-life of 40 years inducing an annual impact during the service-life, on top of the pane replacement, proportional to the additional heat consumption induced by the window.

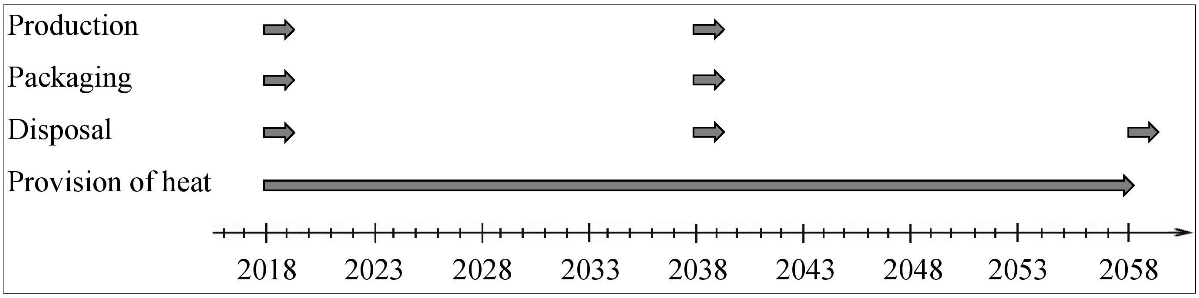

Figure 2: The temporal scope illustrates which years the processes occur. Short arrows indicate an intermittent process, whereas the long arrow indicates a continuous process taking place the entire service of the building in which the windows are installed.

The service-lives applied in our assessment of the windows and the panes are based on average estimation proposed by the Danish Building Research Institute's (SBi) and other industry stakeholders [8].

Our study assesses the service-life aggregated environmental performances expressed as climate burdens induced by installation of double and triple glazed skylight windows. The heat consumption, of the windows during their service-lives, is calculated as if the windows were installed in a newly built house, a renovation project and as if meeting the thermal reference requirements Eref. The provision of district heating (compensating for the heart loss induced by the windows) is modelled according to five different forecasts of the future energy grid. A total of 30 scenarios was hence analysed and are presented in Table 1. The 30 scenarios are split on 3 different "application contexts" of the windows defining the energy balance of the context in which the windows are installed:

- Window installation in a standard/common Danish one family house in the form of the socalled reference as presented by SBi (2018) [9] modelled as a newly built house according to BR18 for a low energy building.
- Window installation in a basic one family house from SBi modelled as a renovation project according to building regulations 1977 [10].
- Using the "raw" energy balance, E_{ref}, as an average window orientation specific energy balance for the window.

The life cycle inventory (LCI) data of the foreground system in terms of manufacturing were provided by the window manufacturing company. The background system was modelled using average processes in accordance with the ILCD recommendations [5]. All systems were modelled using the ecoinvent 3.4 database.

Table 1: The scenario overview shows the 30 scenarios assessed in our evaluation. An "x" indicates the included window type, calculation method and DHG scenario.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
2 layers of glass	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x															
3 layers of glass																x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Ref building: New build	x	x	x	x	x											x	x	x	x	x										
Ref building: Renovation						x	x	x	x	x											x	x	x	x	x					
Eref											x	x	x	x	x											x	x	x	x	x
Heat grid 1: Wind	x					x					x					x					x					x				
Heat grid 2: Biomass		x					x					x					x					x					x			
Heat grid 3: Bio+			x					x					x					x					x					x		
Heat grid 4: Hydrogen				x					x					x					x					x					x	
Heat grid 5: Fossil					x					x					x					x					x					x

Practical reasons made it necessary to assume that the technology for production and the handling of EoL would not change within the next 40 years, although this might not be temporally representative (at all – hence a partial dynamic assessment!). The new window pane, which is estimated to be installed after 20 years use of the window, will hence be produced applying the same technology as used today. It is considered out of scope for this project, to forecast such waste processing technology innovations. The thermal energy consumption across the use stage was modelled relying on forecasts. Our assessment is hence applying a dynamic perspective for the energy supply.

3. Results

The Global Warming Potential (GWPs) quantified for the LCAs of double and triple glazed skylight windows covers 30 different result sets. In order to organise the presentation of the results, two default scenarios were selected. The default scenarios include the energy composition grid 1 (i.e. wind, pls. see Table 1), while the calculation of the quantification heat consumption is based on the newly built reference house as presented by SBi (2018) [9].

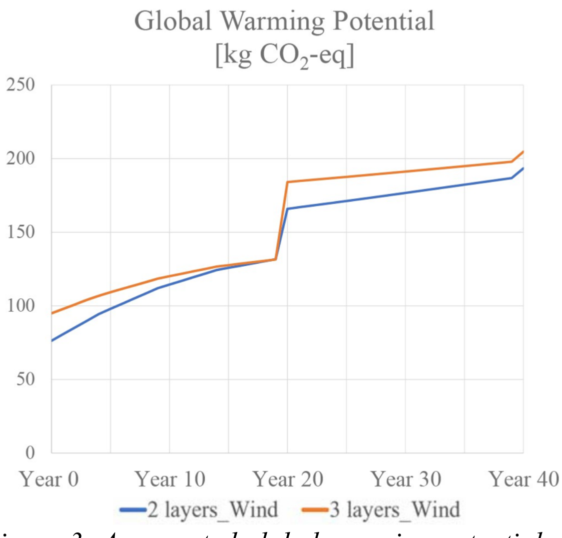

Figure 3: Aggregated global warming potentials, for scenarios 1 and 16. The scenarios are based on DHG 1 (pls. see Table 1), and the energy consumption is calculated for installation in the newly built reference house relying upon a dynamic energy supply.

Thus, scenario 1 for the double glazed window and scenario 16 for the triple glazed window are presented here in the paper (more result combination will be presented during the presentation at the conference), unless otherwise stated.

Further diversification of the results in accordance with Table 1, focusing on energy supplied by wind, biomass and hydrogen are presented and compared in Figure 4.

To assess whether the orientation of the windows will induce changes to the conclusions drawn in the study presented here, different window orientations were also tested and assessed. Double and triple glazed windows were (thermally) modelled as oriented south and north, respectively. The results were compared with the weighted orientation used in the remainder of this study.

Figure 4: Accumulated GWP of double and triple glazed skylight windows modelled in 3 different application situations new building, a renovation project and a reference scenario (i.e. raw energy balance of the window), 4 different energy supply scenarios; 2 layers=2 layered glass, 3 layers=3 layered glass, Wind=wind energy dominated scenario, Biomasse=biomass dominated energy scenario, Bio+=biomass+biogas and Brint=Hydrogen

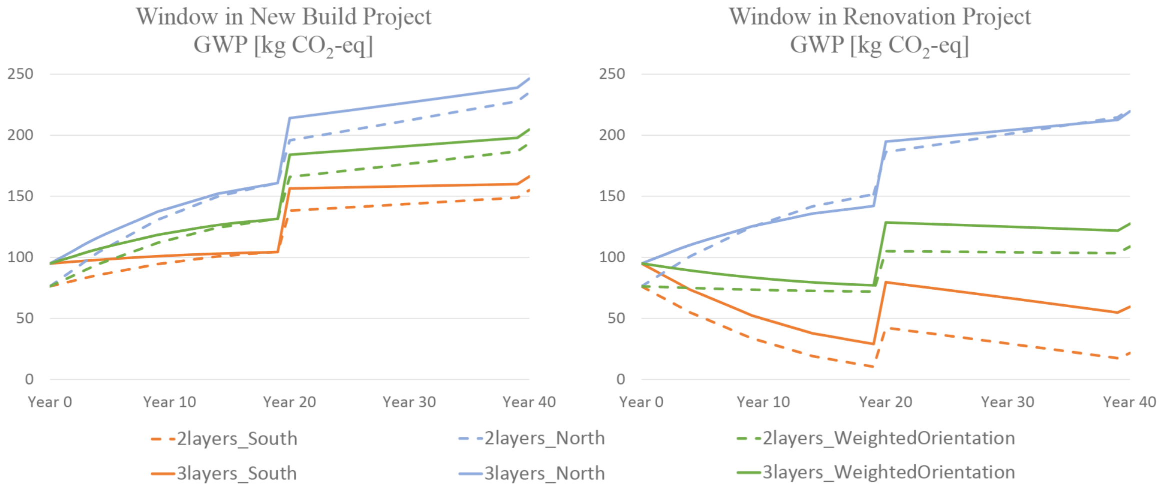

Figure 5: Accumulated GWP of north, south and weighted orientations when windows are applied in the reference house and assessed using a dynamic energy supply. Solid lines represent the 3 layered glass and dotted lines represent 2 layered glass .

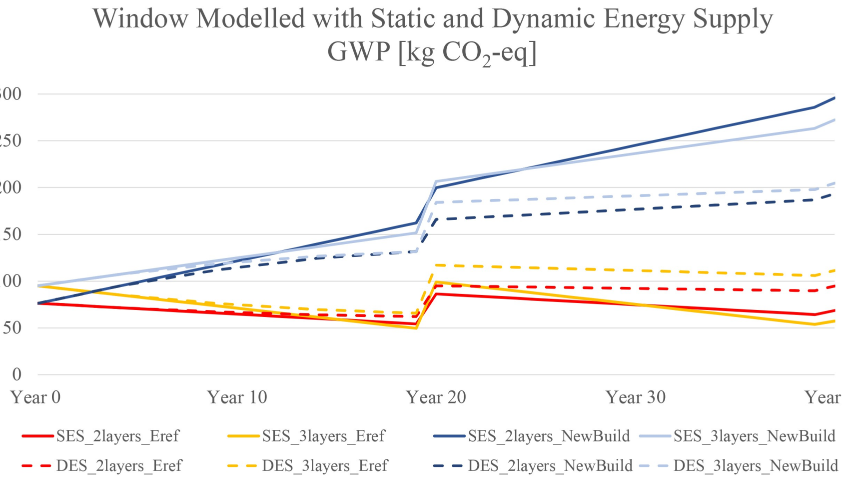

Figure 6: Accumulated GWP of double and triple glazed windows modelled with a dynamic energy supply (DES) and a static energy supply (SES). The colours illustrate the same window (i.e. the same application context and amount of glazing units) modelled with a static grid (solid lines) and a dynamic grid (dotted lines).

4. Discussion

For the application of a dynamic energy grid composition which is highly dependent on wind power, the results reveal that triple glazed windows in terms of GWP are performing inferior to double glazed windows as presented in Figure 3.

Figure 4 shows that the accumulated GWP of the double glazed window is lower compared to the triple glazed window independent of the various dynamic future energy supplies. Figure 4 also shows that the four fossil free scenarios for the future Danish energy grid composition induces similar impacts of comparable magnitude for the same window and applications.

The orientation analysis results as presented in Figure 5 does not deviate from the overall results: The orientation of the window does not change the fact that the GWP of triple glassed windows exceeds that of the double glassed windows if changes in the energy supply, compensating for the energy loss induced by the installation of the windows, is accounted for assuming a sustainable (which for a Danish context most likely will be wind power based) future thermal energy supply.

Results presented in Figure 5 on the time aggregated GWP of the double and triple glassed windows show that double layered glass performed better than triple layered independent of whether the windows are installed in a reference building representing the (recent) historical average building or in a new building complying with the Danish 2018 building requirements. On the other hand, Figure 6 shows the importance of using a dynamic approach instead of a static approach. Indeed, the best performing alternative, in terms of climate change, actually flips from triple layered to double layered when assessing the GWP performance of the two windows applying a dynamic approach.

5. Conclusion

Our results show that, when applying a dynamic energy grid, compensating for the heat loss across double and triple layered windows, and assessing the GWP of these two types of windows, reveals a consistent preference for double layered windows. Introducing a thermal energy provision from a temporally dependent source complying with the Danish energy policy, reveals a more complicated picture. Applying a dynamic energy supply reveals that that flip in preference observed yielding and overall preference for triple glazed windows does not occur if the assessment takes into account a greening of the energy supply. Generally the differences in GWP performance are so small that these are considered within the uncertainties of assessment form, meaning that the correct conclusion to the study is that: *by taking dynamic changes in the energy supply of buildings into account, it is illustrated that there is no (statistically significant) reason to choose triple glazed windows over double galzed if only considering GWP performance of the building and choosing triple glazed windows could yield GWP over-optimized buildings.*

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Perimeter blocks in different forms – aspects of daylight and view

Sundborg B[1,2], Szybinska Matusiak B[1], Arbab S[1]

[1]Faculty of Architecture and Design, Department of Architecture and Technology, Norwegian University of Science and Technology (NTNU), Trondheim, Norway. [2]Research Institutes of Sweden, RISE, Sweden

Bengt@dtark.se

Abstract. The perimeter blocks in cities are usually rectangular and follow the streets. The buildings are mostly of similar height within each block. However, perimeter blocks can be developed in many various forms. Geometric options such as chamfered corners, varied building heights and different positioned openings in a broken perimeter block are analyzed in this paper regarding the aspects of views and daylight in city planning. The choice of evaluation criteria is based on scientific discourse in the field of daylighting. As in the new European standard, "Daylight in Buildings", the following three parameters are included in calculations: solar radiation, daylight level and view out. Computer-based daylighting simulations and calculations of view parameters are performed for different designs of the perimeter blocks with equal density, FAR = 1.33. The simulations have been carried out for Stockholm. That means roughly the same shadows as in Oslo, Helsinki, Tallinn, St Petersburg and Anchorage, all close to the same latitude (60°N). In lower latitudes, e.g. Southern and Central Europe the shadows are shorter. Nevertheless, the ranking of the alternatives will be similar. This study confirms that geometrical changes can improve the conditions for views and daylight in the perimeter blocks. The advantages in the tested urban design alternatives are considerable compared to the perimeter block of the standard type.

1. Introduction

Many different aspects shall be considered in the design of buildings. The famous old principle: "Form Follows Function" is important and has great relevance also in the construction of modern sustainable settlements.

However, in the pursuit of densification and economical optimization, the issues of views and daylight are missing in many projects. Those aspects are strongly dependent on the shape of buildings and their close surroundings. This study aims to show how the shapes of urban blocks can be developed to improve the daylight access and the views in urban settlements. The improved quality of daylight and view in the studied alternatives can be reached with the same density Floor Area Ratio (FAR) as for the conventional alternatives. The density is here defined as FAR, Floor Area Ratio = total floor area/plot area. A constant value of 1.33 has been chosen where the entire plot has been enclosed by 10 meters of street, which means a total area of 80 x 120 meters (1,33 corresponds to 2,13 counted on only the built plot of 60 x 100 meters). A Floor Area Ratio (FAR) of 1,33 is a relative low value for central districts but high in a suburban context.

In an economical assessment, based on prices on the market, the improvements in daylight should be weighed against the added cost for the improved building shape. Potential savings in energy consumption for the electric light must be calculated as well as other relevant values in the total economical overview.

2. The Alternative Types of Perimeter Blocks

The book Urban Forms [1] describes the development of the urban block from the middle of the nineteenth hundred until now with many influential European examples and even some American new urbanist projects. The book raises questions how we can keep qualities from the old town districts in our contemporary developments. The French-British quartet of authors advise a detailed look at existing settlements considering their morphology including the scale, the streets and the shape of the buildings. Inspired by this book we examine some very typical urban layouts focusing at daylight and views.

An extensive investigation of the heat energy demand including the daylight aspect was done in 2014 with comparison of many different city districts in Berlin, Paris, London and Istanbul [2]. The approach in this study is different; we consider only a few simplified configurations to quantify and explain the impact of the specific shapes. An important study by Mark DeKay describes how the different geometry of a standard atrium building impacts daylighting conditions [3]. Atrium buildings are often erected as perimeter blocks and DeKay touches on certain variations. We aim at extending the knowledge with research on some more shapes. International comparisons over rectangular street grids show large variation from town to town. Some have quadratic shapes but most of the grids have rectangular shapes with considerably different dimensions (length vs width of the block). The variation of the street grids within a town is smaller. The usual regulations for the urban blocks within a specific city district contain standardised measures of length and width.

This study looks to possible alternative regarding the shape to the conventional perimeter blocks in street grids. Following sustainable design recommendation, the blocks are oriented east-west. Different compass directions will be investigated in future research. Larger urban blocks have the advantage of being able to contain more complicated structures of buildings. Such blocks also create long facades, which is a disadvantage regarding uniformity and has been pointed out by urban theorists as e.g. architect Rob Krier. The assumed size of the blocks has dimensions which are easy to analyse; 100 meter in east-west direction and 60 meter in north-south direction. The scale is representative for the Nordic countries as well as the rest of Europe though the average size of blocks is larger.

The famous study of different built forms by Martin and March had three alternatives: (a) 'pavilions', (b) 'streets', and (c) 'courts' [4]. The third alternative consists of perimeter blocks. In this study differences between several alternatives of perimeter blocks are examined. We look more in detail to the town planning than common in urban studies. The first alternative to the standard perimeter block is the same block with chamfered corners, a modification which is often used. The most famous example is the large extension of the old city during the nineteen hundred in Barcelona. Chamfered, instead of right-angled corners in the court yard have been used from time to time world-wide. The sizes of the chamfered corners in this study are based on functional aspects regarding the windows and following the principle of keeping the same floor area ratio as in the standard block. This principle is true in all alternatives.

Other options to develop the block are openings between the streets and the courtyard. The experience of the neighbourhood depends on how the openings are positioned, i.e. in the corners of the block or in the middle of the blocks. In frequent practical use these two types vary both in proportions and in scale. This study explains the experiencers in physical figures on daylight and sightlines. The two last alternatives with variated heights, 4 and 5, are developed within this project in an attempt to find new strategies. All alternatives have been developed in Sketch Up-drawing, see figure 1.

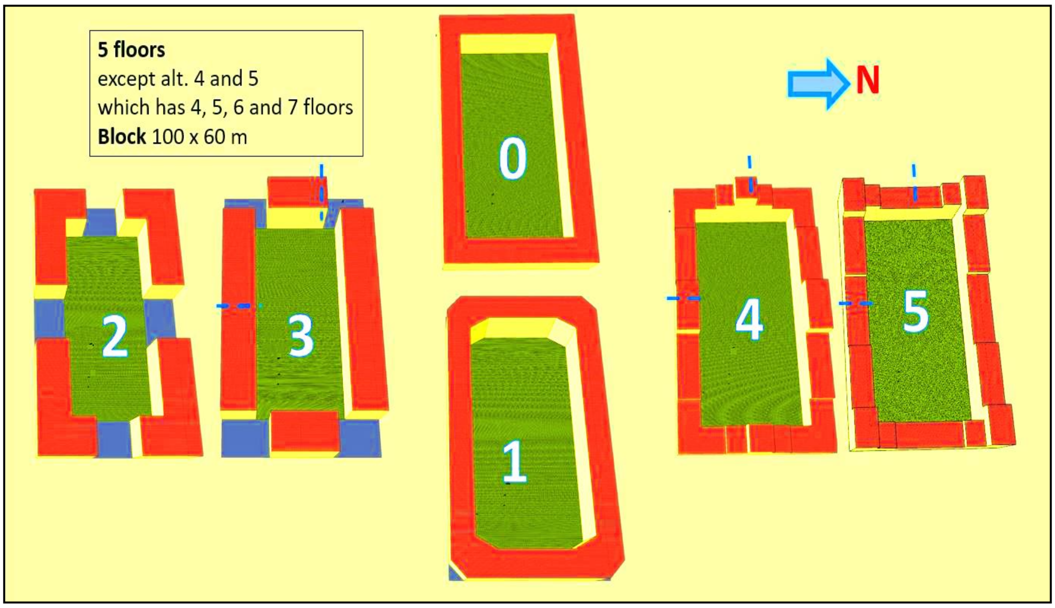


Figure 1. The six different types of urban blocks.

0. The conventional perimeter block (NULL) 0 is followed by five alternatives:
1. Chamfered corners in the outer corners of the building as well as in the courtyard.
2. Openings in a broken perimeter block positioned in the four midpoints of the building.
3. Openings in a broken perimeter block positioned in the four corners of the building.
4. Varied building heights around the courtyard with fewer floors in the corners of the block.
5. Varied building heights around the courtyard with more floors in the corners.

3. Daylighting Strategies in Urban Settlements

It is impossible to create satisfactory daylighting conditions during the whole day in dense settlements. It is always necessary to resolve the priorities between outdoor and indoor spaces as well as which parts of the day and the year. Especially difficult to handle is the sunlight at high altitudes due to the large variation of the azimuth angle (compass direction) during the day and across the seasons, as well as low average solar elevation angles through the year.

To develop strategies for daylight requires a focus on the different times of the day. In people's every-day life the needs and desires vary depending on the type of buildings such as buildings for seniors, offices or kindergartens as well as the activity. A midwinter strategy leads to openings between the buildings in a North/South direction which is opposite to a strategy for the extended summer when the sunlight from east in the morning and west in the evening is highly appreciated. We have many possibilities to formulate goals and evaluation criteria connected to them, and it is easy to calculate many relevant metrics by computers. However, joining strategies together (e.g. making calculations on the yearly basis) often fails because the iterations will converge instead of diverge.

During many years' equinox studies have been very popular among practitioners as well as researchers. But the equinoxes are not suitable to analyze sunlight from east or west simply because in those two days the sun is positioned precisely at the east or west during sunrise or sunset, also it is on the horizon. That gives strong arguments for studies between equinox and summer solstice. The classic Bioclimatic Chart is still relevant, it describes the limits for human outdoor comfort depending on temperature, humidity, air movement and solar radiation [5]. The outdoor temperature in most Nordic cities is not high enough to create comfort (temp. > 20o happens only occasionally) - compare the Chart with climate data as https://climatecharts.net/. Nevertheless, in the cities along the Oslo/Stockholm/Helsinki latitude, the period around May 1st is the time when people start to sit outdoors thanks to the direct sunshine, example on the Nordic climate see figure 2. To improve human comfort by developing spaces with much sunshine/heat, sunlight strategies should be accurately tested. This study is intended to contribute to this development.

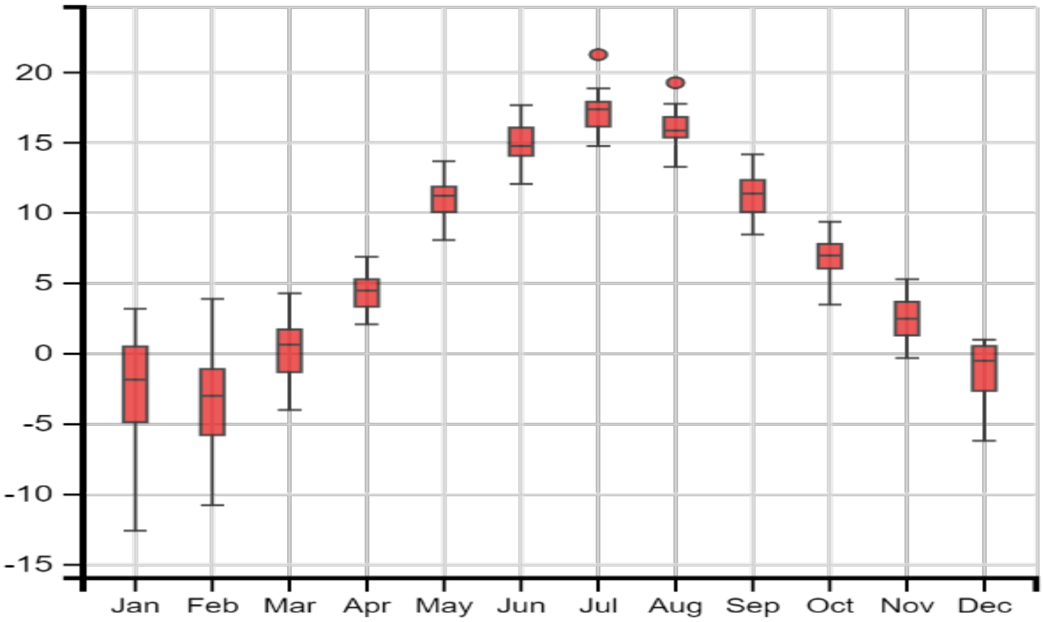


Figure 2. Distribution of monthly mean temperature (C°) Stockholm, Sweden. (data:www.ncdc.noaa.gov/ghcnm/ distribution, © www.climatecharts.net)

3.1 The Shadow Maps

Shadow Maps are important tools in town planning. The shadows from surrounding obstructions as mountains, trees and buildings affect the conditions at the outdoor spaces as well as in apartments. Most of the obstructions are permanent. The shape, size, orientation and position of the building must therefore be developed during careful considerations. The shadow map also specifies surfaces on ground and facades which have sunlight qualities outdoors and indoors. That information can be used by planners to create daylight qualities for the residents.

The comfort zone for sitting outdoors in the sunshine on the balconies and in the courtyards can also expand by windscreens in cold days and by sunscreens in hot days. The needs of daylight vary, both in quantity and quality, between different groups of people and even between individuals. Anyway, we may roughly agree that in residential areas interesting periods to study are in the morning and in the evening because almost all residents are at home, contrary to during noon when people are at work, schools and on weekend trips, etc. This is also the most difficult time for daylighting due to lower sun angles than at noon. Besides the shadow maps for the western sun (representing even the eastern sun in the morning) we also show the less critical shorter shadows in the middle of the day. The western sun represents also the eastern sun in the morning because the shadows are the same although mirrored in the opposite direction.

All the blocks in the study are orientated in east-west direction. The position of the sun is in the west in the shadow patterns at the top, in the other six in the south, see figure 3. Depending on the clockwise movement of the sun the shadows also move. The minutes just before and just after the exact cardinal directions for the sun are especially interesting. All the facades orientated to the south can be in sunshine at 18:07 PM but on the contrary at 18:08 PM the facades orientated to the north are in sunshine (Stockholm, Latitude 59.3, 1st of May, DST = Daylight Saving Time). The shadows for the 1st of May also describe the conditions at the 11th of August. During the 101 days in between the sunlight distribution is better with a maximum at summer solstice.

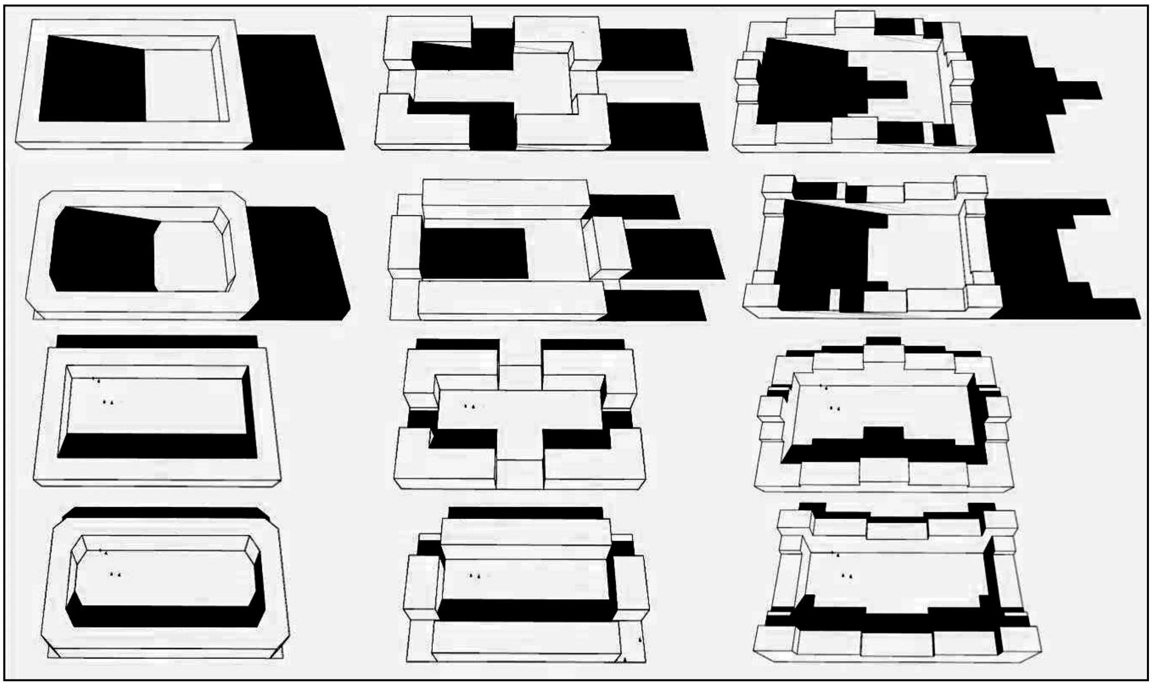


Figure 3. Shadows the 1st of May. Latitude 59,3. The six evening patterns at the top has sun in the west, the six lower patterns are at noon and has sun in the south.

The alternative with its chamfered corners (alt. 1) has very similar shadow patterns as the conventional perimeter block (alt. 0). Both alternatives have advantages. The best in the alternative 1 is the orientation of the windows in the chamfered corners. They result in more diffuse daylight and longer sightlines see table 1 and 2. Considering openings to the courtyard, it is better with the openings in the corners of the block (alt. 3) than in the middle (alt. 2) regarding the facades and its windows. The alternative with lower heights in the corners (alt. 4) has better daylight condition on the windows than the conventional perimeter block with five floors all around. In the alternative with higher heights in the corners (alt. 5) the advantage is a sunny spot in the middle of the courtyard.

4. Assumption of the facades as representative for the windows

The generated data is for the facades except for the ground values. Solar radiation on facades and daylight level on facades are values in our studies to describe conditions at the windows. We assumed that the windows are evenly distributed along the facades. This assumption is common in general studies as ours because no special details or local conditions are known.

5. The Daylight simulations

The methodology of the daylight simulations is based on the scientific discourse in the field of daylighting with origin from an early European collaboration [6] and recently formulated in the EU standard [7]. Each alternative of settlement has been analyzed in a cluster of 3 x 3 blocks, all the same type. The daylight conditions in the six alternatives are described in the following way:

- Sunlight radiation on façades and on plots, average values, during the 1st of May from sunrise to sunset (kWh/m^2).
- Sunlight radiation on the first floor of all facades, average values.
- Vertical Sky Component on the first floor of all façades (VSC), average values. 50% is the maximum value.
- Sky Component on the plot area (SC), average across the plot; 100% is the maximum value including visual access to the whole hemisphere.

The facades on the upper floors have good distribution of sunlight in all alternatives. The challenge is to create good daylight even for the worst cases, that is the first floors. Therefore, we have separate calculations for the first floors regarding both radiations and vertical sky component.

All the simulations are performed with DIVA for Rhino, a well-recognized tool for climate based and static daylighting calculations. The DIVA (Design, Iterate, Validate and Adapt). A plug-in for Rhinoceros software, enables effective calculations of daylight metrics, e.g. daylight factor, using the Radiance/Daysim engine. The climate data for Stockholm was used as well as its geographical location. By keeping the reflection factor of the block surfaces and the ground close to zero (0,01%) the daylight factor script in DIVA was used to calculate SC and VSC.

Table 1. Results of the Daylight Simulations

Model	**Radiation, first floor** (kWh/m2)	**Radiation, façade** (kWh/m2)	**Radiation, courtyard** (kWh/m2)	**VSC, 1st floor** (%)	**SC, courtyard** (%)
Alt. 0	**2.41**	**2.72**	**3.42**	**34.40**	**70.91**
Alt. 1	**2.47**	**2.77**	**3.41**	**35.28**	**69.98**
Alt. 2	**2.45**	**2.75**	**3.65**	**35.28**	**73.17**
Alt. 3	**2.47**	**2.78**	**3.07**	**35.35**	**65.73**
Alt. 4	**2.32**	**2.73**	**3.32**	**33.85**	**69.54**
Alt. 5	**2.33**	**2.72**	**3.55**	**33.70**	**72.39**

The following observations may be done based on the simulation results. With chamfered corners (alt 1) the solar radiation on the facades and the vertical sky component are higher compared to the alternative conventional perimeter block (alt 0). Regarding the courtyard the result are the opposite, higher for the conventional perimeter block (alt 0) due to slightly lower obstruction angles.

With openings to the courtyard (alt 2 and 3) the solar radiation on the facades and the vertical sky component are both higher compared to the alternative conventional perimeter block (alt 0). Regarding the courtyard the result is the highest for openings to the courtyard in the middle (alt 2) and the lowest for openings in the corners (alt 3).

With the same height of all parts of the building (alt 0) the solar radiation on the facades are almost the same compared to the alternatives with varied heights (alt 4, 5) except for the first floor where it is higher. The shadows are slightly smaller along the facades with lower heights in the corners of the block (alt 4) and slightly smaller in the courtyard with higher heights in the corners of the block (alt 5). Further studies are needed to explain all results regarding variations of the height.

6. The Views in the Urban Areas

The quality of views in the outdoor environment depends on people's visual experience. Qualitative details such as beautiful streets with well-designed outdoor furniture and decorative façades are important elements of the visual perception. A good example on opinions and desires about the view from a window is a study at an office from 2015 [8]. Beautiful distant views were not highly ranked as expected which show how important it is to investigate the actual specific situation because human perception is complex. Town planners must exploit opportunities relying on development of the architectural details of high quality. Anyhow, the length of the sightlines is regarded as the positive contributor of the view quality and is reviewed in this research. It may give a basis for the layouts of attractive views.

6.1 The View Calculations

The views in the six settlements of different urban blocks have been compared. That means that the distances of the horizontal sightlines from each window were calculated regarding the obstructing surrounding buildings using the Grasshopper software. All distances are in meters. Two types of distances have been calculated for each window:

1. Average distance to obstructing facades.
2. Perpendicular distance to obstructing facades.

Then the averages from all windows for the whole block have been processed for both values. All distances to the obstructing facades in the surrounding buildings are measured within a 138-degree cone except for the perpendicular distances. The cone represents the average visibility from a window considering the reduction caused by the obstructions in the window frame. In an earlier study about Tower Blocks we calculated that angle [9].

Limitations and assumptions for the calculations of the alternatives (see figure 1) are:

• For the first four block alternatives, model 0-3, all facades have been analyzed in 2D regarding maximum free view, minimal free view, perpendicular view and average free view (m) for one floor (all five floors have the same conditions). For options 4 and 5, all facades have been analyzed in 2D regarding maximum free view, minimal free view, perpendicular view and average free view (m) for all seven floors.

• Each block structure has been analyzed in a cluster of 25 x 25 blocks where the center block refers to the block on which the measurements were made. Each quarter's façade has been served with measuring points at ~ 2 meters intervals and all facades have been analyzed. Each measuring point has 416 (1080 for 360 degrees) range measurements in the 138-degree cone.

• All analyzes of the view have taken place in 2D along the horizontal plane. Max length for free view is set to 1000 m. 90% of the length of the façade has been analyzed, so as not to create measurement points directly adjacent to the building's corners.

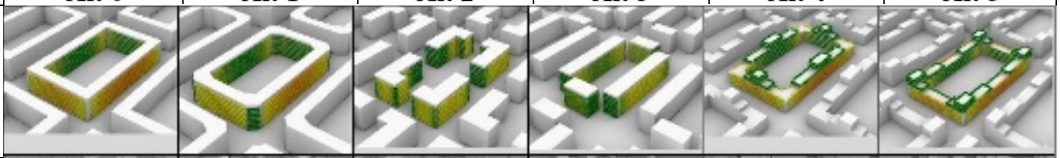
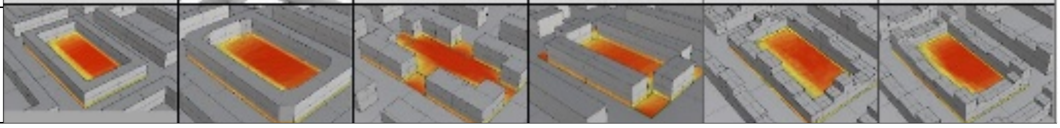
Table 2. Results of the View Simulations

Model	**138° width obstruction distance,** average (m)	**Perpendicular obstruction distance,** average (m)
Alt. 0	**36.56**	**35.67**
Alt. 1	**39.24**	**37.23**
Alt. 2	**41.13**	**26.78**
Alt. 3	**43.98**	**36.47**
Alt. 4	**55.68**	**39.61**
Alt. 5	**55.01**	**35.41**

In the case of a closed perimeter block it is better for the views to develop chamfered corners (1 better than 0). In addition, when building a closed perimeter block it is also better for the views to develop a variation in heights (4 and 5 is better than 0) because it offers long sightlines. In the case of a perimeter block with openings, the openings in the corners give longer views. (3 is better than 2). The average distances to the opposite façade are illustrated by colours in table 3 in the first row. The steps are from the EU standard, the chapter for view recommendations:

EU standard: 6 m ≤ **Minimum,** RED < 20 m ≤ **Medium,** YELLOW < 50 m ≤ **High,** GREEN

Table 3. Perspectives of obstruction distances and solar radiation.

Model	Alt 0	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5
138 Width obstruction distance, average (m)						
Solar Radiation, (kWh/m2)						

7. Conclusions

The research shows advantages regarding views and daylight for most alternatives compared to the conventional perimeter blocks. It is quite understandable that openings to the courtyards are effective but the choice between openings in the corners or in the middle of the block depends on the local urban context and actual preferences. If it is the view from the windows and the daylight indoors together with the conditions along the facades which really matters, the first choice is therefore openings in the corners. If there are some conditions in the central part of the courtyard which are important, then the best choice is openings in the middle of the block.

The chamfered corners of the building in the courtyard and in the crossings increases the daylight on the facades compared to the conventional rectangular perimeter block even if the changes are relatively small. The average views are the best in the alternatives with varied height, 4 and 5.

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Lifecycle analysis of finishing products enhanced with phase changing materials

Petr Zhuk[1]

[1]Architectural Science of Materials Department, Moscow Institute of Architecture (State Academy), Rozhdestvenka street 11, Moscow 107031, Russia

peter_05@bk.ru

Abstract. Applicability of phase changing materials (PCMs) in buildings by their integration into the structure of finishing materials structure in the form of particles is especially high as a mean of providing heat-insulation during summer. Materials containing particles with phase changing behaviour are successfully applied at objects with large daylight areas, focused on active utilization of sunlight energy, among others. Utilization of PCM components allows saving considerable amount of energy due to possible refusal of air-conditioning while providing heat-insulation during summer.

The paper deals with the lifecycle analysis of gypsum-based finishing products. Main challenges with respect to the lifecycle of products with PCM components are the preservation of their longevity as well as their potential for reuse/ recycling. Through the example of PCM-enhanced plaster covering and gypsum plasterboard factors affecting the preservation of the advantageous thermal properties of PCMs over extended periods were studied, along with options of refining materials and products containing different amounts of PCM components.

The results of the research allow comparing similar materials with the use of PCM components and without them as well as analyzing the life cycle related environmental performance of PCM-enhanced finishing materials.

Introduction

Thermal insulation during summer is an important aspect of energy-efficiency provisioning in buildings for different functions. It can contribute to both primary energy savings and greenhouse gas emissions reductions, along with an improvement of the thermal comfort. On the economy side, not only energy costs can be reduced, but also investment costs for cooling/air conditioning systems can be reduced or entirely avoided.

One way of providing latent heat insulation is utilization of particles with phase-changing components in finishing materials. In this case excessive solar radiation energy is directed to support phase changing within those materials. It is reasonable to compare the effect of construction materials with phase-changing components utilization with that of building conditioning system utilization. This allows energy saving and achieving better level of thermal comfort during cooling period due to refusal of climate control equipment utilization. Climate control equipment is energy-expensive and requires scheduled change of filters, which can accumulate pathogenic flora. At the same time, different phase-changing components can be used in different construction materials, from concrete slabs [1], heat insulation based on cellulosic fibers [2, 3], gypsum boards to finishing materials such as plasters and paints.

An analysis of the lifecycle environmental impact of all of the above-mentioned materials was performed. Introducing phase-changing components somewhat influences material's lifecycle and, therefore, a problem of comparing similar finishing materials' (both with and without PCM) impact during their lifecycle becomes current. As an example of such materials, gypsum boards and gypsum binder based plaster coverings were chosen.

1. Methods

One of the most important lifecycle aspects in current research is Phase Changing Materials (PCM) operating longevity as components of finishing materials. To assess the longevity, methods harmonized with the Quality Assurance RAL-GZ 896 were used [4]. Results of the research according to this paper suggest defining a number of successfully completed cycles, rating by indicator of cyclic stability as well as data on possible damage situations. During the test it is necessary to exercise control over PCM's functional criteria such as the range of phase-changing temperature and the amount of saved thermal energy. Under the RAL-GZ 896 requirements, definitions of these criteria are made at the start and at the end of the test. During the current research, criteria definition was performed no less than three times, which was necessary to clarify dynamics of PCM's properties change. Changes of samples' mass and thermal conductivity depend on testing samples' size and do not describe properties of a material as a whole. Samples of gypsum plasters and gypsum boards parts with size 20 x 20 cm were tested. Paraffins were used as PCM. Injection of paraffins was performed in two ways: (1) drenching through material's surface and (2) incorporating into finishing materials' structure in the form of microcapsules with diameter from 5 to 10 μm. High-endurance polymeric capsule was used as a shell, which, along with granule size, provides component's stability against different mechanical impacts. Paraffin has the following properties as a PCM: F_p around 25 ^{0}C, ΔH=110 J/g, which substantially corresponds to products under Micronal® trademark. Above-described material's parameters allow reaching maximum environmental thermal energy saving in amount around 110 kJ/kg of material. Under such parameters PCM accumulates excessive environmental thermal energy when its temperature becomes higher than 25 ^{0}C [5]. Incorporation of microcapsules was performed in two ways: (1) through microcapsules' dispersion in tempering water as well as (2) in form of powdered substance, which is mixed with binding agent in form of dry plaster mortar. The amount of granule particles incorporated was similar for both materials. This amount was 3 kg per square meter of finishing's surface. Finally, the lifecycle was defined and analyzed for different production specifications of finishing materials.

As far as the lifecycle analysis is concerned, it was performed using well-recognized methods. In particular, such methods and indicators as CML, Cumulative energy demand, Eco-indicator-99, Ecological footprint, Oekoindex OI3 [6] were analyzed and discussed. For simplicity and due to a limited number of indicators, Oekoindex OI3 method was chosen. The main indicators chosen for conducting an environmental impact assessment during lifecycle were primary energy consumption, global warming potential and acidification. These three criteria are taken into account during the complex Oekoindex OI3 calculation [7].

The important stage during the lifecycle of finishing materials with PCM is the materials' recycling stage at the end of their service life. Different ways of separation gypsum base and paraffin-containing components were considered. The main method being considered was a method of components' separation using moisture. Thermal processing methods proved inefficient due to PCM damage under high temperatures.

2. Results

During materials' functionality testing with regard to heat-insulation during summer, cycling stability was defined. Under this indicator, testing materials corresponded to different classes according to the RAL-GZ 896. In particular, materials with drenching (both plaster mortars and gypsum boards) failed to reach even F-class (from 50 cycles). This was caused by shallow invasion of PCM, wherein plaster mortars survived less temperature load cycles without losing their properties (less than 15), gypsum board samples demonstrated the result of around 20 cycles. Incorporation of PCM granule in form of dispersion or powdered substance showed good results in cycling stability (A-class, more than 10.000 cycles). Testing results are shown in Table 1.

Table 1. Results of cycling stability testing of finishing materials

Name of material with PCM components	Result of test for PCM incorporation as a powder, number of cycles	Result of test for PCM incorporation as a dispersion, number of cycles
Gypsum-based plaster		
Sample 1	12.450	9.500
Sample 2	14.250	7.450
Sample 3	15.150	5.450
Sample 4	20.050	5.500
Sample 5	18.450	8.150
Gypsum board fragment		
Sample 1	22.450	10.650
Sample 2	27.550	12.450
Sample 3	25.350	11.350
Sample 4	23.150	10.600
Sample 5	21.000	11.450

Results shown in Table 1 demonstrate that gypsum board slabs and plaster mortars (with PCM incorporation as a powder) belong to A-class in cycling stability (> 10.000 cycles), while plaster mortars with PCM incorporation as a dispersion belong to B-class (> 5.000 cycles). The cause of low class for this materials group lies in irregularity of PCM components' distribution within the material, including excessive granule proximity to surface. Tests were performed until the loss of ability to consume excessive thermal energy, with a step after every 50 cycles. Supposing that during internal utilization of PCM-containing finishing materials up to 300 phase changings per year can occur (which is approximately 1 changing a day), 10.000 (A-class) provide more than 30 years duration of minimal service life for a PCM-containing material [5]. Plasters with PCM incorporated as dispersion have slightly shorter working life. But working life of such materials with PCM is purely comparable to that of the finishing material itself. Researches show that sometimes results for products (plaster mortars with PCM incorporation as dispersion) slightly differ from results for PCM granule, which is somewhat inconsistent with the RAL-GZ 896 data.

Cycling stability testing results are important for lifecycle analysis because they define, to a great extent, the length of the operation stage. Let's consider production (which in this case will include raw materials preparation), operation and recycling as main stages of the finishing materials' lifecycle. The following discussion will begin from the production stage.

PCM dispersion in tempering water directly during plaster or gypsum board production as well as powder produced by drying this dispersion and added in dry mixes, which are stored in sacks or silos depending on required quantity, can be used in production. Production scheme of dry mix for plaster being researched is shown in Figure 1.

During the production stage energy expenditure for paraffin and granule with PCM should be taken into account. In case of PCM incorporation in form of powder costs of drying under diffusion of dispersion for powder production should be taken into account. In case of PCM incorporation with tempering water as a result of mixing it is impossible to achieve desirable longevity of working life, despite that from the energy capacity point of view this process is less expensive, it is hard to achieve homogeneity in distribution of granule along the gypsum board product or within plaster coating.

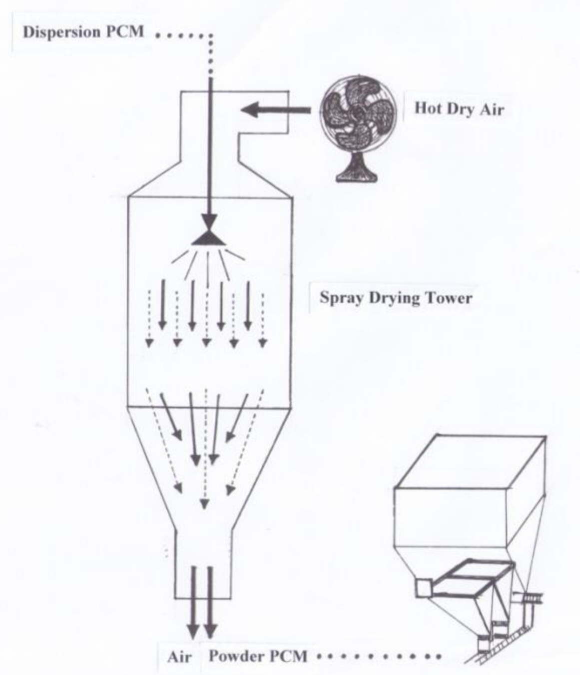

Figure 1. Production scheme for plaster with PCM in form of powder

The assessment results on the basis of the considered indicators for plaster and gypsum board slabs with PCM and without are not a far cry from each other. This proves the efficiency of using PCM components for achieving a passive heat-insulation effect at the material operation stage.

The service life, related to effect of using excessive thermal energy in a room for phase change in granule is different for different finishing materials. Service life depends on a way of granule incorporation into finishing material as well as room composition, window frames size and glaring, environmental conditions of building location, among others. Generally speaking, considerable effect can be achieved during the operation stage by means of rooms' temperature equalization at comfort level, which makes savings on energy cost of climate control equipment possible. Comfortable microclimate can be achieved for certain temperatures without overheating. Furthermore, heat accumulation can be achieved through a certain level of thermal mass or with help of PCM [8, 9 and 10]. Also, paraffin reaction is instant while mass of constructions reacts slowly. Due to PCM components the following phenomenon occurs: an instant significant excessive energy draw-off, PCM concentration close to surfaces of walls and slabs, fast release of energy remains as a result of ventilation. Calculation of microclimate improvement and gain in economic feasibility can be performed with the help of specialized software and programming tools by designing and modeling for certain conditions (for instance, PCM express programs by [5]).

At the final stage it is important to perform a separation of mineral constituent and paraffin granule. In order to do this thermal or moisture related methods can be used. Experience has shown that utilization of thermal methods leads to disturbance of PCM properties related to phase-changing capabilities. Although moisture utilizing methods turn out to be more energy-consuming (even compared to process of recycling finishing materials without PCM), they allow a more thorough recycling. As a result, there are the following indicators of energy consumption and impacts related to global warming potential and acidification (Figure 2). The assumptions and data bases are described below.

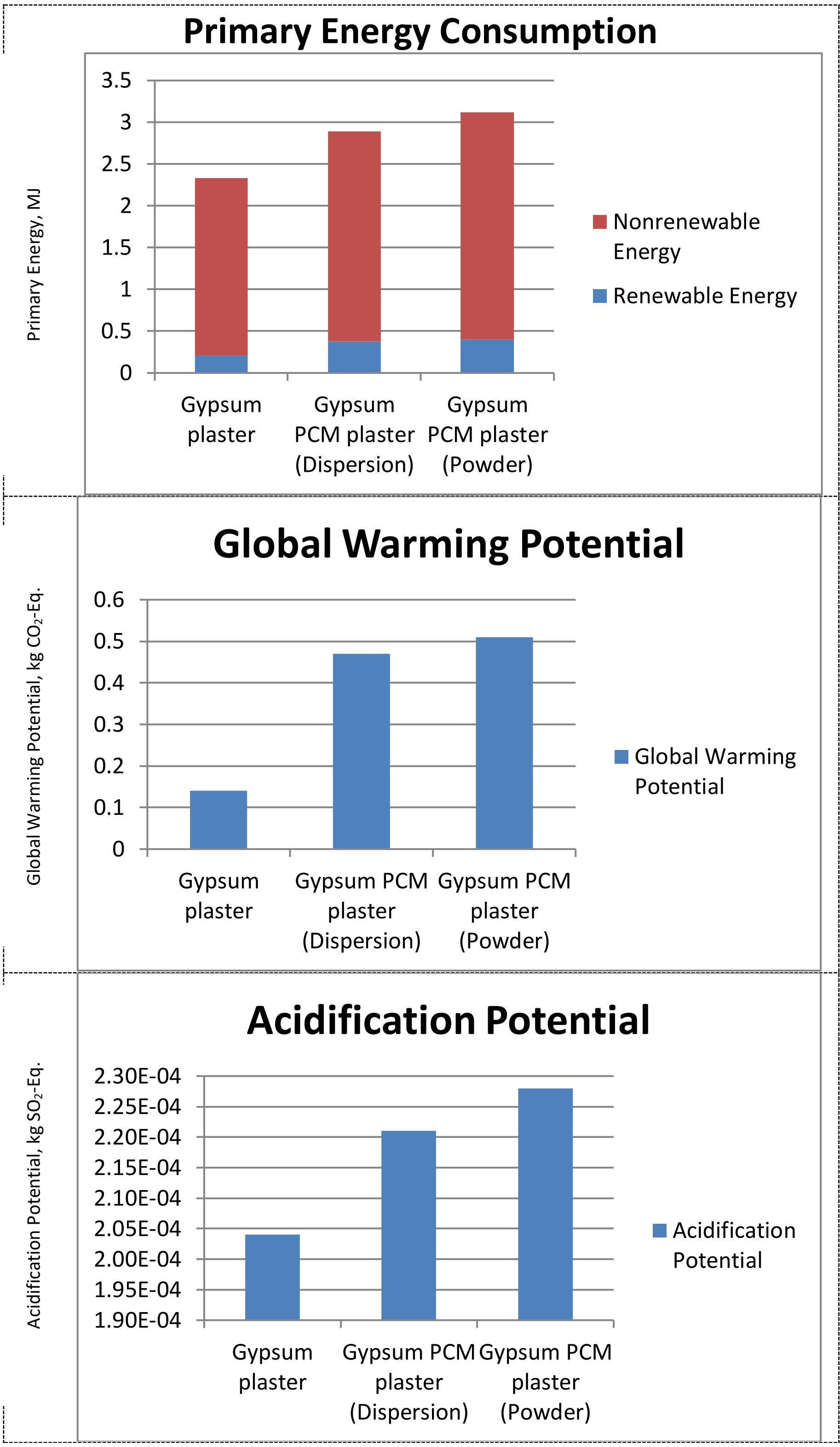

Figure 2. Comparison of three types of plaster based on three environmental indicators. Note: All figures represent the production stage only and are expressed per kg of material

Primary energy consumption during the lifecycle of different technological options is normalized per functional unit, which in case of plaster is 1 kg. Energy consumption during the operation stage was calculated using eco2soft method, developed by the IBO Austrian Institute for Healthy and Ecological Building [7]. Calculations were performed for the lifecycle with the postulated gypsum plasterboard service life of 30 years during operation in Central Europe climate conditions taking into account production and recycling stages. Due to lack of EPD for PCM containing materials a correlation of data received under the given research with the EPD data for similar materials without PCM (in particular, for gypsum plaster) [11, 12].

Taking into account energy saving during the operation stage due to reduction/avoidance of air conditioning energy consumption, which amounted around 100 kWh per annum for a testing room on under roof floor of free-standing residential building (area of surfaces finished with gypsum plaster with PCM was equal to 70 m^2), total energy consumption by lifecycle stages are displayed at the Figure 3.

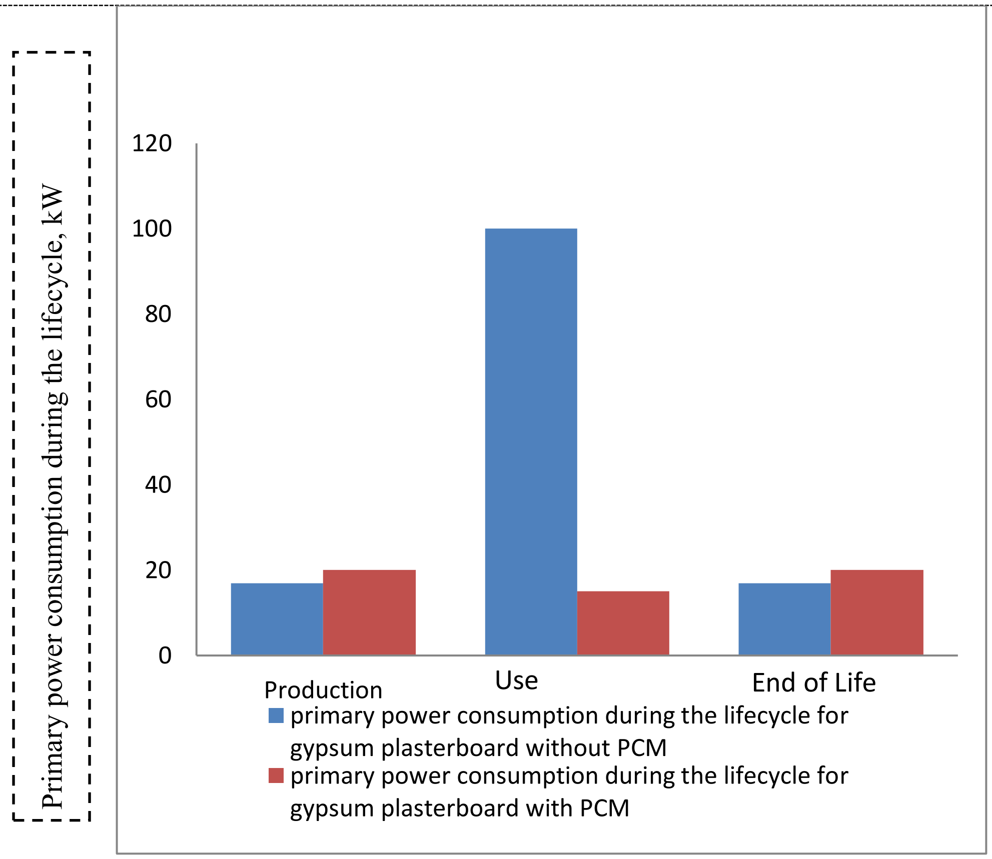

Figure 3. Comparison of primary energy consumption per life cycle stage for gypsum plasterboard with and without PCM

The information presented at the Figure 3 state that saving in energy consumption at the material's operation stage greatly surpasses slightly more high energy consumption rates at production and lifecycle end stages, related to granule with PCM production, incorporation and distribution within plaster structure and problems of components separation during recycling of served-out material. Figure 3 shows the scale of energy consumption that occurs during the lifecycle stages of the plaster, i.e. production, operation and end of life. In addition, it was taken into account that during the operation stage climate control equipment in rooms with the use of PCM can be waived. The figure 3 is a qualitative display of comparative power consumption scales during materials' lifecycles and can be interpreted in such a way that slight increase of expenditures during materials' production and recycling stages a significant effect at the operation stage can be achieved.

A principle, similar to the one used in assessment of B1 (utilization), B2 (maintenance, cleaning) and B6 (power consumption requirement) stages in Environmental Product Declaration (EPD), was used for comparison of primary power consumption values during the lifecycle. Calculation of conditioning costs using simple plaster (without PCM) resulted in approximately 1,5 kW for plastered surface of 67 m^2 [5]. Also the data on plaster consumption for a square meter in kilograms (including the amount of injected PCM) and acceptable original plaster life duration (which is 15-20 years for interior plastering) is known. Therefore, it is possible to make a comparison by functional unit of proceeded surface (1 m^2) or by unit of dry plaster with known consumption (in kilograms). Not only primary power consumption is important for the purpose of accurate comparison, but also other environmental indexes as well as economic and social effects which were not considered in the given research. However, literature sources provide interesting data on these indexes. In particular, CO_2 emission index, calculated through primary power consumption for conditioning of building with gross floor area of 5902 m^2, accounts for more than 100 tons per year [5]. Data on plaster with PCM depreciation life gives indexes ranged from 2 to 5 years, depending on building type, enveloping structures, environmental and other conditions. Based on this data, experts calculate general economic effects occurring on replacement conditioning systems with plaster or other finishing materials modified with PCM.

3. Discussion

Indicator results of environmental impact during the full lifecycle of finishing materials with the use of PCM are generally comparable to indicator results of similar materials without these components [11, 12]. This proves the insignificant environmental impact of PCM production and operation.

Increase of environmental impact can be observed during raw materials preparation (PCM granule production), production of finishing materials with the use of PC components and at the stage of recycling at the end of their operating life. Separation of mineral constituent and granule with organic components provides for higher level of finishing material components recycling.

Considerable environmental impacts can be achieved at all times during the useful life of a building due to significant saving on climate control equipment, because PCM longevity allows calculating for such a long period.

4. Conclusion

Basing on the results of the conducted research the following conclusions can be made:

- one of the most important parameters of finishing materials utilizing PCM is their cycling stability, which, depending on the way of granule incorporation, amounts for decades under given design operation condition and provides for working life of phase changing component comparable to working life of finishing coating as a whole;
- preparation of raw materials (including production of the phase-changing component itself and granule with it), as well as gypsum board and plaster mortars with PCM granule, are associated with a slightly larger environmental impact compared to regular finishing materials;
- at the operation stage due to creation of comfortable conditions in a room without the use of air conditioners and other climate control equipment energy consumption effect is achieved as well as reduction of greenhouse gas emission, expressed as GWP and acidification;
- recycling of finishing materials with PCM requires a higher energy consumption compared to similar regular finishing materials, but this effect is insignificant and does not have a crucial impact on general positive evaluation of finishing materials with PCM lifecycle;
- calculating amount of PCM granule being incorporated in finishing material structure as well as special aspects of their distribution along layers from surface to depths of coating play an important role which allow achieving the most effective heat-insulation during summer.

Utilization of PCM in finishing materials for interiors allows achieving savings when creating a comfort microclimate during summer. This reduction of environmental impact considerably surpasses effects occurring during PCM production, incorporation into material and recycling after the end of the lifecycle, which can last for decades.

Outlook

The main directions of PCM development and utilization must include lowering energy consumption of paraffin production as well as developing effective product's recycling methods at the end of its lifecycle.

Acknowledgement

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Designing a smart factory for mass retrofit of houses

Lange K[1], Kraemer U-B[2]

[1] Jade University of Applied Sciences, Elsfleth, Germany
[2] Province of Overijssel, Zwolle, Netherlands

kerstin.lange@jade-hs.de

Abstract. The North Sea Region (NSR) contains 22 million houses built in 1950-1985 that cause 79 Mton CO2 emissions annually. Current deep retrofit home renovations are carried out on a limited-scale production and only in small projects. This results in the problem that nowadays renovation costs are way too high and the pace of renovation is far too low. Large scale renovations of existing homes towards energy-neutral are currently not addressed in the North Sea Region. Still, the retrofit of houses in the North Sea Region is essential to reach the European energy and climate objectives. However, the building sector in Europe is not creating the necessary production facilities. The target of the just started INTERREG project INDU-ZERO is to develop a blueprint for a production facility that can produce wide suitable renovation packages at a high volume and low cost.

1. Introduction

The North Sea Region (NSR) contains of a wide range of outdated housing (one-family houses and apartment buildings with poor insulation and high energy demands) built between 1950 and 1985, that do not meet the present-day and future energy and living standards. These households in each country in the NSR all have a structural demand for heat (heating and hot water) and electricity. In order to meet EU environmental objectives, the NSR countries all need to focus on renovation, resulting in energy-neutral houses in order to reduce CO2 emissions. At the moment, mostly manual production facilities exist that can offer renovation solutions (often based on timber frame construction) for a maximum of 500 homes per year. As a result, the costs of renovations are high and the quality varies too much. Due to the high costs only a small number of homes per year are deep-renovated at the moment. Large scale renovations of existing homes towards energy-neutral are currently not addressed in the NSR region.

In the EU-funded Interreg project INDU-ZERO (Industrialisation of house renovations towards energy-neutral) the aim is to develop a blueprint for a production facility, based on Smart Industry and Circular Economy, that can produce wide suitable renovation packages at a high volume (15.000 units/year) at low cost (50% of current price). The consortium of the just started project consists of industry, government and knowledge institutes of six countries in the North Sea Region. This transnational collaboration is needed to combine all necessary knowledge and experience and to guarantee adoption of the project results.

The structure of this paper is as follows: In chapter number 2 the European background of the outdated housing situation and the consequences are described. In the third chapter a review of existing research projects which target the sustainability in the building sector is given. In chapter 4 the INDU-ZERO approach is described. In the fifth chapter the first results of the first deliverables are described, followed by the sixth chapter where the next steps will be specified. The last chapter contains a short conclusion.

2. Background in the North Sea region

Renovating the current houses in NSR is a serious challenge for meeting EU objectives. On the one hand, the potential of houses to be renovated is high. On the other hand, the market failure in the building industry hinders a faster renovation pace.

2.1. Potential of houses to be renovated

There are a total of 22 million houses and apartments in the North Sea Region (calculated on the basis of TABULA Building Typologies) [1] that should be renovated to become energy-neutral within the scope of this project. The number of outdated houses of the NSR partners within this project scope per country are: Belgium 500.000, The Netherlands 4.3 Million, Germany 4,8 Million, UK 9,6 Million, Norway 810.000 and Sweden 1,2 Million. The current CO2 emission of an outdated house is about 3,6 tonnes per year per house. To meet the EU 2030 objectives, almost 2 million houses per year would have to be renovated in the period 2018-2030 in the NSR. With the current state of technology, a small number of renovation packages per factory can be produced and a very limited number of such factories exist. The capacity of the current factories is to a large extend used for new buildings. For the NSR, an insignificant number of renovation packages can be produced at the moment. The NSR therefore seriously lacks production capacity.

2.2. Market failure in the building sector

Unfortunately the EU energy and climate objectives in the NSR cannot be significantly influenced by the building sector at the moment. Currently, the INDU-ZERO partners experience that the building sector has looked only locally and regionally at one project at a time. This is why the production of renovation packages for renovating houses towards energy-neutral is still small-scale. Each house or apartment is served by means of tailor-made offers and most of the work is carried out manually. Due to the local approach, the costs for renovating houses to energy-neutral range between € 80.000 and €120.000 per house/apartment. In addition, the quality of the work varies due to the manual approach, so that no uniform performance guarantee can be given. No standardized renovation solutions are available for the EU market on a large scale. As a result, the cost for individual or low scale renovations into energy-neutral housing is too high to persuade house owners. Main reasons for the market failure of the building industry are:

1. Workload in the industry is high at the moment;
2. Suppliers experience these types of developments as a threat for their existing business;
3. In the current supply chain the producers and providers of (end) products are mostly Small Medium Enterprises;
4. The industry invested in traditional structures;
5. Lack of an upscaled Original Equipment Manufacturer (OEM) position that is found in other market segments;
6. The industry by itself will not initiate the proposed breakthrough in this project and has no incentive for innovation.

In order to meet the long term EU climate and energy objectives, the NSR outdated housing stock needs to be renovated into energy-neutral. These renovations must be solutions which will be suitable for the next 30 years, in order to meet future climate and energy objectives.

3. Research Review

Other research projects in the field of energy efficient building exist. They focus on different aspects than the INDU-ZERO project.

Build with CaRe: The aim of the Interreg-funded Build with CaRe project was to mainstream energy efficient building design by raising awareness and increasing knowledge of the potential of energy savings. In collaboration with the building sector, a transnational strategy for increasing energy efficiency in buildings was developed. Within the project, an education and information programme was carried out to change behaviour in the complete building chain. This aided the setting up of a transnational knowledge and information network.

Transition Zero: Transition Zero is an EU Horizon 2020-funded project, carried out by Energiesprong, to establish the right market conditions for the wide-scale introduction of net zero energy homes across Europe. The aim is to kick-start net-zero energy refurbishment markets in the UK and France, using the social housing sector as a catalyst. This should be achieved by introducing performance-based solution requirements on integrated refurbishment packages and by establishing long-term, warranted energy performance contracts. Therefore, the regulatory and financing conditions for net-zero energy refurbishments have to be improved.

More Connect: The social and environmental urgency of large-scale integrated retrofitting of the European building stock is widely acknowledged and supported by Member states. However, as the European building sector is fragmented, it has not been able yet to devise a structural, large-scale retrofitting process and systematic approach. The aim of the EU Horizon 2020-funded project is to overcome these barriers by applying prefabricated multifunctional renovation elements which have the potential to reduce costs, renovation time and disturbances for occupants. At the same time, quality and performances (both in terms of energy efficiency as indoor climate) should be enhanced.

Faster and Better to Zero on the Meter (SBNoM): As the technical feasibility of zero on Meter (NoM) has been proven, the objective of this project is to accelerate and improve the industrialization of such renovations. This should be achieved through a chain approach in which supply and demand are linked. This involves the industrialization of NoM, standardization and the offering of recognizable 'packages' for these renovations. The costs should be reduced by industrialization and smarter installations or material use.

The INDU-ZERO approach is based on the findings of the above mentioned projects and knowledge. Automation and the development of a factory was not part of the former projects.

4. The INDU-ZERO approach

The overall project objective is the innovative up scaling and industrialisation of renovation solutions towards energy-neutral for NSR homes built in the 1950's to 1985's (which are in general of poor quality with respect to energy consumption, indoor climate and comfort), to lower costs, improve quality and increase the implementation of the renovations in the current housing supply in NSR.

Therefore, two main targets have to be achieved:

1. A smart factory blueprint which in itself is replicable in many countries will be developed. A production facility for thousands of renovation packages should not only be suitable for one type of house or one type of country, but consider the requirements of different countries. Otherwise, it would require different developments and factory designs, which would address a limited amount of houses, and therefore reduce the chance of realising mass scale renovation. Thus, this approach requires many countries to be involved to develop a factory design that is flexible and replicable throughout many NSR countries.

2. The developed elements of the renovation packages will be tested and produced for showcasing. The newly developed renovation packages will be produced and mounted as showcases in different NSR countries. However, the production will still be done in a conventional manufacturing process. The construction of the smart factory itself is not part of the project.

To design the blueprint for a Smart factory suitable for manufacturing renovation packages for renovation towards energy-neutral, the following steps have been identified:

- A selection of a maximum of three renovation packages has to be identified. These three renovation packages have to be suitable for all partner countries.
- Based on the chosen packages the concept process of automating the manufacture of the renovation packages for façade and roof components has to be developed. Therefore, suitable automation tools, e.g. robots, conveyor belts, drilling tools etc. have to be designed and/or selected. The automated production process of the renovation packages has to include factory lay-out, logistics, production data management, installation, building information management and simulations.
- Based on the designed processes, a Virtual Reality model (VR model) will be developed. This quiet new method of virtualization is chosen to present the projects´ results not only to the scientific audience but also to a wider range of target group like potential house owners or investors.
- The developed renovation packages will be produced as prototypes for testing. After testing, the renovation packages will be produced for showcasing. In selected partner countries, a real retrofit of an existing house will be implemented.

5. First results

For developing wall and roof elements, the structure of the elements and the materials to be used has to be determined. Four types of composing elements were considered as a starting point: Timber frame structure (TF), metal frame structure (MF), structured sandwich panel (SSP) and structural insulation panel system (SIPS). After a short description of the potential structure of the roof and wall elements, the evaluation and decision process of the choice of structure is depicted.

5.1. Overview on structures of wall and roof elements

The four structures to be compared base on different construction methods and materials.

- Timber frame structure (TF): Wood framing, in construction, is the fitting together of pieces of wood and sheets to give a structure support and shape. Modern light-frame timber structures gain strength from rigid panels (plywood and other plywood-like composites such as oriented strand board (OSB) used for parts of wall sections). In between the gaps joists insulation like glass- or mineral wool is placed. To meet stringent insulation demands, like for example in the Nordic countries, an additional insulation layer made from expanded polystyrene foam (EPS) can be placed on one side of the element. On this, the outer cladding is applied. A ventilation gap is needed to keep the timber and insulation dry. [2]
- The metal frame structure (MF): The main structural components of light metal or steel framing are made of galvanised cold formed steel sections. These can be prefabricated into panels or modules. In between these metal frame sections insulation like glass- or mineral wool is placed. On an additional insulation layer on the outer side, the outer cladding can be applied. Depending on the insulation that is used, a ventilation gap could be needed. [3]
- The structured sandwich panel (SSP): SSP, like structural insulation panel systems (SIPS), are used in the construction industry. [4] The SSP is a sandwich structured composite which consists of an EPS insulation and an OSB sheeting positioned between two layers of fibreglass. The OSB serves as a mechanical attachment layer to provide fastening opportunities. These layers form a light but very strong panel. Like in the other panels, an outside cladding is possible.
- The structural insulation panel system (SIPS): SIPS, like SSP, is a sandwich structured composite. It usually consists of an insulation layer of rigid core glued between two OSB

panels. The core insulation might be expanded polystyrene foam (EPS), extruded polystyrene foam (XPS) or polyurethane foam (PUR).

5.2. Assessment

The methodology used to prioritize the kinds of structure of the wall and roof elements to be further developed in the project based on a semi-structured decision process in three expert groups. For the assessment of different structures and materials each group of experts had to assess the design of the structures timber frame (TF), metal frame (MF), structured sandwich panel (SSP) and structural insulation panel systems (SIPS) on the following predefined criteria:

- Costs: The concept of total cost of ownership (TCO) is used for the assessment of each technology. Total cost of ownership do not only consider the purchasing price of a product. Moreover, all direct and indirect costs involved in buying and using a product over its life time are counted in to help buyers and owners decide on different alternatives. [5]
- Circularity: The renovation packages to be developed in the project should be based on the principles of circular economy and optimized for low embodied energy. Circularity describes the sustainability of a product considering its whole live cycle. Circular building concepts and Cradle-to-Cradle frameworks imply radical changes for the construction sector and have to be considered. [6] [7]
- Effectiveness: Effectiveness describes the effort to make a good insulation panel with integrated technology like heating and ventilation. Characteristics like thermal insulation or thermal bridges, sensitivity to humidity, deformation or delamination have to be considered. The possibilities for upscaling automation the production process are also taken into account.

In a first step, the characteristics of the four structures with regard to costs and circularity were discussed, taking the timber frame structure as the starting point. The results were fixed on a two-dimensional coordinate system (see figure 1). Next, the characteristics of the four structures with regard to costs and effectiveness were assessed. The results again were fixed on a two-dimensional coordinate system (see figure 2). In order to finalize the assessment, the results were discussed in the peer group to aggregate the findings in a joint figure.

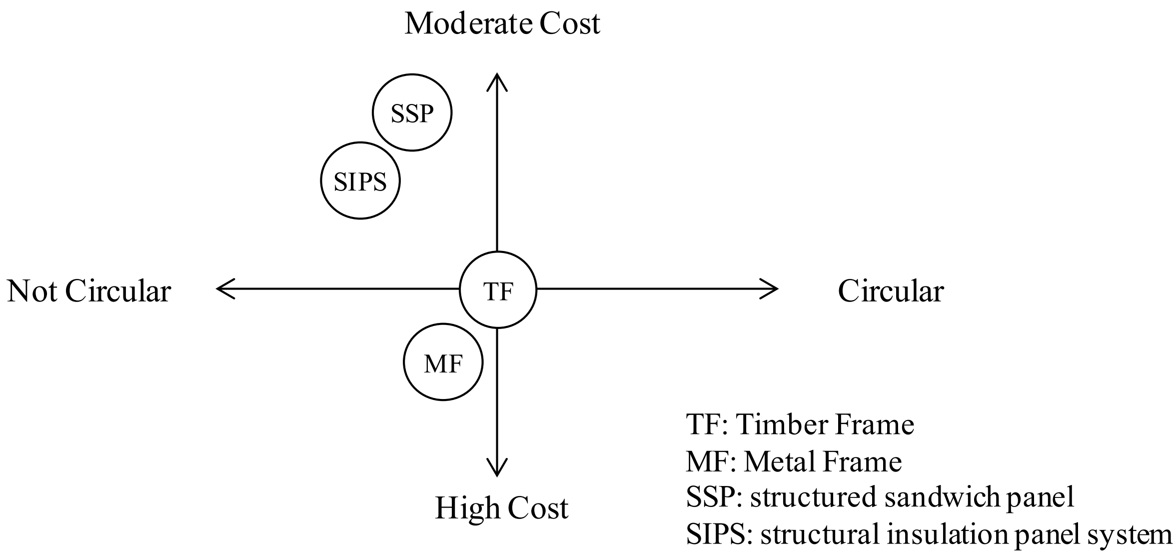

Figure 1. Assessment of structures – Circularity and Costs

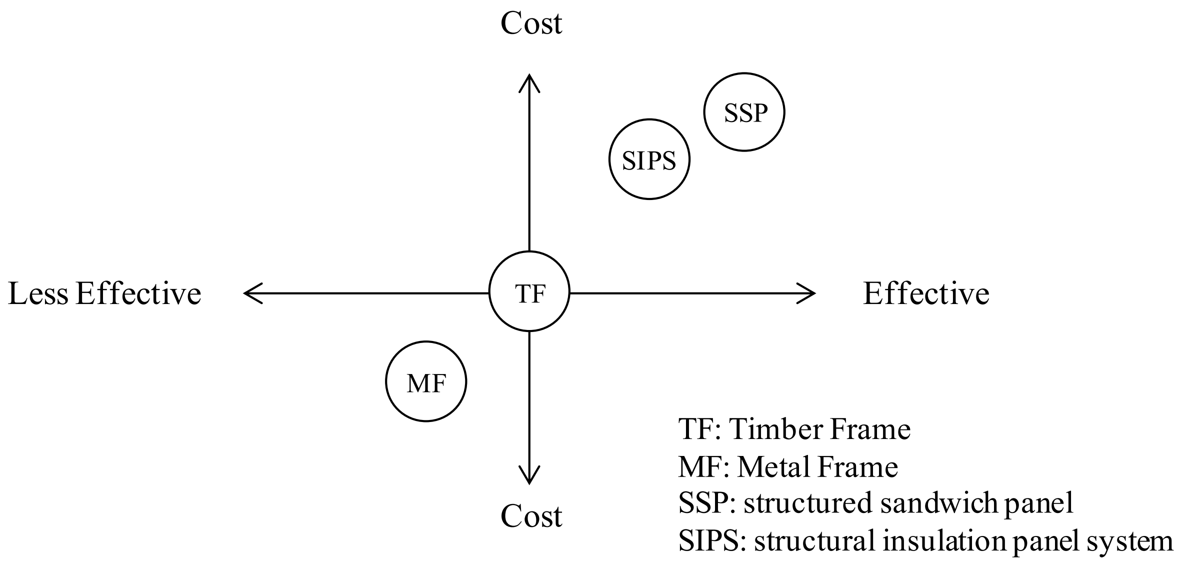

Figure 2. Assessment of structures – Effectiveness and Costs

The positioning of the four structures in the coordinate system was a long and controversial process. Different points of view had to be balanced. To give a short overview, main arguments for each structure are depicted in the next section.

5.3. Discussion of main criteria
All structures and their advantages and disadvantages had to be evaluated and compared. Therefore, not only the as-is-situation has to be considered. Also potential future developments had to be discussed.

Timber frame structure (TF):
Circularity: A timber frame wall consists of different materials each with its own circularity. Main materials of the wall elements are: Timber frame, glass- or mineral wool insulation, oriented strand board (OSB), expanded polysterene foam (EPS) insulation, damp barrier foils and the cladding. In theory each component could be separated and recycled on its own. However, actual wood frame constructions are difficult to disassemble as there is contamination due to adding spray foam in corners, adding glue to between panels or (chemically) treating materials to make them resilient. Although timber frame has a potential for a good circularity this treatment has a big negative impact on the recyclability of the used materials. Timber has a low carbon footprint and is renewable. Softwood species are fast growing and some are grown widely across (northern) Europe. Untreated softwood can be downcycled in wood based products or as fuel.

Effectiveness: Wood has relatively good thermal insulation values compared to other building materials. As the frame is self supporting, the choice of insulation can be tailored to the environmental situation. Softwood when exposed to humidity can deform and create air gaps. Thus frame and insulation need to be kept dry and ventilated to prevent sagging. Looking at the production process it is important to note that timber frames can also be prefabricated into panels or modules.

Cost: Timber is relatively expensive per volume. However, softwood is cheaper than hardwood, even when it is FSC certified.

Metal frame structure (MF):
Circularity: A metal frame wall consists of several different materials with their own circularity. Main materials of the wall elements are: Steel frame, glass- or mineral wool insulation, chipboard (OSB),

EPS insulation, damp barrier foils and the cladding. Like wood frame constructions, these are difficult to disassemble due to the addition of spray foam or glue. Raw materials are non-renewable. The production of steel has a high carbon footprint. It requires a lot of energy and material and releases CO2 during the process. Still, steel is quite easy to recycle. Steel frames even have a possibility to be re-used.

Effectiveness: Because of the 'c shape' of the metal frame, insulation is held in place very well and hardly any sagging occurs. As the frame is self supporting, the choice of insulation can be tailored to the environmental situation. However, there is a big risk of air gaps where the insulation does not fill up the frame correctly. Metal itself has very bad thermal insulation values. There is a very high chance for thermal bridges. Thus, an additional layer of insulation is needed to dampen this effect.

Cost: Metal frames themselves are quite expensive to produce.

Sandwich panels (SSP):
Circularity: As the structured sandwich panel (SSP) and the structural insulation panel system (SIPS) are sandwich composed panels, an end-of-life recycling and reuse is difficult. Although some components might be easy to reuse, most components are glued together. Thus, separating materials is difficult and labour intensive.

The virgin raw materials for the production of OSB have a low carbon footprint. FSB certified OSB is available. Raw materials can contain recycled woods like chipped construction wood. However, OSB needs high heat and pressure to be produced, just like plywood, particleboard and MDF. The reuse of OSB is difficult due to its relatively low durability. Recycling of OSB is difficult as well. OSB waste is usually incinerated and used for energy. Moreover there are limited possibilities for downcycling (e.g. downcycled boards).

Effectiveness: The main advantage of SSP modules compared to SIPS modules is the size and thus the handling possibilities. SSP walls and roofs usually consist of one or two large panels (up to 15m). This minimises the mounting effort and thus the construction time at the construction site. Moreover, this minimises joints which minimises air penetration. Because of the EPS foam which is an integral part of the wall (less gaps) the insulation core and raw insulation values are good. As SSP panels have very few internal structures, the insulation value is very homogenous and thermal bridges are eliminated. The production process can easily be automated due to the structure of the panels.

Cost: OSB, used in both sandwich structures, is less expensive than plywood and similar fibre/composite boards.

Structural Insulation Panel Systems (SIPS):
Effectiveness: SIPS walls and roofs usually consist of multiple smaller standard size panels. Linking these requires the mounting of timber beams in the wall which is an additional time consuming process at the construction site. Moreover, this diminishes the R value locally. One particular weakness of these SIPS panels is air penetration at joints or penetrations. Still, due to the hard foam insulation core, raw insulation values tend to be good.

Cost: OSB, used in both sandwich structures, is less expensive than plywood and similar fibre/composite boards. Looking at the insulation core of the SIPS module, costs for EPS are low. Other materials like extruded polystyrene foam (XPS) or polyisocyanurate foam (PIR) or polyurethane foam (PUR) are more expensive. The production process can be automated.

To conclude, the sandwich structures result to be more promising when developing a smart factory with the aim of reducing the cost of retrofitting houses on a large scale. The assessment of the effectiveness shows that the SSP modules even outmatch the SIPS modules. First, SSP is cheapest due to the use of EPS and OSB, both cheaper as other components in the SIPS module. Second, the SSP production process is less complex as less components and materials have to be handled. This results in a reduced construction time and costs. A further argument is the possible size of the SSP modules which can lead to a minimised mounting effort and thus a reduced construction time at the construction site. However, the circularity of the sandwich panels is not assessed that good compared to the timber and metal frame structures. To reduce the effort of separating materials and thus to improve circularity, the connection between different layers and alternatives for the OSB and EPS will be investigated in the next steps. Future developments and solutions could be found in debondable or environmentally friendly glue or mechanical connections like click systems.

6. Future Outlook

The next decision will deal with the selection of the house types to be renovated. Depending on the house type, the renovation packages and the wall and roof elements as well as their production process in the smart factory have to be designed.

For each partner country (Netherlands, Belgium, Germany, the UK, Sweden and Norway) the housing stock regarding existing house types (e.g. detached house, demi detached house or terraced house) has to be analyzed. The challenge of this step lies in the differences in the types of residence in all the different countries. Moreover, different roof types for each type of residence have to be considered. In the end, three house types have to be identified which are of interest for all partner countries.

Following these basic decisions on module structure and type of residence and roof, the production processes for these modules have to be identified, analyzed and optimized for a smart mass production of modules for retrofitting houses in the North Sea Region.

7. Conclusion

The aim of this transnational approach is different to current regionally centered projects in the retrofitting sector of existing houses. The practical implication lies in the development of a blueprint for a smart factory which is able to produce house elements on a large scale. Up to now, high-volume solutions for renovations towards energy-neutral are still not available. In order to ensure the right choice of module structure this paper describes the research implication of the step of assessing different common types of walls and roofs. Based on this decision as well as the choice of the type of residence to be considered, the next steps of developing the smart factory will follow. Here, the automatization process, robotics and logistical aspects will be focused.

Acknowledgments

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Austrian Universities and the Sustainable Development Goals

Körfgen A [1], Glatz I[1], Maier S[2], Scherz M[2], Kreiner H[2], Passer A[2], Allerberger F [3,1], Kromp-Kolb H[4], Stötter J[1]

1 Institute of Geography, University of Innsbruck, 6020 Innsbruck, Austria

2 Working Group Sustainable Construction, Institute of Technology and Testing of Construction Materials, Graz University of Technology, 8010 Graz, Austria

3 Representative for all students involved in *forum n*, Austrian-wide students alliance for sustainability. Further involved: D Steinwender, L Schmalzl, S Preiml, J Hueter, A Göd

4 Center for Global Change and Sustainability, University of Life Sciences and Natural Resources, 1190 Vienna, Austria

stephan.maier@tugraz.at

Abstract. In 2015, the United Nations released the 2030 Agenda for Sustainable Development, adopted by 193 countries, containing 17 Sustainable Development Goals (SDGs). The goals address social as well as economic and environmental challenges in a holistic approach. Participating university members of the Alliance of Sustainable Universities in Austria (ANU), a cooperative work platform that promotes sustainable development at universities in Austria, picked up on this impulse by developing approaches for universities to address SDGs in research and education. The article presents the cooperative process of developing a project with the aim of supporting political decisions for SDG achievement, establishing the SDGs in research and education and intensifying collaboration between universities. Besides interactive workshops and methods to develop the project, a mapping supported the team to find well-established and also underrepresented SDGs in research at universities in Austria.

1. Introduction

The challenges of the 21st century, such as climate change or biodiversity losses, are of high complexity, requiring holistic approaches [1]. Here, the 17 Sustainable Development Goals (SDGs) with their 169 targets released as Agenda 2030 aim at all spheres of sustainable development including social, ecological and economic aspects.

In order to break down these goals to distinct implementation tools, a stakeholder integration on different levels is necessary. Political approaches evolved to be "siloed" in their respective corners of their spheres of action [2]. This also contributes to the problem that SDG achievement is still far away and often "blurred" through spill-over effects and other obstacles difficult to capture. Indicators are an important and helpful tool to measure progress, but it must be ensured that the appropriate criteria are applied. Scientific support is necessary to outline options that can be taken for SDG achievement and to critically reflect on SDGs and targets. Presumably, in some cases this will need the introduction of additional indicators to the ones applied so far.

The role of higher education institutions (HEIs) can be described as follows. As "change agents" HEIs drive forward sustainability through problem-oriented real-world research, critically reflect on goals, integrate sustainability into research and education and thus educate future decision makers. They can give scientific advice for decision-making through science-policy dialogues [3].

In Austria, universities are articled to the performance agreements (German: Leistungsvereinbarungen) which each university contracts with the Austrian Ministry of Education, Science and Research every three years [4]. These performance agreements contain the basis for the content-related development and strategic profile formation of the universities. In the framework of the performance agreement period of the years 2016 to 2018 the Austrian Ministry additionally invited the universities to intensify their pioneering task for a sustainable and future-oriented development of society, environment and economy according to the Brundtland Report from 1987 [5] in order to engage with the increasing global challenges. Austrian universities as autonomous educational and scientific entities also create their own development plans where they explicitly concretize their profile formation and define their overall concepts including content like future development goals, strategic orientation and measures.

The project UniNEtZ (German: Universitäten und Nachhaltige Entwicklungsziele, Universities and Sustainable Development Goals) has been developed in order to support political agenda setting in Austria, to integrate sustainability into research and education and to strengthen collaboration between universities. The aims of UniNEtZ are summarized as follows:

- Development of a catalogue of options on how the SDG might be achieved in Austria, taking a systemic approach to achieve measures compatible with all SDGs
- Address SDGs in universities in research, teaching, life-long learning, responsible science and in university management
- Identify research needs and develop research projects across universities
- Create added value through cooperation and new combinations of knowledge
- Improve interdisciplinary co-operation within and between universities
- Interaction with stakeholders from politics, administration, economy and civil society
- Attempt at interaction with the "other 50%", those people left behind, as socially vulnerable groups, e.g. long-term unemployed people)
- Build capacity amongst researchers, teachers and students regarding the issues addressed by the SDGs

2. Project development and methodological approaches

2.1. Project development

Since April 2017, several workshops have been launched in order to sharpen the project's goals and develop the scope of the bottom-up initiative UniNEtZ. In a first impact-workshop in May 2017, participants from different universities and the Austrian Federal Ministry of Education, Science and Research (BMBWF) identified factors that stimulate a successful implementation of sustainability at universities and help to realize the planned project. According to the participants, there are several factors that are effective in supporting the operationalization of the further process on different levels (see Table 1). As driving variables, the group identified three factors: support by the Austrian federal government ministries, a central coordinating project management and an SDG mapping to identify research focus areas of the involved institutions.

Table 1. Success factors that help to achieve the defined goals of the UniNEtZ project. The factors were identified during a workshop in May 2017 with stakeholders from universities and Austrian ministries (Source: adapted from FASresearch 2017 [6]).

Type of variable	Success factors applied to UniNEtZ
Drivers: preconditions and requirements for the process, lever in the initial project phase	• **Federal ministries**: support and interest of the political stakeholders involved • **Project management**: central project management and coordination • **SDG Mapping**: identifying research strengths of the participating universities in order to orientate the further process accordingly and help to focus thematic fields
Make-or-break variables: necessary for the process	• Clear **target definition** of the project • **Innovation**: development of new knowledge and building of new cooperation • **Thematic focus** based on competencies and demands
Outcome variables: indicators measuring if the defined goals are approached	• **Awareness-raising** at universities • **Network** of motivated people • Integration into **tasks of the university** • Integration and interactions with other **societal stakeholders**
Buffer variables: factors directly impacting the goal, must be clarified in advance, support the process	• **Resources**: financial incentive structures for the project support • **Interactions**: consider various interactions between SDGs, targets and indicators

Based on the identification of these factors, further workshops focused on sharpening the goals of UniNEtZ (see section 1) and developing the project framework were organized. Once the scope of the project had been outlined, the universities started to integrate the core ideas of the project into the performance agreements for 2019-2021 between universities and the BMBWF. The universities involved have been in a constant dialogue with each other and with the ministry in order to drive forward the implementation of the structural framework conditions of the project. By December 2018, the integration of UniNEtZ into the performance agreements was completed.

Parallel to the project development, information events helped to gain a clearer picture of the SDGs and related topics. For example, experts such as Keywan Riahi (IIASA) gave inputs on the role of universities in sustainability transformations during a workshop in June 2017. Further, the question of how interactions between scientific and societal fields could be strengthened was a core topic during the project development. Figure 1 shows the timeline of the project with a development phase, thematic focus setting and official start of working on SDG options.

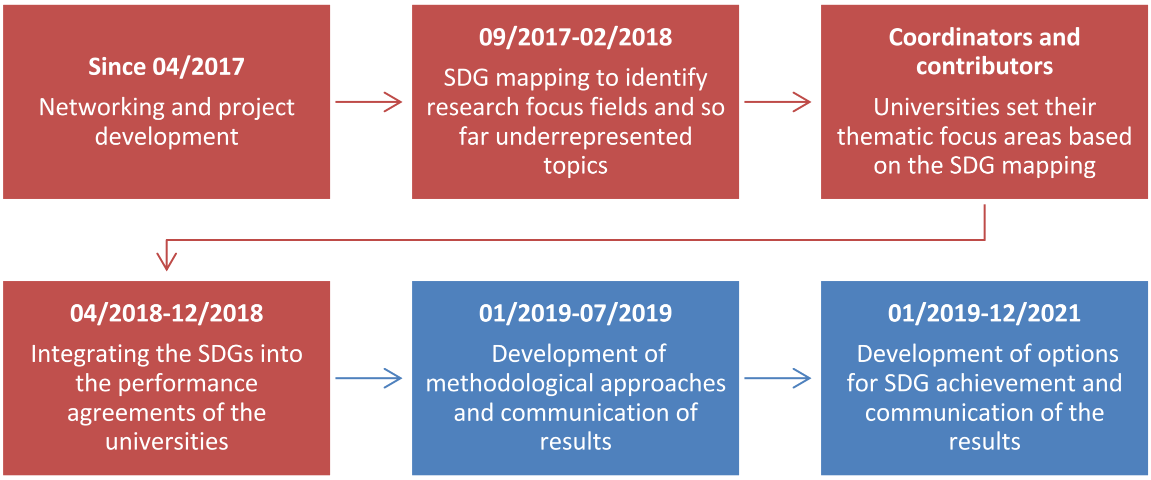

Figure 1. Project timeline since 2017: Red boxes indicate completed milestones. Blue boxes show current or future working packages.

In addition to the structural project development, intensive dialogues helped to integrate important stakeholders from the BMBWF into the process. Both, workshops and bilateral talks with respective stakeholders were held on a regular basis. During a presentation workshop in May 2018, the results of the SDG mapping (see section 2.2.) and the preliminary integration of the project UniNEtZ into university structures at that point were presented and exchanged with stakeholders from the BMBWF, other ministries and the Federal Chancellery.

2.2. SDG Mapping

In order to support the process of finding focus areas for each university, an SDG mapping was conducted from September 2017 until February 2018 [7]. As a method a mapping tool was developed in an interdisciplinary process with a duration of about half a year. Data on publications and project activities from 13 universities were investigated according to SDG relation and thematic focus fields. In total, about 15,000 publications and 17,000 projects from the period 2013-2017 were extracted from the internal research documentation systems of the involved universities and made available for the mapping.

The mapping is based on a keyword catalogue, containing about 1,000 keywords in English and German. To develop this catalogue, the Agenda 2030 was screened for prevalent words as a first step. Synonyms were derived from these words in a semantic approach, and these were matched with keyword lists from other studies [8]. In an iterative process, these keywords were discussed with stakeholders from the partner universities and tested via the search tool. The tool is based on a Python script, which screens the available data for respective keywords and displays matches. Titles and abstracts of the available datasets were screened with the developed keyword catalogue, retrieving statistics on the distribution of the SDGs. These give an insight into the thematic focus areas of the universities.

It could be shown that some SDGs are “mainstreamed”, e.g. SDG 4 (Quality education), whereas other SDGs represent instead the niches covered by individual universities, e.g. SDG 3 (Good health and well-being). This also reflects the current participation of universities in UniNEtZ.

2.3. Coordinators and contributors for the SDGs

Based on their previous activities, the universities decided to on take roles as coordinators (in German *SDG Leiter_innen*) and/or contributors (in German *Mitwirkende*) for specific SDGs. These coordinative and contributing roles have been integrated into the performance agreements of each university. If a university is coordinator for a specific SDG, the responsible team coordinates all activities related to this SDG and gathers the inputs of the contributing universities. Contributing members help to gather expertise and knowledge in order to develop measures for determining how the SDGs can be realized in Austria. Both coordinators and contributors have very close involvement with the SDGs, their specific goals and indicators (see Figure 2). To date (03/2019) 19 coordinations and 58 contributions have been covered by the following universities and institutions including Alpen-Adria University Klagenfurt, Danube University Krems, Graz University of Technology, Johannes Kepler University Linz, Medical University of Innsbruck, Montanuniversität Leoben, Mozarteum University Salzburg, University of Applied Arts Vienna, University of Graz, University of Innsbruck, University of Music and Performing Arts Vienna, University of Music and Performing Arts Graz, University of Natural Resources and Life Sciences Vienna, and Paris Lodron University of Salzburg, University of Veterinary Medicine Vienna, Climate Change Centre Austria, Geological Survey of Austria and Central Institution for Meteorology and Geodynamics.

The mixed backgrounds and interdisciplinary setting of the project enables a synthesis of available expertise to approach the SDGs holistically. However, each specific SDGs will not only be approached from different disciplinary backgrounds, but bridges and interdependencies to other SDGs will be considered as integral parts of the project with the aim of identifying synergies and trade-offs. These interdependencies will need to be viewed from the beginning of the project in order to develop holistic solutions and options for measures on how to implement SDGs.

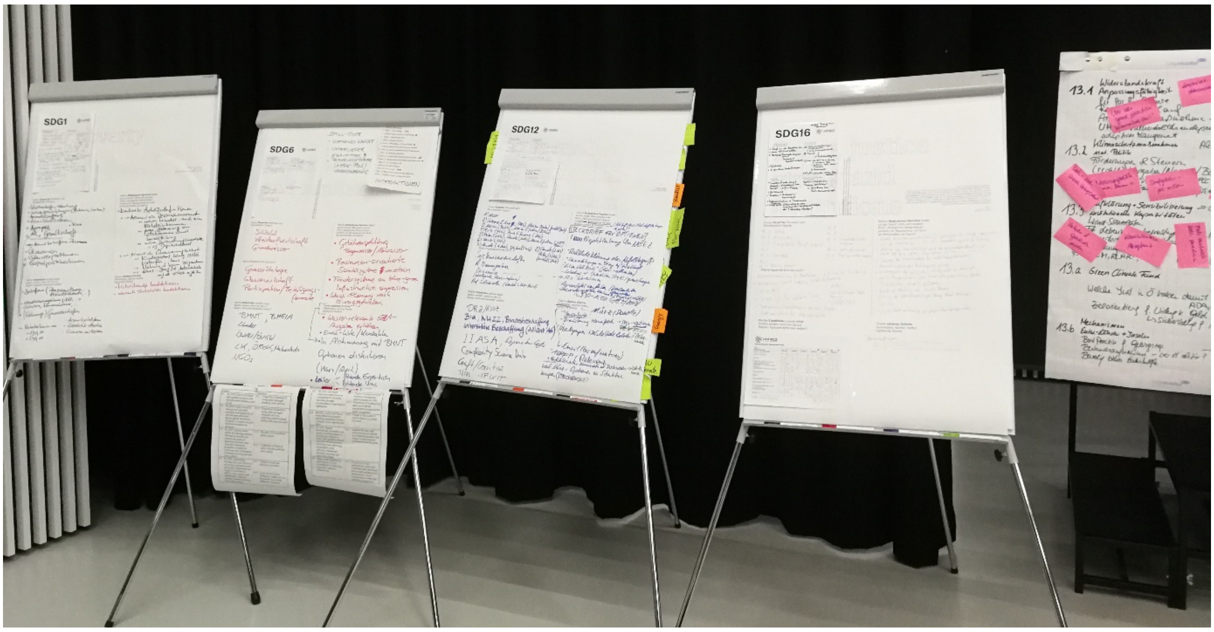

Figure 2. First working session on the SDGs – brainstorming available expertise, definitions of the SDGs and its targets and related indicators (Source: Kernegger 2019)

2.4. *Artistic formats*

Artistic formats are integrated into the methodic scope of the project as a means of achieving innovative approaches for the SDGs and will continue to support a) thematic approaches towards the SDGs and b) communication with the public and different stakeholders. The official UniNEtZ kick-off event 21st - 22nd January 2019 is an example of how artistic formats of the kind enable alternative approaches to the topic. In the scope of the event, students and associates of the University of Applied Arts Vienna prepared the format "Knife, Fork and Pen" that gave impulses for a creative brainstorming process on the SDGs during the lunch break (see Figure 3). “Knife, Fork and Pen” turned out to be a productivity-enhancing tool for elaborating the first contents during the kick-off meeting lunch break. The long dining tables were covered with paper tablecloths and divided according to the SDGs. An assigned seat number

on the table ensured a sound mix of people and ideas in to the context of their thematic backgrounds. 8 to 10 people per SDG introduced and discussed contents and ideas during the first course of the meal. After the sounding of a gong the SDG was changed by assigning a new seat number. All the ideas and suggestions that were developed during the 3-course menu and the accompanying three discussion rounds were written down on the paper tablecloths.
A project-internal working group will continue to foster such formats and support the project team with methodological innovations and communication approaches.

Figure 3. The kick-off event with its interactive lunch time session (left) and working groups (right) (Source: Ruiz Cruz 2019)

3. Structure and special aspects

3.1. Governance structure of UniNEtZ

The UniNEtZ project currently has the active involvement of 15 universities and three scientific institutions in an open consortium. This means more institutions can join the project at any time during the working process. By anchoring the project into the performance agreements between the universities and the BMBWF and the signing of a Memorandum of Understanding, the 18 institutions have committed themselves to implementing the objectives of the project within the next three years. UniNEtZ aims to (i) develop an options paper for the Government to achieve the SDG objectives, (ii) strengthen the networking of scientific institutions within Austria, and (iii) promote the anchoring of the principles of sustainability in research and education. The institutions involved are thus complying in this project with the demand of the BMBWF, which states that universities should take more responsibility for real-world problems and societal needs (Third Mission / Responsible Science).

Several different organizational units operate within the project, acting on a strategic or operational level (see Figure 4 and Table 2).

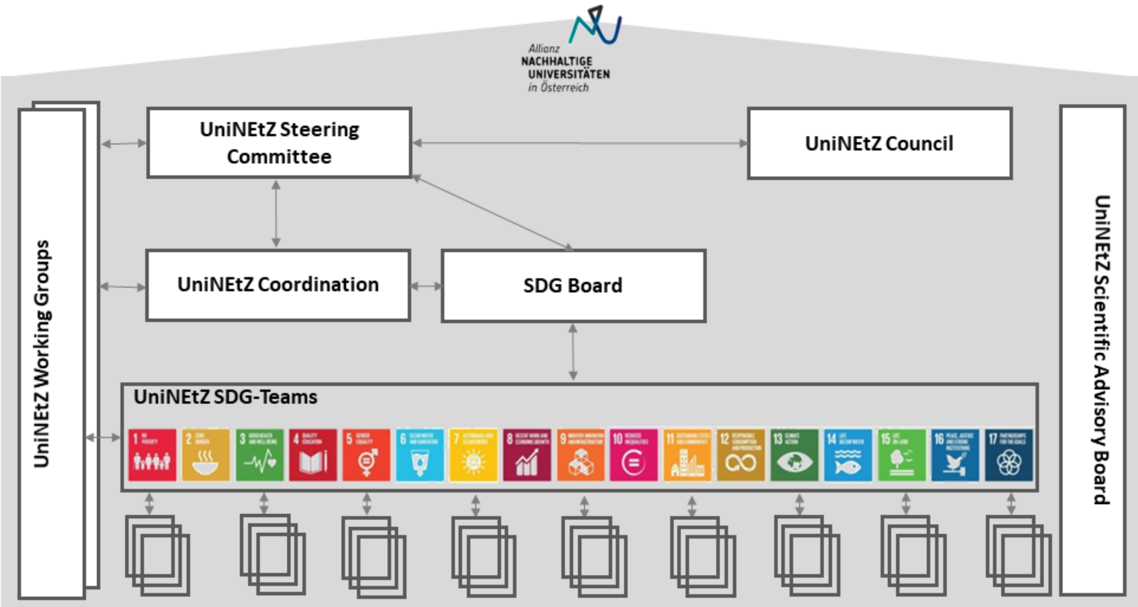

Figure 4. Structure of the UniNEtZ project.

Table 2. Structure of the UniNEtZ project with the different organizational units acting on a strategic or operational level.

Function	Description
UniNEtZ Council	This committee takes strategic and financial decisions in the project. Each participating institution, including the group of students, has one vote.
UniNEtZ Steering Committee	This committee leads the project and is active on a strategic as well on an operative level. It consists of three persons.
UniNEtZ SDG Board	This board works on methods and contents related to SDGs and possible options. Its members coordinate the activities for each SDG and guarantee the linking of all SDGs. Every SDG has one vote.
UniNEtZ SDG teams	These SDG teams compile the options to fulfil the SDGs related to Austria-related challenges. Further, they consider interactions with other SDGs and abroad.
UniNEtZ coordination	This level represents the operative central coordination of the project. It is the central contact point for all committees and members.
UniNEtZ Scientific Advisory Board	This committee (to be set up) is composed of scientists, politicians and economists. It accompanies the project with scientific and strategic advice.

3.2. Options to achieve the SDGs

Within the three years project duration, SDG-related options will be developed for how to contribute to achieving the SDGs in Austria. In this context, an option is supposed to be policy relevant but not prescriptive. Thus, no recommendations will be made, but the options will be presented to the government as a support for decision-making processes. Every option must be assessed regarding synergies and trade-offs with other options, all targets and indicators. Option packages can possibly be identified to mitigate disadvantages and strengthen synergy effects. The scope of possible options is limited to solely to those that lie within a political mandate for Austria; however, special care will be taken to include options that help reduce negative spill-over effects making the achievement of the SDGs more difficult in other countries, especially developing countries.

When developing an option, a scientific standard must be adhered to. This guarantees traceability, reproducibility and comparability. Within the project, there will be a specific working group to develop an adequate methodology (WG methodology). Further details will be outlined in the current months. One of the main goals of the WG is to develop a concept to merge the options of the different SDGs in a systemic model. To ensure a scientific standard, (i) an analysis of the actual situation and developments will be made on the basis of existing data and statistics. Here, it is important to critically illuminate the quality of the data and their relevance to the research question. (ii) Furthermore, a system analysis will be performed for the influencing factors considering different system limits. For this purpose, positive and negative feedback loops in the system (synergies and trade-offs) are given particular consideration. (iii) The solutions proposed so far in Austria and their effectiveness must be discussed. (iv) A literature and practice analysis of solutions implemented in other countries should be carried out. (v) Based on these steps, the systems diagram can be improved and will then serve to make sure no relevant leverage points yielding additional groups of options have been overlooked.

3.3. Students – partners on equal terms

There is no doubt that students are the biggest stakeholder group at universities. The most important responsibility of universities is to enable students to strengthen their reflective faculty and that teachers and students jointly work together in order to develop contemporary action knowledge [9]. Hence, if HEIs intend to act as change agents in a credible manner and thereby attempt to foster a transformation towards sustainability, it is crucial to open up a space for a collaboration with students, where they are seen as partners on equal terms.

Within UniNEtZ, such an involvement is taken seriously as a main concern and was discussed in particular at the kick-off event in January 2019 by a working group consisting of students and professors of various universities. It was decided that students will be formally represented by the student association *forum n*. Founded in November 2018, *forum n* aims at building up an Austrian-wide network of student initiatives and individuals in the context of sustainability. In doing so, *forum n* is contributing to the development of a sustainable and thus future-orientated higher education landscape in Austria. The *forum n* is part of the UniNEtZ Council (Figure 4) with the same voting right as all the other universities. Besides this structural embeddedness on eyelevel, students have the possibility to contribute to any SDG they are interested in, whereby a particular focus is on SDG 4 – Quality Education. Hence, UniNEtZ is an important platform for students to participate in an interdisciplinary dialog with scientists from different universities and disciplines. Furthermore financial support is also granted to facilitate the involvement of students, e.g. at UniNEtZ-events (e.g. meetings of SDG groups), and to enable them to set up their own projects related to UniNEtZ. An eyelevel collaboration of this kind recognizes that students can act as crucial change agents and multipliers not only at their universities, but also in their societal environment during their studies and beyond as future decision makers. The structures and "modi of collaborations" which will be implemented within UniNEtZ can serve as basis for how a continuous and long-term cooperation of *forum n* and the Alliance of Sustainable Universities in Austria can be realized. In this sense, the "eyelevel approach" of UniNEtZ can also serve as a best role model for other networks or projects where students should be involved as partners on equal terms.

3.4. Ethical aspects and guiding principles

Agenda 2030 and its SDGs can be understood as a global effort to overcome the challenges originating from the Anthropocene and its multiple and complex processes of change. There is wide agreement that this is no longer a simple interplay of action and impact on the challenge side and reaction and adaptation on the response side. Thus, solutions which have been successful for quite some time are also no longer adequate as they miss the complexity and the, both spatially and temporally, multi-scale character of the challenges.

As a consequence, there is an ever-growing understanding that this challenging situation, which might even be seen as a key question for the survival of the human-environment Earth system as a whole, can only be mastered by a comprehensive socio-ecological transformation. Transformation means not purely addressing the challenges but reflecting on and rethinking of the value system on all scales [10], from the individual to group and societal level, which is seen as a key driver of all human activities [11]. Only when addressing these ethical aspects, can the systems at risk be transformed.

Within this value system sustainable development respectively the SDGs may be seen as the guiding pole star. That does not mean that SDGS, targets and indicators are applied and investigated, uncritically. On the contrary, they are brought into question, evaluated according to ethical principles and, as a result, further applied or discarded.

Against this background, the UniNEtZ consortium is fully aware that ethical aspects must be guiding principles of all research activities within the project. By doing so, the consortium is not only contributing to the idea of responsible science but in a further sense is making it become a reality. All in all, UniNEtZ can be characterized as a value based and society-oriented project by which the 18 contributing institutions show their willingness and potential in the newly arising field, the purpose of a University's Third Mission in order to address societal and economic challenges within the cultural-environmental sphere.

4. Excerpt of first results

In this section we present an excerpt of first results within the ongoing UniNEtZ project. The networking and exchange of information between the participating universities is already taking place on a comprehensive scale. Through numerous workshops within each SDG, the first necessary steps have been taken to meet the requirements of the UniNEtZ project. It is interesting to observe how different ideas and approaches within the individual SDG groups are discussed, brought together and implemented.

As already mentioned, one of the crucial tasks of the project is the systemic consideration of interdependencies among all developed options in order to holistically identify synergies and trade-offs. For this reason, a 2-day workshop has already been held under the title "Systemic approach for a holistic consideration of options”. In the course of this workshop, the participants were introduced to the basics of system dynamics and the modeling language. Finally, attempts were also made to develop systemic interdependencies within selected SDGs, with a focus on the correct application of the modeling language. Figure 5 shows some impressions from the workshop where a systemic approach was applied to the exemplarily selected topics “waste” and “education”. Systemic interdependencies as well as impacts were related to these topics.

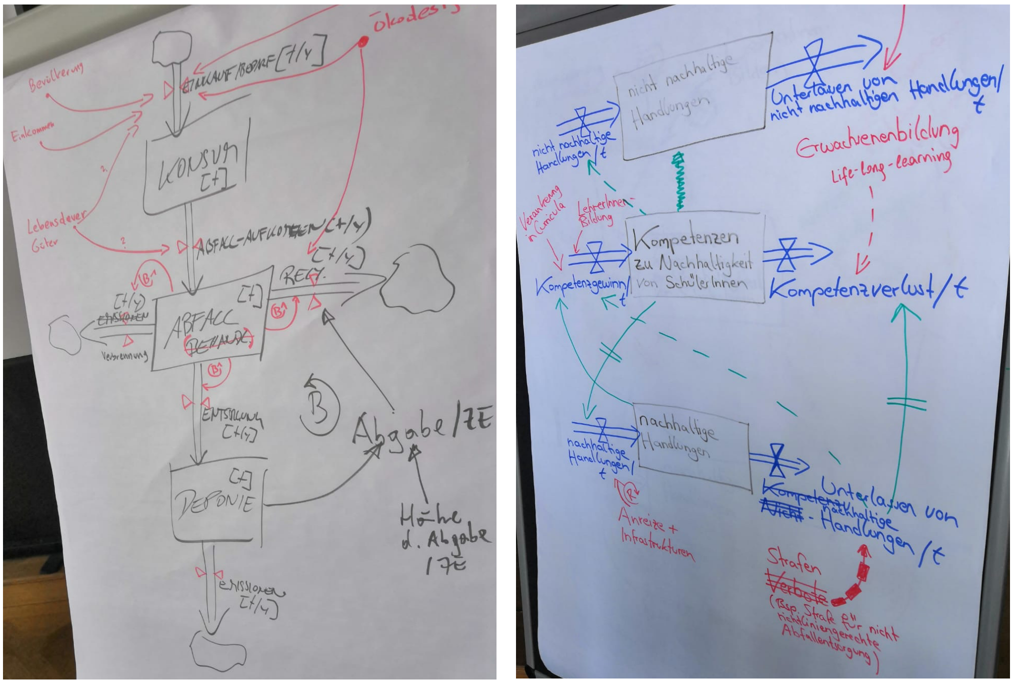

Figure 5: Application of a systemic approach within exemplary topics (Source: Working Group Sustainable Construction Graz University of Technology 2019)

Another ongoing activity is the continuous involvement of students in the SDG topic as well as in the UniNEtZ project. As an example here, a master's thesis, which has already been completed, can be mentioned. The topic of the thesis was the *investigation of the systemic approaches' application within SDGs in the last years and the identification of relevant fields of action in the field of sustainable construction*. Another positive aspect is the interest and willingness of students to present and disseminate the contents of their master's theses at conferences (e.g. SBE19 or ENOVA19).

5. Conclusion and Outlook

By setting the structure for collaborative work between the participating institutions, the framework conditions for working on options for how to achieve the SDGs has been laid. There is solid expertise available to work on the SDGs. During the next months, the team will work towards a first report, outlining the methodological approaches in developing measures for how to achieve the SDGs and giving examples of options. Following the identification of the research strengths a first step has been taken on working in a more targeted manner on the SDGs.. In order to fill existing gaps, expertise will be further extended in the near future by involving further stakeholders and partners. Appropriate methods and communication formats on how to involve these stakeholders will be developed.

One important group to be addressed is that of the students, as drivers of sustainability, change agents and future decision makers [12-13]. In order to integrate sustainability into higher education, investigating which topics and approaches are already contained in university curricula can help to focus the agenda more towards sustainability issues and real-problem based education and research.

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Architectural Education for a Post-Fossil Future

Roswag-Klinge E, Pawlicki N, Crabbe M
Natural Building Lab Technische Universität Berlin

roswag-klinge@tu-berlin.de

Abstract. The transformation to a post-fossil future will require us to radically rethink the way that we live, build, consume and educate. Currently in Europe the construction sector is responsible for nearly 40% of direct and indirect CO_2 emissions [1] and 30% of waste [2] generated. With these numbers only increasing, young designers will carry a huge responsibility for reducing the sector's impact on the environment. Yet in many cases architectural education continues to place form-making in the centre of the curriculum at the expense of an understanding of the complexities of planning in a post-fossil future.
Since its inception in 2017, the Natural Building Lab (NBL) at the Technische Universität Berlin has been exploring new methods of architectural education with the premise that new models and formats are needed in order to equip young designers with the tools they will need to affect change in a rapidly changing, globalised society. The projects undertaken by the Lab up till now have put an emphasis on self-determined learning as the vehicle to involve students proactively in urban-change processes. The first built projects from the Lab, while in diverse contexts, all combine circular, LowTech construction principles with the performance of natural building materials to produce a vision for a post-fossil architecture, often designed and realised by students in trans-disciplinary collaborations. The paper will look at the challenges facing architectural educators and how the Natural Building Lab is aiming to frame its pedagogic strategy based on the realities of resource scarcity and climate change.

Figure 1. NBL Collaborative Design Workshop, TU Berlin fall 2017

1. Introduction – The Big Picture

The current “perfect storm” of social, political, economic and ecological conditions internationally shows little evidence of abating despite the increasingly dire warnings of leading experts. In 2015 the Stockholm Institute for Climate Resilience published an update on their 2009 research on Planetary Boundaries, of the nine boundaries they identified three are already beyond the “zone of certainty”, three more are already close to their limit and two cannot yet be scientifically quantified. [3] Sadly, the indications that pursuing a policy of growth of any cost would eventually lead to us to calamity were already identified in 1972 by the Club of Rome. Meanwhile international policy such as the UN’s Sustainable Development goals, the Paris Climate Agreement or any number of high profile climate legislation seem unable to make any real empirical progress with political institutions increasingly paralysed by the rise of a new politics of populism fueled by an increasing disenfranchisement with the political establishment across the political spectrum. Encouragement can be had from the increasing mobilisation of a new generation of climate advocates such as Greta Thunberg or the gains made by green parties in the 2019 European Parliament elections in the wake of the Extinction Rebellion protests. Nevertheless, the outlook remains bleak and it is now certain that within a generation the realities of climate change and resource scarcity will require us to completely rethink the way that we live, work, consume and interact with each other and our environment at all scales.

Despite on-going sustainability efforts and increasingly earners public discourse and activism, the building sector remains responsible for around 40% of the European energy consumption[1] and 50% of the overall use of material resources. In addition, around 60% of the waste in Europe (approx. 750 Mio. Tons) is classified as construction and demolition waste (CDW)[2] generated by the building sector. The challenges facing the building sector to meet the targets set out in the Paris climate agreement are enormous and span scales and the traditional disciplinary boundaries.

2. The Post-Fossil Architect

In order to face the challenges facing the profession in times of upheaval, there is a huge potential for architects to use their specific skill set to co-produce new knowledge that can help society combat the challenges posed to the built environment by climate change. However, this will require us to reconsider the position of the architect in a wider societal context. Architects occupy a difficult position in the climate debate, because on a basic level, an architect is someone who designs and constructs buildings – traditionally ever more, bigger and more resource intensive buildings. This is why clients appoint architects, and it is without a doubt seen as our key competency and it is the service for which we usually receive financial remuneration. Furthermore, designing buildings receives the most focus in our education and it is the skill with which we generally most identify ourselves – nearly all of our institutions, associations and presumptions are built on this premise.

For the next generation of young designers scarcity will be the theme that dominates discourse in the profession for the near future. The way that the dynamics of material scarcity will affect all aspects of our lives is only just beginning to be researched. Yet the way that we define and understand scarcity as a concept has potential to open new fields of agency for design practice. Working within the limits of externally defined boundaries has always belonged to the creative process of architecture and design – typically the architect is forced to work within the limits of the site or budget provided by the client in order to be able to realise their masterpiece. However, when we consider design practice as more than just the creation of a series of more or less beautiful of objects, and more as an intervention in an increasingly complex series of processes that react to existing systems and contexts, then working with scarcity is already an unavoidable part of our remit.

Over the last decade neoliberal economists and politicians have used scarcity as the legitimisation for a number of highly damaging austerity measures, cutting social support, infrastructure and services in the name of limited resources. Jeremy Till formulates the central presumption at the heart of this idea of scarcity as a false belief that, “human needs are unlimited, but the means to achieve them are scarce” [4]. In their essay “Design of Scarcity”, Goodbun et al. challenge this idea and argue for a new understanding of scarcity as a dynamic socio-material condition, one arising from the uneven distribution of power and resources and one which can be designed and influenced, rather than an inevitable endgame for the global consumer economy [5]. This understanding of scarcity has serious implications for design practice and provides the framework to imagine a new and expanded field of agency for designers more able to affect change in a rapidly changing globalized society where the challenges posed by climate change span institutional and disciplinary boundaries.

3. The University

Yet despite these challenges architectural education at most international universities is still largely based on the model of the École des Beaux Artes from the early 19th century **Error! Reference source not found.**. The daily image at the nearly 60 architecture schools in Germany for example is characterized by work and presentation formats that put students in competition with each other and design studios set up as a masters studio with a teaching person who sets the content and task. A lack of reference to 'reality' - the architectural practice and the challenges of the non-academic world - is often formulated as a critique to this system. According to the UNESCO/UIA Charter, the only paper on architectural education that is globally agreed on, ‘greater diversity is needed […] in architectural education and training‘.

In times of scarcity of resources, where the effects of climate change are threatening the lives of many people and leading to global migration and conflict, architects are also calling for a radical shift in thinking. An important approach is the training of young architects, who have the ability to reflect critically, to independently develop new solutions and thus to be aware of their responsibilities as planers. In order to make global urbanization and construction processes socially, ecologically and economically sustainable and thus future-oriented, architecture practice and education must use a cooperative working method across the borders of disciplines and social classes.

4. Learning Approach

The Natural Building Lab (NBL), which was founded at the end of 2017 at the Institute of Architecture of the Technische Universität Berlin, is seeking a methodology to address imbalance by enabling students to learn in a self-determined and collective process. Many of the cornerstones of the concept deliberately challenge existing notions of authorship and authority established within the university and professional context. This section will outline some of the key aspects of the Lab’s learning approach and how they relate to the idea of a post-fossil architect outlined above.

4.1. DesignBuild Methodology

The DesignBuild methodology dates back to the Community Design Movement in the US in the 1960s, whereas similar approaches can be witnessed before that time in schools like the Bauhaus, Talisien West or the Black Mountain College. Today there are more and more architecture schools worldwide undertaking projects where students are physically involved in the realisation of their designs in collaboration with local communities and NGOs. Networks like the DesignBuild XChange Network [7] and the Design for the Common Good network [8] are showing the power and the relevance of this global movement.

The first DesignBuild Studios in Europe, apart from the endeavors of the 1920s and undertaking regular, yearly project cycles were established in the late 1990s – the Mexikoprojekt (Prof. Ingrid Götz, TU Berlin), the DesignBuild Studio at TU Wien (Peter Fattinger) or the Live Projects at Sheffield School of Architecture. For 20 years a huge number of projects was realised by different chairs at TU Berlin. The EU funded research project “European DesignBuild Knowledge Network” (EDBKN) [9] initiated by Ursula Hartig, Simon Colwill and Nina Pawlicki at Habitat Unit (TU Berlin) as part of an international consortium developed criteria for DesignBuild projects and has set up the international network dbXchange.eu.

Definition of DesignBuild and its methodology by EDBKN: DesignBuild Projects are components of higher education in the field of built environment that allow students to be physically involved in the materialisation of their designs. DesignBuild Projects must: be based in higher education; have a brief, budget and timeframe; be built; have students involved in the design AND construction of the project; be of architectural, social, cultural, scientific, technical or artistic relevance. The Natural Building Lab is carrying on the DesignBuild tradition at TU Berlin.

4.2. Trans-disciplinary Collaboration

The image of the architect established by the modernists was of one expert who could control the building process from the start to finish. The complexity of the contemporary building process requires skills and knowledge that go well beyond the expertise of one discipline. This has resulted in a fractured field where experts from different disciplines struggle to integrate their different areas of knowledge into a linear, phase-based design process, which is often not conducive to collaboration. By integrating input from other disciplines at an early stage of the design process and fostering a truly collaborative instead of competitive spirit, it would be possible to eliminate many of the process-based difficulties that arise and thus improve the efficiency of the project process by recognizing synergies, opportunities and problems at an earlier stage. Yet while inter-disciplinary working remains a popular buzz word in the industry, in reality restructuring processes to truly enable trans-disciplinary collaboration is a huge challenge and requires a bottom-up rethink. It is of huge importance that the different disciplines become used to working collaboratively during the early stages of their studies.

4.3. Co-production and Co-ownership

We see a changing role for designers in a societal context, one of the architect as a moderator and facilitator. There is a huge potential for architects to use their unique skill set to integrate skills, knowledge and input from project actors into complex design processes by working on an equal level. Only through an integrated and participative methodology can true shared ownership of outcomes be achieved. By placing a high value on this input from actors outside of the profession, it is possible to co-produce knowledge and foster a shared authorship. Thus architecture becomes a tool and vehicle to instigate bottom-up change in society, as opposed to being limited to an artistic service only available to the few.

Figure 2. Building Cycle, structural test, January 2018

Figure 3. Community Collaboration, Building Cycle December 2017, CRCLR hall, Berlin Neukölln

4.4. Self-determined learning

Heutagogy is an emerging field of research into the effectiveness and practice of self-determined learning processes [11]. With the proliferation of digital media the way in which we access and consume knowledge has changed beyond recognition and pedagogic methods and institutions are struggling to catch up. Traditionally universities place a high value on the one-way transfer of knowledge from teachers to students and this is the premise upon which accepted teaching formats and institutions are built. Yet when we move from the perspective of “knowledge hoarding” to one of “knowledge sharing”, we begin to unlock the true potential of a two-way learning process for both the “teacher” and the “student” (Fig 2 and Fig 3). Furthermore with the ease in which digital media allow us to access new knowledge, there is a potential for institutions to place a renewed focus on skills (how to apply knowledge) and most importantly values (why to apply knowledge).

5. Teaching, Research & Practice

The main activities of the Natural Building Lab can be roughly grouped into three disciplines – learning, research and practice, with synergies and overlaps existing between them. For instance, a DesignBuild studio project can easily incorporate aspects of all three themes as will be discussed later in this paper. The emphasis is on blurring the boundaries between these often-separated aspects of architectural practice at an institution by focussing the sharing of knowledge between projects. This section will briefly outline the way that the approach is applied in these three fields.

5.1. Learning (The Studio)

The central part of the Lab's learning approach is the design studio, in which 15 to 35 students in the Bachelor or Master program collaboratively produce solutions to a changing set of themes. One of the challenges of the studio format is an established culture of competition among students, one born out of the competitive nature of design practice – the design competition being the traditional battleground in which architects pitch their ideas against each-other to win a contract. Yet the anonymous design competition reduces the scope of an architect's services to an artistic/technical service, especially because the competition always starts with a fixed and non-negotiable brief. Basing the studio format solely on the reference of a design competition hugely limits the creative potential of the process and only serves to further entrench a culture of "knowledge hoarding".

As a critique to this culture NBL studios place an emphasis on collaboration by encouraging participants to work in larger groups of 4 and upwards, sometimes even the whole studio will work together on one project. This forces students to confront themselves with the challenges of working in large and diverse groups, whether by finding ways to reach a consensus among a group of individuals from varying cultural backgrounds or by learning how to best utilise the varying skills and interests of group members, they are able to develop skills essential for a collaborative and open-minded design practice.

The studio also fosters collaboration by challenging the accepted formats of presentation and tutorials, where an emphasis is usually on the students being given direction by a panel of experts within a highly charged and hierarchical atmosphere. This format retains then principle that the instructor somehow is possessed of the answer, and to obtain it the student must follow the rules [12]. NBL's key format is a weekly stand-up discussion set up as a circle, this challenges the established hierarchy between teacher and student. Prior to the discussion of a project another group is identified as responsible for feedback and this group will start the discussion. Members of the chair will join the discussion but not pass judgement on a given project, the emphasis is on a collaborative learning process for student and teacher alike. This method, working on an eye level within the whole team promotes the self-discovery of the students and enables them to contribute each with their own qualities to the process. Another challenging culture is the value of students work, typically students work for the whole semester on a design studio, which after a presentation is added to the portfolio and then forgotten. Furthermore, students are not deemed as capable or responsible enough to work with real clients or materials – first one has to learn the technical skills before being able to apply them in practice. The DesignBuid methodology clearly challenges this tenant and the application of this in practice will be discussed in a further section. Yet the benefits and potential of giving students the opportunity to apply their ideas in a real context greatly changes how they consider the ownership of their ideas.

An NBL studio will always aim to provide students with the chance to work with real contexts, actors and materials during the design process. By providing this context for their work, participants gain valuable experiences that are for their future practice. (Fig 4.)

5.2. Research (The Lab)

The subject of what constitutes research within the field of architecture is one that has always been discussed controversially. Especially the question of whether design in and of itself can be considered as a form of research is one that is especially bitterly contested by thinkers on both sides of the divide. The Natural Building Lab aims to place research within the context of shared knowledge production integrating it into the other disciplines of research and practice. With an established expertise in the field of natural building materials and a strong link to a number of projects completed by the office ZRS Architekten Ingenieure, the NBL is able to provide a bridge between new and experimental concepts and its applications for users on the ground.

Design studios can be conceived on the basis of findings from a research project, as with the award-winning project Infozentrale auf dem Vollgut which will be discussed in more detail in the following section. In that case providing students with access to ideas and concepts about the use of recovered timber as a resource for new construction, which eventually led to the realization of a pavilion, allowed the research project to showcase its findings in a larger scale and more prominent case study project than would have been otherwise possible. Furthermore, the experimental nature of the project provided further findings and knowledge, which could be reintegrated and furthered by the research team. Again, in this instance the idea of individual authorship is challenged by the production of new knowledge in a collaborative integrated process.

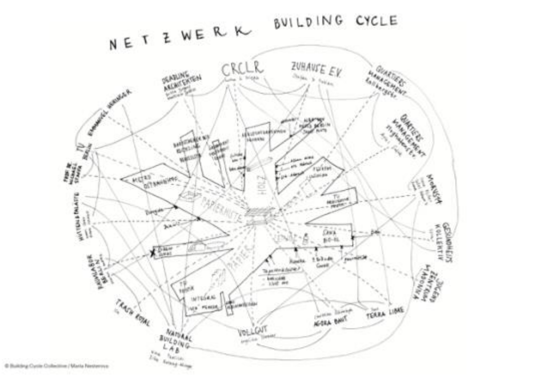

Fig 4. Building Cycle network, partner connection and material resourcing

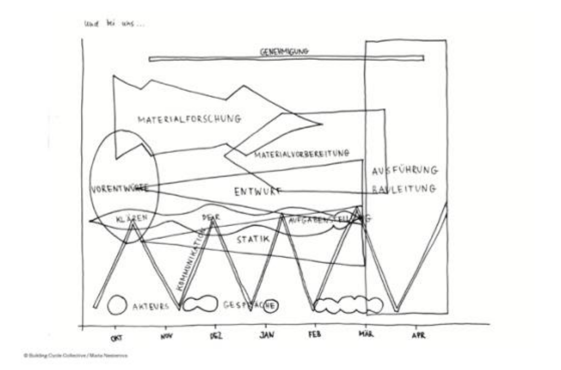

Fig 5. Building Cycle, workflow, design and construction

5.3. Practice (The City)

The NBL emphasizes a *critical* architecture practice based on a critical understanding of external conditions, in this case external to the context of an architecture school. This practice can take the form of hands-on construction and experimentation in 1:1 or an application and testing of ideas developed in the studio to a real context.

Often design projects will be initiated with the set aim of designing and realizing a building task. Architectural design often takes place on paper, or increasingly on a screen, and while it is possible to teach the theory of construction, there is no substitute for hands on experience. The realities of a DesignBuild project also show the inadequacy of seeing a building project as a linear process in which a series of phases are completed one after another (Fig. 5.). This mindset limits the ability of different disciplines to locate synergies at different stages of the project by always focusing on one complete package of work at each stage of the process, an aim which understandably becomes the focus of each party's attention.

The opportunity to experiment in 1:1 with real materials gives students the chance to apply their knowledge responsibly in a creative context. The Lab is also equipped with a 300sqm research and workshop space where 1:1 prototypes, pre-fabrication processes and research on earthen materials can take place all year round. Furthermore, the NBL Hub, one of the results of the first master studio in

2017/18, is a 70 sqm reversible arch structure based on the idea by Leonardo Da Vinci designed to be transported by cargo bike and assembled by 2 people within 10 minutes. The Hub provides a mobile outpost or workshop space and can be used to provide a space for events and encounter in the neighborhoods where projects are based (Fig 6 – 8).

Figure 6. NBL Hub transported by cargo bike

Figure 7. NBL Hub, assembly

Figure 8. NBL Hub, mobile outpost

6. From Building Cycle to "Infozentrale" – the first NBL project

The "Infozentrale auf dem Vollgut" was designed and realised by a group of 36 students as part of the BUILDinG CYCLE design studio from the Natural Building Lab at the Technische Universität Berlin in Winter Semester 2017. In co-operation with the research project RE4, a building embodying circular construction principles was realised from waste materials as a DesignBuild project, offering an answer to questions relating to resource-positive construction in an urban context and embodies a new method of architectural production for a post-consumer society. In the opening weeks of the project the student groups undertook a material research, where innovative low-tech constructive elements were created using a wide range of waste materials Through this research the groups established a network, through which they were able to source larger amounts of the waste materials used for the building – recovered timber and cardboard. The load bearing structure of the building is formed from timber recovered from local demolition sites and a dismantled architectural installation from the International Garden Festival 2017, thus providing a second usage cycle for this valuable resource. The 8m x 10m roof structure is formed by a pre-stressed grid of layered and interlocking re-used timber beams with reversible connections designed for disassembly. For the wall elements an experimental system was developed utilising stacked upcycled cardboard fruit boxes filled with shredded paper as insulation and covered with recovered large format posters and plot drawings – common waste materials within the architecture faculty. The project embodies circular construction principles and serves as a prototype for a LowTech post-fossil architecture based on the realities of resource scarcity and climate change (Fig 9 and Fig 10).

Figure 9. Infozentrale, installation roof construction, timber beam lattice grid

Figure 10. Infozentrale, raw construction, timber beam grillage, fixed columns

During the design and construction phase, the students networked with around 200 participants on and around the site in order to get a deep understanding of the situation and to anchor the project locally and to resource materials for building (Fig. 4). The project set new standards for the Natural Building Lab's work and achieved feats above and beyond the aims set at the project's outset. The entire pavilion utilised connections and materials that could be easily executed using hand tools and with the minimum of previous experience, as such the building sets a standard for a LowTech building system that can be adapted and reformed by the end user. Thus the project sets itself up as an alternative to the standard and highly commercialised standard methods of architecture production typical of the fossil-economy. Furthermore the project succeeded in establishing a number of new material networks and cycles within the neighbourhood, connections which have been documented and can be further built upon in further projects. As a DesignBuild project the studio succeeded in integrating a wide range of inter-disciplinary collaborations both within the university and with actors on the Vollgut Areal and from the surrounding neighbourhood. The finished Infozentrale (Fig 11 and Fig 12) serves as an embodiment of these principles and as a built prototype for a post-fossil architecture based on the realities of resource scarcity and climate change. The Infozentrale has since been awarded as a runner-up in the Deutsche Holzbau Preis 2019 and with a special prize in the Holzbau+ Competition 2019.

Figure 11. Infozentrale, south-west elevation

Figure 12. Infozentrale, indoor space.

7. Taller Tropical, Moravia, Medellin

The Taller Tropical Moravia is the latest in a series of interventions which seek to promote environmental education in the Moravia neighborhood of Medellin, through the collective construction of a community space for meeting and learning. The project was conceived by the Moravian community leaders and international students, within the framework of Urban Lab Medellín | Berlin, a cultural and academic exchange between the two cities that began in 2016 with the goal of developing local solutions for global challenges.

Starting with the premise that the integral and sustainable development of cities can only be built collectively, the platform linked inhabitants, civic movements, NGOs, artists, students and professionals from different disciplines, and actors from the private and public sectors; to discuss, research, design and build together. During summer schools in Medellin and Berlin, workshops, events, conferences and interventions were held in the public space, such as the renovation of the Tropical Oasis Stairs in Moravia.

Throughout this process, scenarios and strategies were developed to transform Moravia into a sustainable model neighborhood. At the Berlin Summer School in July 2017, 9 Moravian leaders raised the idea of converting El Morro areas into a laboratory for environmental and food education. This proposal called "Sowing Life" (Sembrando Vida) was elaborated with students of several universities and the inhabitants of Moravia. Due to a certain slowness of reaction from the public administration, the project could not be executed this year. However, the process has raised awareness on the issues that the project sought to address, a wide network of allies and a wealth of knowledge. The community continued asking that the project be carried out and promoted the development of a Plan B: the Taller Tropical Moravia in September 2018. The project is a collaboration with and based on previous projects at Habitat Unit, TU Berlin (Fig 13 – 15).

The Taller Tropical was designed and realised by an inter-disciplinary design studio at the Natural Building Lab with architects and civil engineers. During the realisation phase participants collaborated directly with local tradesmen, a Columbian bamboo construction collective, local school children and members of the local community. The project is the embodiment of shared ownership, authorship and production and an example of how a small intervention can instigate larger change processes in an international context.

Figure 13. Taller Tropical Detail, platform

Figure 14. Taller Tropical, two-story bamboo structure located on the first floor

Figure 15. Taller Tropical Detail, frame corner

8. Conclusion & Outlook

After nearly four semesters of activity, a broad network of projects and partners has developed around the Natural Building Lab, and this continues to grow with each new project. We understand the Lab as a network through which diverse actors can co-operate in activities aiming to induce long-term societal change for the betterment of the planet and those who inhabit it. With the first class of NBL "graduates" departing the university this Autumn, we are excited to see how this network will develop and how the values and skills learned during student's studies can be applied to the wider working context of post-university graduate jobs. Certainly, every semester has seen a core group of studio participants forming a "collective" to further pursue the themes and collaborations introduced during the semester in the longer term. This is a very encouraging dynamic and shows that giving students the opportunity to work with real people, places and materials allows them to develop the confidence to pursue their ideas independently and to position their ideas with the context of wider societal and architectural discourse. Furthermore, it allows students to form their own ideas about the role of an architect in a societal context based on these experiences.

The Lab's network is also growing to encompass a number academic and industry-based collaborators for research projects spanning from the circular potential of earthen building materials to questions surrounding what we can learn about a climate adaptive and resource efficient architecture from pre-fossil cultures. The findings from these projects set the basis for further integration of teaching, research and practice activities.

In conclusion the challenges facing young architects in times of scarcity are huge and will require them to question the established norms and preconceptions existing in architectural practice at large.

Only by placing an enhanced emphasis on the collective over the individual and collaboration over competition will the sector by able to successfully navigate the dramatic changes that will be required to remain relevant in the face of climate change and resource scarcity. The Natural Building Lab is seeking to equip young designers with the knowledge, skills and values they will need to define a new role and potential for architects in a post-fossil society (Fig 15).

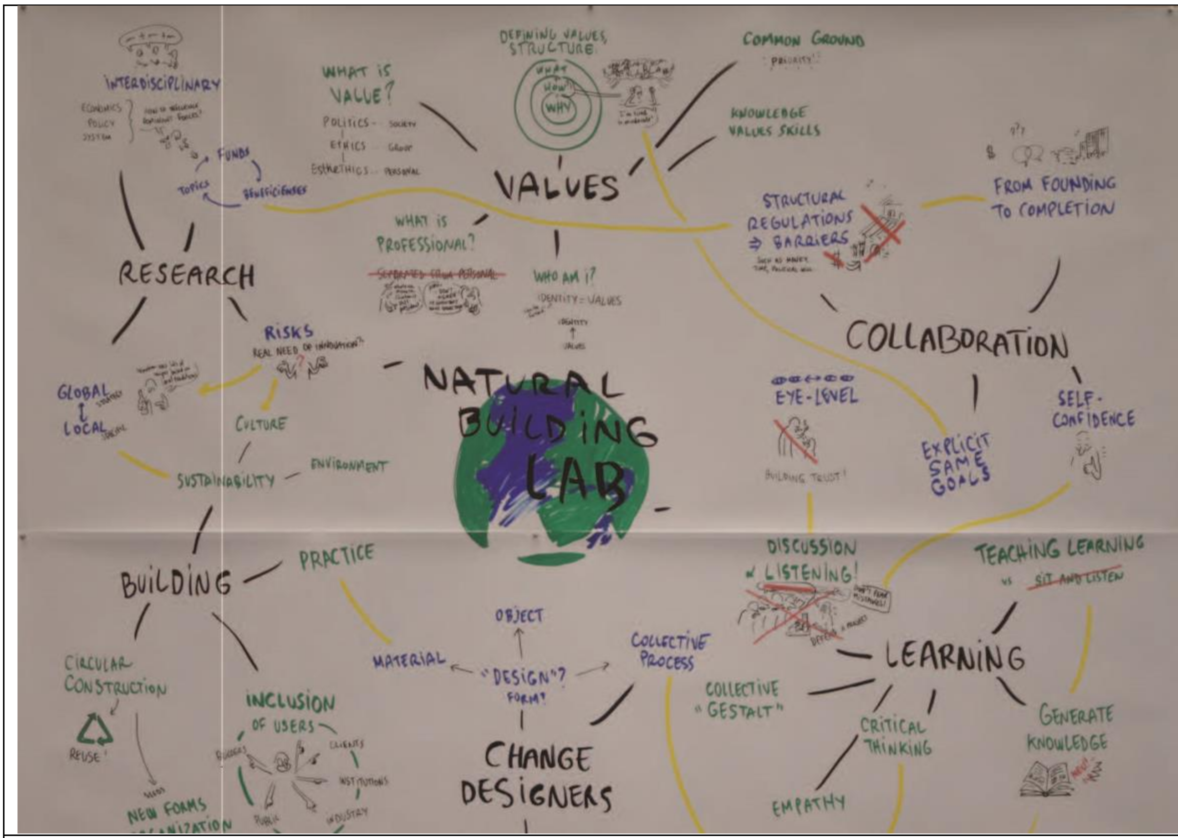

Fig 16. Natural Building Lab, Launch April 2018, NBL Documentation of discussion about the direction of the department with 50 members of international network.

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Affordance-based Design Method: A Case Study of University Campus

Gupta D[1], Uma Maheswari J[2]

[1]PhD Scholar, Department of Civil Engineering, Indian Institute of Technology Delhi, India
[2]Associate Professor, Indian Institute of Technology Delhi, India

durvagupta492@gmail.com

Abstract. Development of a built environment encompasses urban design, land use, transportation system, and accommodates patterns of human activity within the physical environment. Holistic development of built environment requires a multidisciplinary design team of urban planners, architects and sustainability advisors from an early design stage. Literature and industry-practices show growth of designer's techniques and competencies, sustainable development capabilities, and user-centric prospective in the early design. However, there is a lack of systematic method and all-inclusive approach to design a built environment. Thus, proposed research aims to develop a design method which is user-inspired, stakeholder conducive and environmentally conscious from an early design stage. To achieve this aim, an affordance-based design method is proposed and demonstrated through a case study of university campus. Affordance-based design method has been used for design of complex systems by capturing user needs, stakeholder ideas and generating design options. The proposed design method provides decision-making guidelines to designers, design space to incorporate stakeholders, and affordances to achieve sustainability. The proposed design method has potential to shift design and development of built environment from designer-controlled process to systematically organized process.

1. Introduction

The goal of urban design of built environment is to improve the quality of life, enhance system efficiency and limit environmental impacts. Built environment encompasses all forms of buildings; civil engineering infrastructures both above and below ground such as transportation system, utility systems, and telecommunication systems; and landscapes around buildings [1]. Urban design of built environment is closely linked with the user behavior and requirements. The design of every system of built environment is initiated by analyzing the user needs. Designs are more effective when user needs are considered and retained throughout design and development of built environment [2]. Observations from design practice suggest that user needs are considered at the start of the development but are often neglected during detailed design due to inadequate user-centric approach.

Another important aspect linked with the built environment design is the need for coordination among key stakeholders such as civil engineer, architect, MEP designer, and environmental advisory during designing, planning and constructing. However, stakeholder coordination is still a bottleneck in the design management [3]. Additionally, sustainable development goals of 'sustainable cities and communities' recommend environmentally conscious design of built environment. Green building certification programs and energy efficient technologies are some initiatives in this direction. However, incorporating environmental measures in a design process is multidisciplinary in nature and thus becomes a challenge [4].

According to the Royal Institute of British Architects, the design process consists of three sub-stages: concept design, developed design and technical design [5]. Hence, the three aspects, viz. user requirements, stakeholder integration, and environmental consideration should govern the design in all the three sub-stages. However, in practice, sequential design process is not being ensured.

To address this gap, the research extends affordance-based theory to devise a structured approach for design of built environment. Maier and Fadel have applied affordance-based theory to the design of artefacts [6]. Various systems of built environment can be treated as artefacts and designed by following a set of procedures to fulfil the needs of user. This structured approach is termed as Affordance-based Design Method (DM) which aims to incorporate user needs, stakeholder coordination and environmental consideration. The proposed DM is demonstrated through a case study on urban design of a university campus. The observations from the case study are discussed in the light of existing literature to emphasize the potential of proposed DM.

2. Literature Review

Several engineering design theories have evolved over time as summarized in Figure 1. Design has been addressed using two theoretical paradigms. First is Simon's Sciences of the Artificial (1969) based on normative, rational and structured approach. It follows certain rules and procedures, and popularly discussed under design as 'science' [7]. Second is design as reflective practice given by Schon's (1983). It aligns with industry practice driven by practitioners' creativity and ideas rather than a set of rules [8].

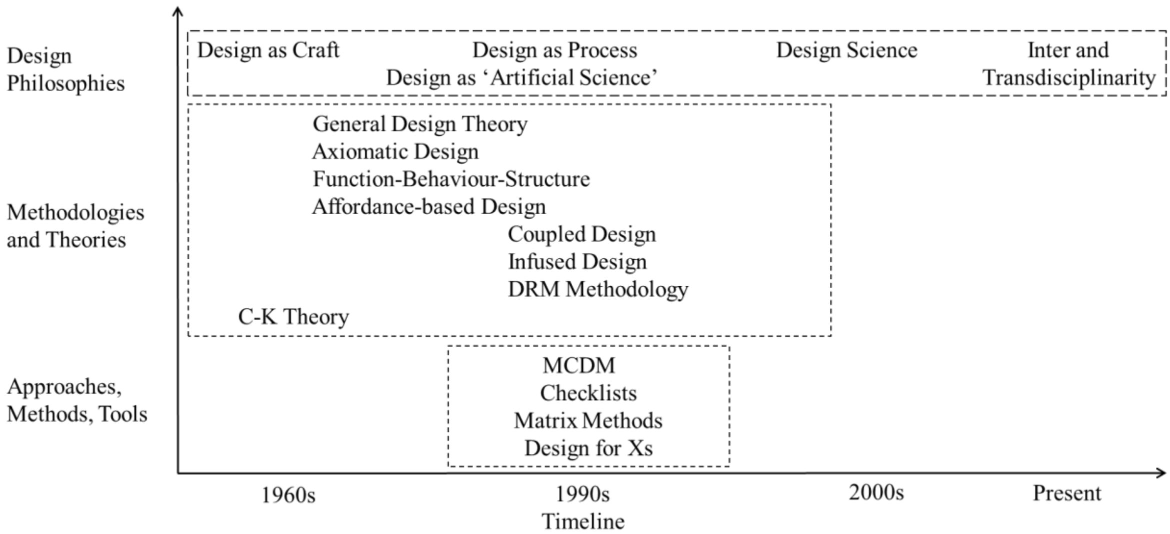

Figure 1. Evolution of Design Theories

Other major theories in engineering design research are – German systematic engineering design by Pahl and Beitz [9], Axiomatic design by Suh [10], Total design theory by Pugh [11], C-K theory by Hatchuel and Weil [12], Design research methodology (DRM) by Blessing and Chakrabarti [13], and Function-behavior-structure methodology by Gero [14].

Maier and Fadel [15-17] argued that existing engineering design theories are insufficient to provide a systematic design method. Thus, they formulated an affordance-based design method. The concept of affordance was first introduced by psychologist James J. Gibson during 1979 in the domain of ecological and perceptual psychology [18]. Later, Norman applied the affordance theory to the design domain and demonstrated human-computer interaction [19]. Maier and Fadel brought affordances in engineering design by asserting user-artefact interactions [6]. The term *affordances* of an artefact means what an artefact should provide or offer. It is described as a set of interactions between artefacts and users, designers and users, and a pair of artefacts, as shown in Figure 2. The complex nature of these interactions give rise to two types of affordances – (i) Artefact-User Affordances (AUA) describes interaction between an artefact and users; and (ii) Artefact-Artefact Affordances (AAA) describes interaction within artefact subsystems.

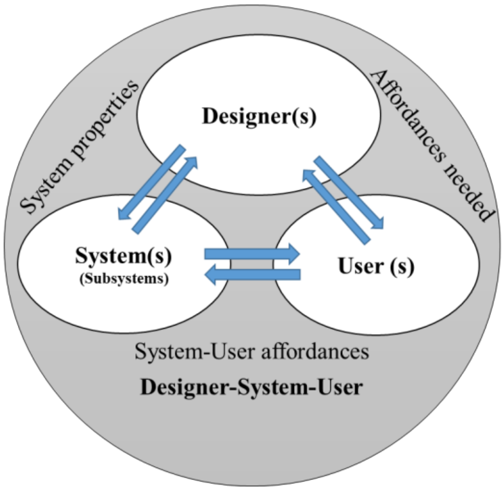

Figure 2. Affordance Interactions within Designer-System-User Structure [6]

The design of built environment is similar to the design of product. Hence, systems of built environment can be considered analogous to artefacts. In built environment design, AUA describes the relationship of a system's users with the system design, whereas AAA describes the complex interactions taking place between key stakeholders and technical aspects of the system. AAA makes it easier to communicate and concurrently design the systems. The concept of affordance in built environment design is suitable because it entails relationship between two systems, incorporates users, and allows proper use of functions of a system in design. These features are included in the DM.

3. Affordance-based Design Method (DM)

Maier and Fadel (2006) defined two fundamental affordance-based methods: a high-level affordance-based design process and a method for designing individual affordances. Previously, high-level affordance-based design process has been applied on several case studies of product design [20-22]. Some prominent works which followed affordance-based design method are generation of consumer specific design specifications [23], and automation of embodiment and detailed design phases of product design [24]. These studies demonstrate the benefits of systematizing and structuring the design process [25, 26]. Thus, affordance-based design method can be perceived as sequential method which can be adopted at the design stage. However, this method has been applied so far only in product design.

The proposed DM is similar to the existing affordance-based method in product design. Figure 3 is a schematic representation of the proposed DM which consists of two steps. In the first step, value adding and non-value adding affordances are identified and user information module is prepared. Then, a designer information module is prepared to enlist technical inputs for the affordances and develop a generic affordance structure. The module guides designers about what affordances they are expected to provide through a system. It also ensures that any affordance associated with a system are not missed. Further, affordances are prioritized based on the preferences of users and designers. Thus, the first step generates an organized affordance structure at the specification level based on system-user affordances.

In second step, individual affordances are chosen, and their detailed affordances are created. User-groups associated with individual affordances were also mapped. Then, system properties that affect the affordances were identified. Further, properties of other systems that affect the individual affordances were documented. Next, targets and bounds for each property were determined. Since built environment design is constrained by building codes and bye-law, all such constraints associated with affordances were identified at this step. Prescribed numeric range of these constraints adds a quantifiable parameter to a design. At this point, designer gets the understanding of properties, targets, bounds and constraints of the system that affect the affordance. The second step was repeated for all individual affordances to populate detailed affordance structure. Then, effects of the property settings of an individual affordance on other affordance were analysed. This provided a comprehensive affordance structure for the system design. Such a comprehensive affordance structure will support generation of multiple design options.

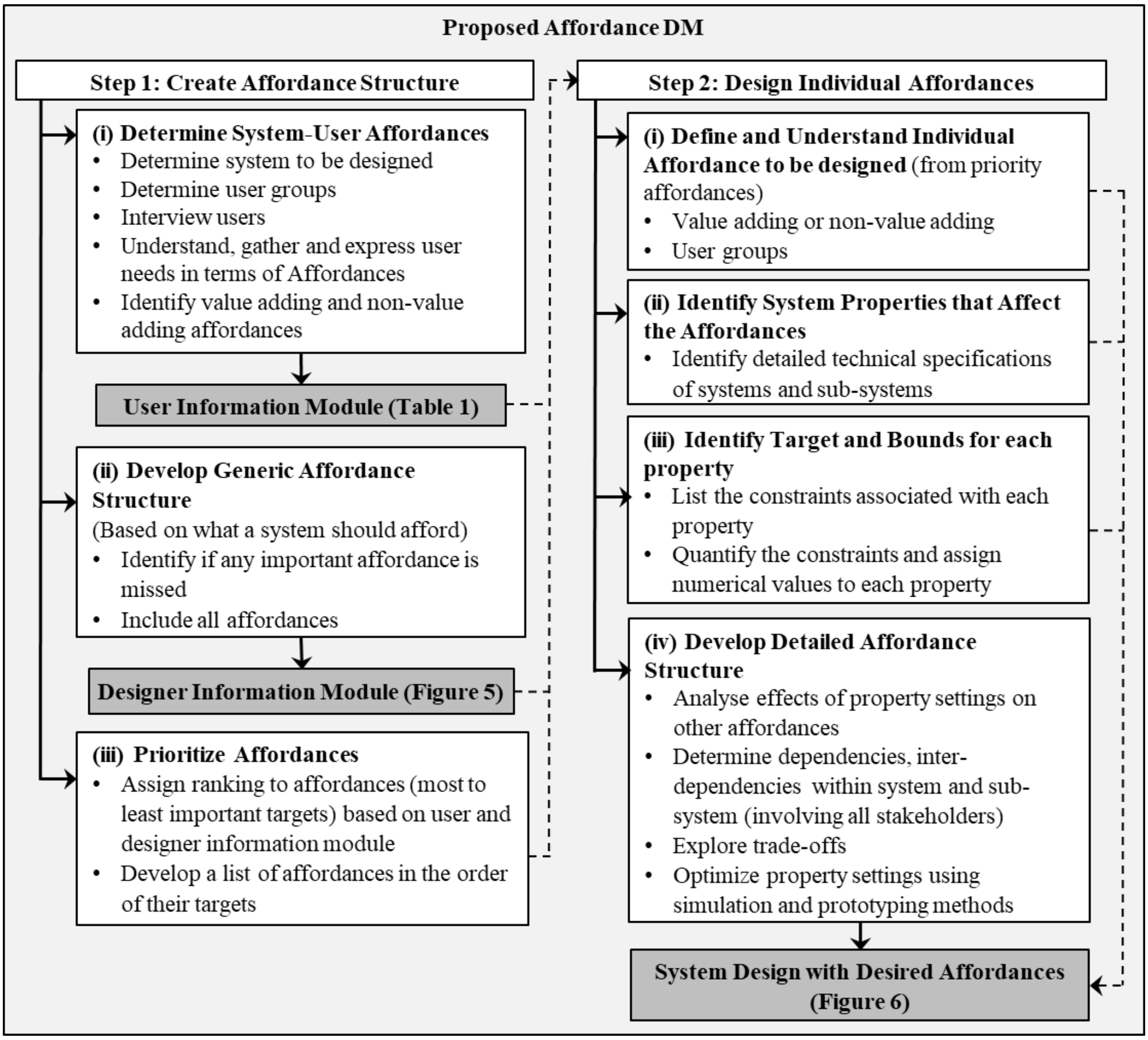

Figure 3. Framework of Affordance-based Method

4. Case Study

The application of the proposed DM is demonstrated through a case study on the design of a mobility network system in the built environment of a university campus. The campus consisted of hostels for students, residential buildings for employees, academic buildings and community buildings. The anticipated growth of campus population is 25%, and its design aims to provide sufficient built-up spaces, building services, utilities and mobility networks in future. The scope of the case study is limited to identifying the affordances and system parameters of mobility network.

The data was collected through participatory action research. The first author participated in the series of design meetings held among users, client and designers. User needs were identified by the designers through five focused group-discussions with the user-groups listed in Figure 4. Each group was represented by five to seven users and the average length of each discussion was three hours. The data collected from the group-discussions was used to develop a designer-system-user structure as shown in Figure 4. This structure forms the basis of designing affordances for the case study.

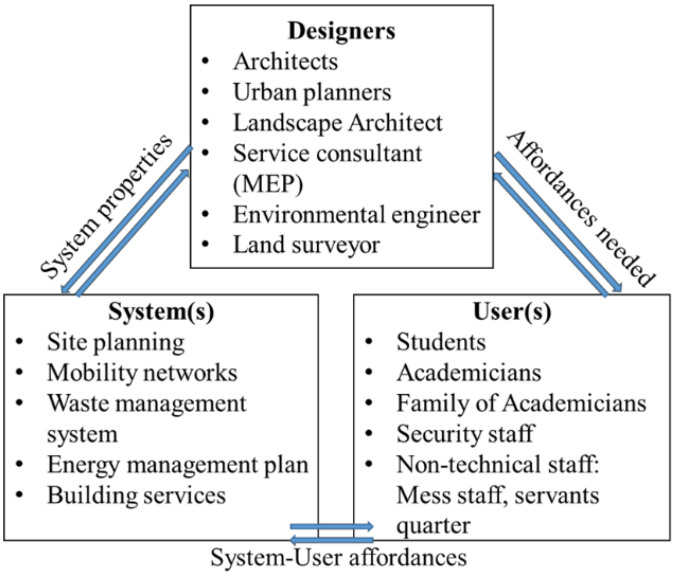

Figure 4. Affordance related Interaction within a Designer-System-User Complex Structure

The collected data from the participatory meetings was analysed for the design of mobility network system using the proposed affordance-based DM. Table 1 shows resultant User Information Module with value adding and non-value adding affordances for mobility network design (Figure 3, Step 1 (i)).

Table 1. Affordances for Mobility Network

Value adding affordances (positive)	**Non-value adding affordances (negative)**
Provide thorough fare movement within campus to all users	Minimize traffic conflicts at some points
Connectivity of campus with the city	Reduce travel time
Facilitate pedestrian movement to all users	Reduce trip length
Integration of all modes of transport system	No Congestion at peak hours
Incorporate comfortable, energy efficient and sustainable ways of transport	Reduce extent and distribution of roads in campus
Provide safe and secure pathways	Reduce urban heat island effect
Access to visitors/city people	
Maintain and maximize green cover	

Next, subsystems of the mobility network such as parking spaces, pedestrian pathways, and vehicular traffic system were identified (Figure 3, Step 1 (ii)). Corresponding technical input for the affordances led to a Designer Information Module as shown in Figure 5. One of the affordances–to reduce urban heat island–is selected for the illustration of 'designing individual affordance' (Figure 3, Step 2 (i)).

The characteristics of Urban Heat Island (UHI) which affect the design specifications of mobility network were listed by the designers. Alongside, potential interactions among the characteristics of UHI and the specifications of other systems were identified. For example, UHI is affected by building design, building form, building orientation, along with roof and wall design. Shaded blocks inscribed in circles

A1-A2 of Figure 6 depict interactions of UHI affordance with the design specifications of mobility system (Figure 3, Step 2 (ii)).

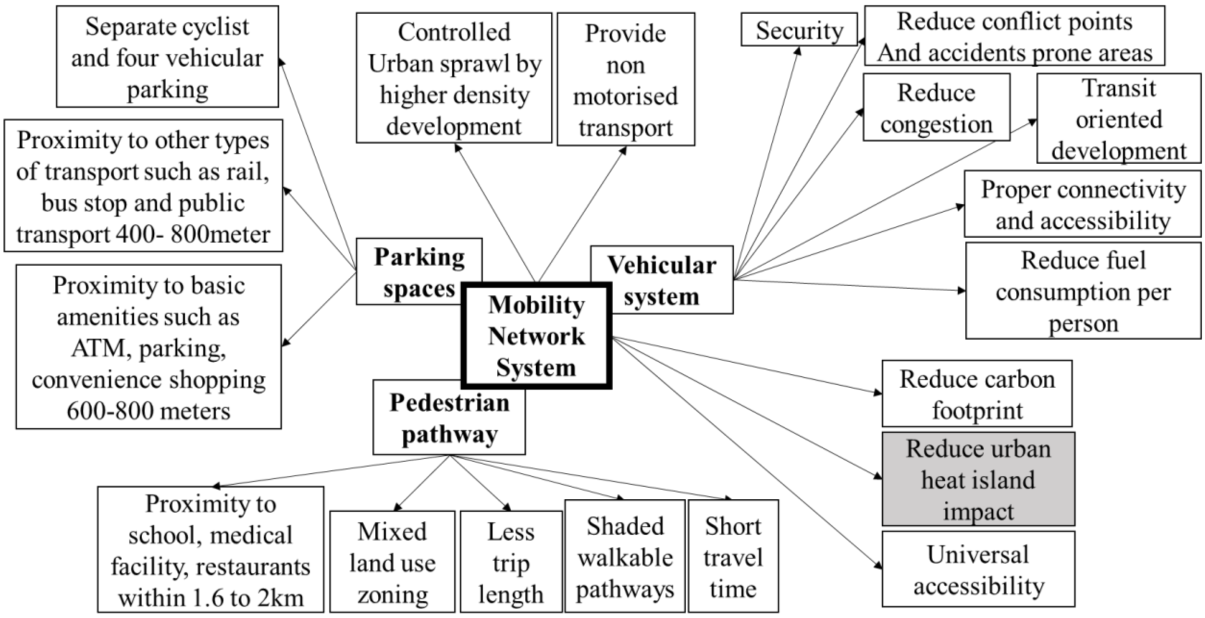

Figure 5. Generic Affordance Structure for Mobility Network System

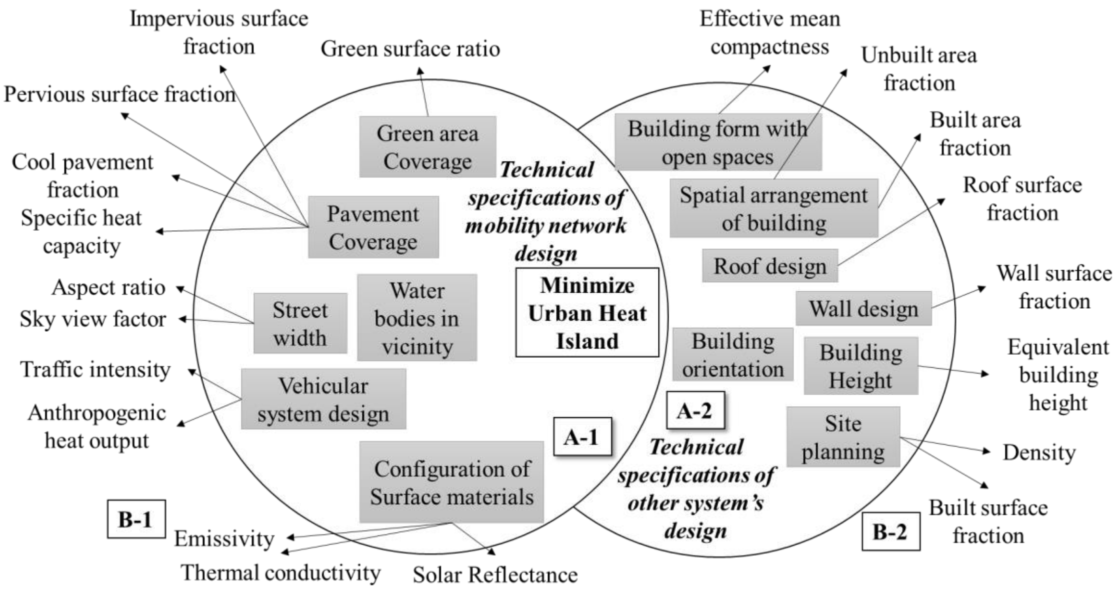

Figure 6. Detailed Affordance Structure to Minimize Urban Heat Island Impact for Design of Mobility Network

After analysing the first level of interaction in A1-A2, next level of interaction (Figure 3, Step 2 (iii)) quantifies associated characteristics of UHI as shown in zone B1-B2 of Figure 6. For instance, 'street width' is a specification of mobility network which is associated with UHI affordance. Street width is quantified using two parameters, 'aspect ratio' and 'sky view factor'. Aspect ratio is the mean height-to-width of street canyons, and sky view factor is the fraction of sky hemisphere visible from ground level. By optimizing these two parameters, UHI can be minimized in mobility network design. Similarly, other design specification can be translated into quantified parameters which will help in simulating alternate design options, analyzing trade-offs and optimizing the system design. Quantification of these parameters will be based on bye-laws and standard code of practice. This provided a detailed affordance structure for one affordance (Figure 3, Step 2 (iv)).

Subsequently, the detailed affordance structure was extended to all affordances to obtain an overall mobility system with desired affordances. The resultant affordance structure will guide the designer as to what the system should offer and how the design should proceed with affordances.

5. Discussion

In the selected project, the designers have approached the design of university campus based on their experience and prevalent architectural knowledge. This approach is similar to design as reflective practice given by Schon. In contrast, this research has applied affordance-based DM, which comes under the theory of design as 'science', on mobility network design of university campus. In this research, the concept of affordance is applied to the design process only for problem definition and conceptual design of built environment. The affordance-based DM (Figure 3) demonstrated through the case study improves the existing design process in the following manner:

- DM paves a way to capture the user needs in the form of affordances and allows them to interact with the designer knowledge and system properties (Figure 3, Step 1(i)). Such systematic consideration of user needs cannot be ensured through existing design process. The study can also be extended to subsequent stages of detailed design and technical design.
- Example of UHI illustrates that DM allows the sustainable target values to be incorporated while deciding bounds and targets of affordances that the design is intended to provide (Figure 3, Step 2(iii)). Though, the presented case study showed the analysis of only one sustainable target, multiple sustainable targets can be analysed using simulation techniques and the DM. Detailed affordance structure will also provide information about parameters required for simulating design options.
- DM traces the web of interactions between systems and subsystems by formulating multiple affordance structures and coordinating multiple stakeholders (Figure 3, Step 2(iv)). For example, affordance structure in Figure 6 visualizes the collaboration of architects, energy analyst, civil engineer, and contractors for site planning, site zoning, and surface material selection. Such extensive affordance structure will guide decision making and assist in trade-off analysis during a design.

Overall, the DM provides a mechanism to transform the information available from users and designers into technical information which drives the conceptual design process. Further, sequential and structured affordance-based DM aids in the evolution and transition of myriad ideas of users, designers and other stakeholders into cohesive concepts which would be eventually be reflected in the designed built environment.

6. Conclusion

Despite extensive literature on managing the design process, there is lack of systematic and all-inclusive approach for incorporating user needs, stakeholder interactions and sustainable values in a design. To address these issues, this research has developed an Affordance-based Design Method for the design of built environment. This affordance-based method is drawn from product design. Potential application of proposed Design Method is demonstrated through a case study on the design of mobility network in a university campus. The research findings suggest that by deploying a sequential analysis in the early design stage of complex systems like built environment, it is possible to incorporate user needs, improve stakeholder coordination, and achieve sustainable dimensions. Evidence from the research indicates that affordance-based DM enhances capability of designers by guiding them through management of design information. These inferences establish the potential of affordances in the design management.

This paper has reported an ongoing research on the development of an Affordance-based Design Method through an example of design of mobility network system. Future research will refine the proposed method by implementing it on design of other systems and their interactions. After refinement of the method by optimizing and prototyping design options, it will be validated by implementation in real-life built environment projects to illustrate its advantages and eventual drawbacks.

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Hoppet - the first fossil free preschool

Hall A[1], Högberg A[2], Ingelhag G[2], Ljungstedt H[1], Perzon M[2], Stålheim N J[1]

[1]The City of Gothenburg, Lokalförvaltningen, Lillhagsparken 13, 402 26 Göteborg, Sweden
[2]Bengt Dahlgren AB, Krokslätts fabriker 52, 431 37 Mölndal, Sweden

maria.perzon@bengtdahlgren.se

Abstract. Residential and commercial buildings give rise to about one fifth of the greenhouse gas emissions in Sweden. One important goal of the City of Gothenburg is to be a climate neutral city with fair emission levels of greenhouse gases in 2030. In order to reach this goal, a demonstration project has been initiated with the aim to build a fossil free preschool - Hoppet. Hoppet will be built with a minimal climate impact and with no fossil resources. This includes everything from production and transport of materials to energy usage in the building. The fossil content and the climate impact of a standard preschool has been calculated, to be used as a benchmark for Hoppet. The result shows that all 250 building products in the reference preschool have a climate impact but finding fossil free and climate neutral alternative products has been found challenging. The climate impact of the building products in the reference preschool is calculated to more than 220 kg CO_2-eq. per m^2. Strategies to decrease climate impact for Hoppet preschool has been developed. For example, product development and innovation has been identified as key issues as well as increased collaboration between different actors in the construction industry. Communicating the project internationally is of high importance to find partners and innovations that don't exist in Sweden as well as to engage other stakeholders to help transform the building sector.

1. Introduction

The City of Gothenburg, in Sweden has set very ambitious goals to take an active role in mitigating climate change. In 2030, Gothenburg is to be climate-neutral, with a sustainable and fair level of greenhouse gas emissions, in order to contribute to the 1.5 degree-target **[1]**. As one of the first municipalities, Gothenburg has set goals, also including emissions occurring outside the city's geographical boundaries, from production of services and goods that are consumed within the city **[2]**. Construction has been identified as one of the city's activities with the largest climate impact. The City of Gothenburg has high standards for energy efficiency in all new construction projects, but so far, no restrictions when it comes to climate impact for building products. The City of Gothenburg is planning to build a lot of residential and public buildings in the coming years. Investments of 8 billion SEK (about 760 million EUR) are planned for 2020-2023.

During the last 10-20 years, the Swedish building sector has been focusing on energy efficiency measures and accordingly, greenhouse gas emissions from heating of buildings have decreased by more than 80% in 1997-2017 [3]. The next challenge is to reduce climate impact from the manufacturing of building products and from fuels used in transportation and on the construction site, considering all parts of a building´s life cycle.

In 2017 the city council of Gothenburg decided to give the city administration a big challenge – to build a fossil free preschool – Hoppet (the name can be translated both to "The hope" and "The leap"). Hoppet is to be built with as much fossil free material and climate neutral construction solutions as possible. The preschool will be finalised in 2021. Another goal for Hoppet is to promote fossil free building products and identify methods and strategies with the potential to be scaled up and eventually to be applied to all building projects in Gothenburg.

1.1. Fossil free construction and system boundaries

The innovation project, Hoppet considers all parts of a building's life cycle, as presented in figure 1, from extraction of raw material, manufacturing of material and products, through transport, to the energy usage at the construction site. Operation and maintenance of the building is also included, as well as demolition. No fossil-based material should be used as raw material and no fossil fuels should be used in production processes, in transportation of products or at the construction site. Reuse and recycled fossil based products are accepted as an alternative to products based on virgin fossil raw material. To minimize the overall climate impact, it is important and to consider the life cycle of the building, in this case in a one hundred years perspective. Thus, for example emissions of greenhouse gases, such as carbon dioxide released when limestone is converted to cement is included.

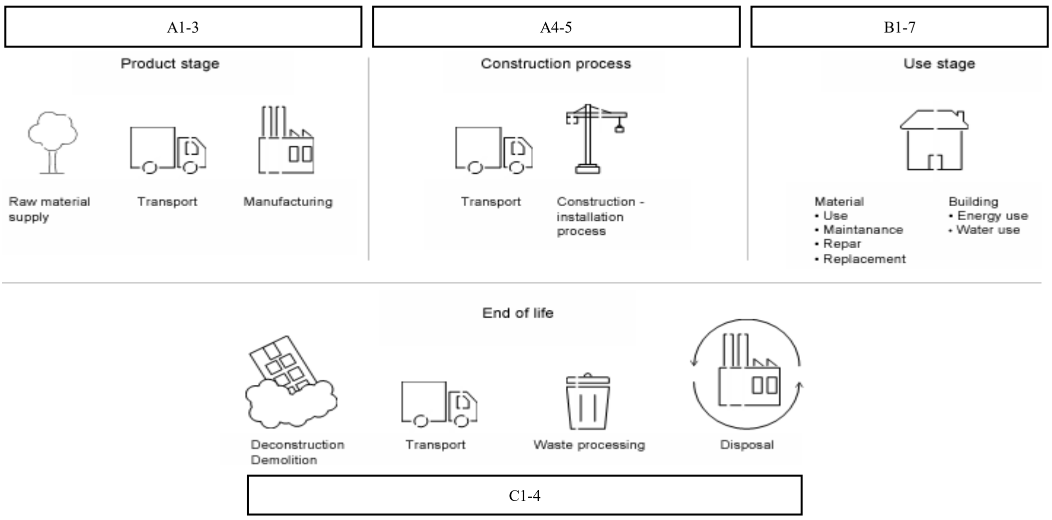

Figure 1. Life cycle stages for a building. Production of building products is referred to as building stages A1-A3, transportation to site is A4 and construction processes is A5. Operation and usage of the building, including energy usage and maintenance, is referred to as stages B1-7. End of life is referred to as C1-4.

2. Methodology – reference preschool and strategies

To get a better understanding of what challenges we need to manage, a first step was to make an inventory of a standard preschool, Byvädersgången, built by the City of Gothenburg. An inventory of the petroleum-based content was made, and a climate impact assessment was carried through for Byvädersgången, which is similar in size as Hoppet. The results are presented in this study, followed by the identified strategies for succeeding in constructing a fossil free preschool.

2.1. Inventory of fossil content in the reference preschool

The preschool, Byvädersgången is considered to represent a standard preschool, built by the City of Gothenburg. The starting point for the inventory was the 230 building products in the preschool registered in the Swedish material evaluation system, Byggvarubedömningen [4]. As a first step, an investigation was carried through to identify the petroleum-based content of all 230 building products. Fossil fuels used in the production processes and transports have not been included in this inventory.

2.2. Climate impact assessment of the reference preschool

As a second step, the climate impact of the preschool was assessed, including lifecycle stages A1-A4 and A5.1. The product list for Byvädersgången in Byggvarubedömningen was supplemented with data for missing products and quantities from contractors and subcontractors. In total, around 20 products were added to the product list. A newly developed calculator for the Swedish construction sector "Environmental impact calculator for construction" has been used to calculate the climate impact [5]. Each product and its climate impact has been compiled in the calculator. When selecting climate data, the following ranking order has been used:

1. Climate data from environmental product declarations (EPDs) with specific or generic data. [6]
2. Climate data from EPDs for similar products. EPDs for products from the same supplier have been prioritized.
3. Generic climate data for the product.
4. In cases where neither EPD nor generic data for the product have been found, generic data for the containing materials have been used to calculate the climate impact.

The ranking order has been verified by IVL Swedish Environmental institute [7]. Generic data in the calculator has been used to calculate climate impact of transportations of products to the construction site (A4) for each building product. Energy usage at the construction site has not been included.

The total climate impact of Byvädersgången has been calculated as the sum of the impacts of the purchased products, according to equation 1.

$$Total\ climate\ impact_{preschool} = \sum_{i=1}^{i=n} [Product(kg) \times Climate\ impact\ (kg\ CO_2 eq./kg)]_n \qquad (1)$$

The list of materials for Byvädersgången is based on purchased quantities, hence waste material on the construction site is included (A5.1).

2.3. Strategies for fossil free construction

In order to reduce the climate impact from construction a large part of the construction industry has joined the initiative *Fossil Free Sweden* and created a roadmap for a Fossil Free Construction Sector. The roadmap describes what technological solutions need to be developed, what investments need to be made and what obstacles need to be removed. In the roadmap it is concluded that there need to be a higher focus on the climate impact from the manufacturing of building products and from fuels used in transportation and on the construction site. Therefore, different strategies were identified in order to reach this goal and several of them have been applied in the project Hoppet. Additional strategies have been identified within the project Hoppet through an iterative process where different stakeholders in the industry has participated in workshops and seminars initiated by the Hoppet project team. [8]

3. Results – reference preschool

The results from both the inventory of the petroleum-based content and the climate impact of the reference preschool is presented in this section.

3.1. Results – Petroleum-based content

The result of the inventory of the 230 building products for Byvädersgången is presented in figure 2 and in table 1. A large part of the products is petroleum based, but to various extents. For example, 16% of the building products consist of 80-100% petroleum-based content. [9]

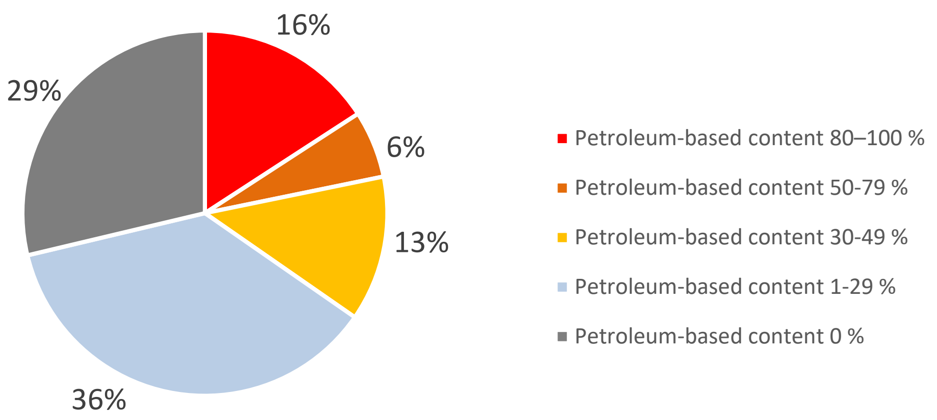

Figure 2. The proportion of the total number of building products (%) in the reference preschool, Byvädersgången. The products are sorted into groups with various share of petroleum-based content.

The result indicates that about 70% of the building products for Byvädersgången consist of materials with petroleum-based origin. The remaining 30% products mainly consist of:

- Metal in plumbing installations; pipes, valves, dampers and mixers (reinforcement in concrete is not included in the inventory),
- Cement or concrete for foundation, staircase, facade, roof and outdoor environment,
- Different types of insulation of stone or glass wool as well as some type of plasterboard,
- Ceramics and leca blocks for bathrooms, kitchens and the outdoor environment,
- Wood products outdoors and in interior decor.

From a life cycle perspective, building products without fossil content can have a large climate impact. For example, the processes for extraction and manufacturing of metals, cement and concrete are energy-intensive and have large climate impact. In addition, limestone in cement and concrete could be classified as a fossil material, which has not been considered in this investigation. Other product groups, such as wood products can in some cases have a relatively high climate impact due to emissions from transports and production processes.

Tabell 1. Building products with various share of petroleum-based content, in the reference preschool

Categories	Products
Red products (petroleum- based content 80-100%)	Pipes and plumbing products, insulation. electrical products, waterproofing and plastic film, foil etc.
Orange products (petroleum-based content 50-79%)	Pipes and plumbing products, cables, artificial grass, foil, surface layers etc.
Yellow products (petroleum-based content 30-49%)	Cables, finishes, concrete joints and color etc.
Blue products (petroleum-based content 1-29%)	Cables, paint, concrete joints, plumbing products, doors and windows, insulation
Grey products (0% petroleum-based content)	Plumbing products (metal), concrete and cement, steel profiles, wood products, leca blocks and ceramics

3.2.

3.3. Results – Climate impact

The results from the calculations are presented for different building components as well as for groups of building products, in figures 3 and 4, respectively. The allocation of building products to the different components, in this investigation, is presented below:

- Basic reinforcement and basic construction: edge support, support walls, factory concrete, primer, concrete base elements and insulation,
- Climate shell and frame: Concrete, insulation, steel profiles, windows, exterior doors, roof boilers, roof drainage, wind protection panels, window drives, sheet metal, rubber strips, sealing layers, plastic foil, sealants and joints,
- Frame supplements: plywood, plaster, coarse concrete, screed, fire joint, internal doors, concrete staircase, leca blocks, fire joint, freezing room joint, steel profiles, walls,
- Plumbing and ventilation: ducts, pipes, dampers, well, motor, donors, housings, insulation, mixers, luminaire grease, WC chair and shower set,
- Electrical and telecommunication systems: cables, VP pipes and flex pipes,
- Transport system: elevator,
- Surface layer: Paint, topcoat, joint, floor, underlay, substructure, washer, tile, panels, adhesive, adhesive floor, linoleum, fire paint, vapor barrier/primer, sealing membrane and plastic mat,
- Other furnishings: cabinets, hatches, drawer fronts, closets, countertops and counters.

The following products have not been included: escape routes, luminaires, push buttons, screws, fasteners, handles, cover strips, ventilation grilles and cover plates etc. in the kitchen/activity rooms. These products have been excluded due to lack of information and/or that the product is not considered to be a significant part of the building's climate impact.

The results from the calculation show that the climate impact of the preschool is 223 kg CO_2-eq per m^2 BTA. Climate shell, frame, foundation and frame supplements together represent 80% of the total climate impact, see figure 3. About 40% of the total climate impact can be allocated to the climate shell and the frame. Surface layers and plumbing represent 12% and 6% respectively. In figure 4 the climate impact for different groups of materials is presented. Products made of concrete, prefabricated concrete, steel and sheet products and insulation have a significant climate impact.

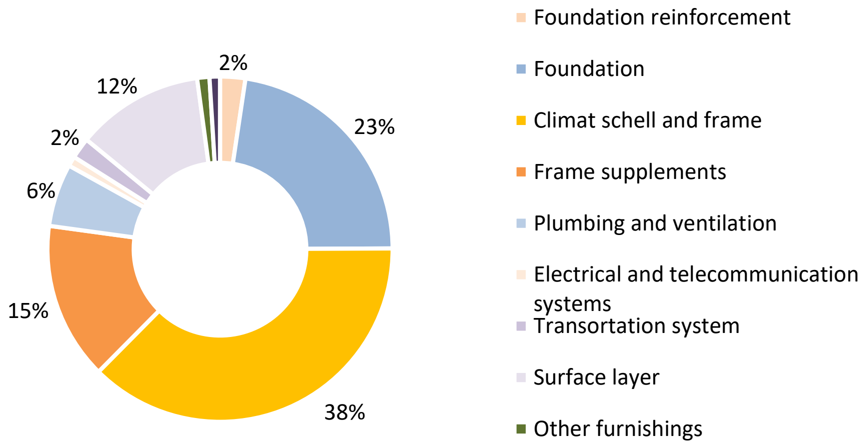

Figure 3. Climate impact of construction components in the reference preschool, Byvädersgången. Life cycle stages A1-A4 and A5.1 are included in the analysis.

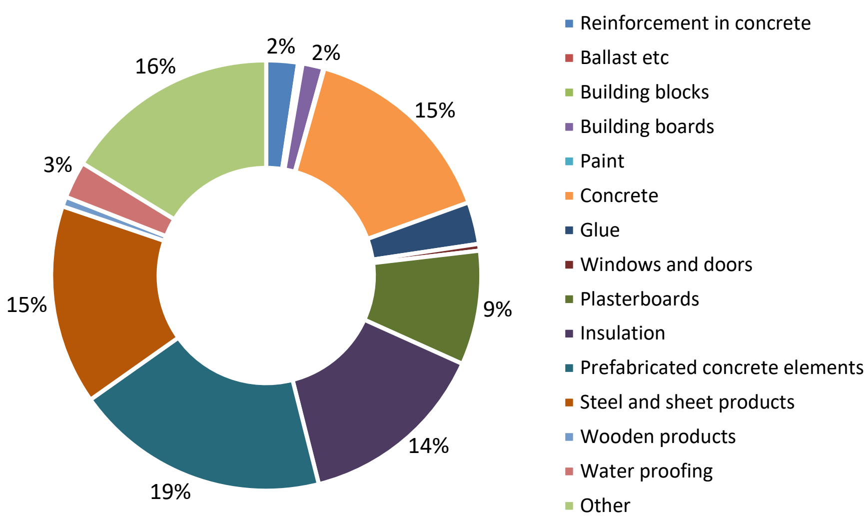

Figure 4. Climate impact of building products in the reference preschool, Byvädersgången. Life cycle stages A1-A4 and A5.1 are included in the analysis.

4. Strategies for fossil free construction

After investigating possibilities for replacing construction materials, by doing a thorough inventory, the project found a sparse selection of fossil free building product already available on the market. The project group then concluded that innovation and new ways of using existing materials were necessary. This, in combination with guidelines from the roadmap for a fossil free construction sector and seminars with stakeholders in the industry, resulted in the establishment of a strategy for progress:

- Biobased building products
- Reused and recycled building products
- Exclude and minimize usage of materials
- Requirements for building products in a life cycle perspective
- Fossil free construction site

Communication is also a vital part of all the identified strategies. Communicating our requirements is important for engaging the appropriate contractor and supplier of building products and to inspire other organizations to set similar requirement to achieve a transformation of the construction business towards climate neutrality. Further research and development is needed for the transition to a fossil free construction sector. Therefore, Hoppet has initiated and take part in several research and development projects, which are described in this section. It is also important to communicate the project internationally to find new partners and innovations that don't exist in Sweden as well as communicating the ambitions of the project to engage other countries and cities to make similar demands.

4.1. Biobased building products

Replacing fossil-based building products with new and existing biobased products is crucial to reduce the climate impact in the building sector. Hoppet tries to promote and highlight such initiatives and initiate research when needed.

4.1.1. Thesis work - Climate impact from wooden construction techniques

In January 2019 a thesis project was initiated focusing on investigating the climate impact and the resource problems related to various wooden construction techniques. Today, many different sectors of the society are looking to the forest for resources, such as the fuel industry, the packaging industry, the plastic industry, the textile industry, etc. Although the forest is a renewable resource, there is a risk that withdrawals of wood resource could become greater than the re-growth. To avoid this, Hoppet want to find the most effective way to utilize the forest raw material and analyze its climate impact. [10]

4.1.2. Research project – Wood foundation

Wood foundations are one part of a building where wood is used to a very small extent. Traditionally, concrete is used. To move towards increasingly biobased buildings, the foundation is a part of the building where an important minimization of the climate impact can be achieved by using more biobased materials. In this project, the ambition is to investigate the possibilities for industrialized production of wood foundations and to evaluate the technical performance. The project involves actors from the wooden house-building industry, developer and research institute. [11]

4.1.3. Research project - Fossil free glue and paint

Today's glue and paint products are largely based on components with fossil origin. In the research project called "Glue and paint", the aim is to replace fossil components with biobased solutions. By developing more components based on forest raw materials, the glue and paint of the future can become fossil free. The project was running from April to December 2018 and was a collaboration between research institutes, chemical companies, property developers, municipalities and many more. The aim is to find grants to continue the project. [12]

4.1.4. Research project - Policy for sustainable bio-plastics

Today, there is a large uncertainty regarding questions relating to ‘how’ and ‘if’ biobased plastics are socially and environmentally sustainable alternatives to the traditional fossil-based plastics. These uncertainties may be one of the of the obstacles to a large market breakthrough for biobased plastics. This project aims to create possibilities and guidance for sustainable decisions made by organizations which manufactures, contracts or uses biobased plastics. Further, barriers and drivers for conversion to biobased plastics will be analyzed and an action plan for how the barriers can be handled will be presented within the research project. [13]

4.2. Reused and recycled building products

Reused and recycled products have a great potential to replace products made from virgin raw material. Even though Hoppet is a fossil free preschool, products with reused or recycled fossil materials will be allowed. It is important to create recycling methods and logistics systems that can enable circularity both for fossil materials and biobased materials in the future.

4.2.1. Research project - Circularity index

This research project is an investigative project with the aim of increasing the use of circular materials. The goal of the project is to develop a new tool, Circularity Index - CIX, which can be used by the construction industry. The development of the CIX-tool will contribute to reducing both climate and environmental impact in construction projects. It is also an important step in creating conditions for more circular building projects in the design stage. The tool will be developed for a test bed, but the experience and the tool will be publicly available and usable for other projects. The project started in January 2019 and will continue for one and a half year. [14]

4.2.2. Research project - Re:pipe

Hoppet is engaged in a research project called Re:Pipe. Re:Pipe aims to recycle plastic material from old pipes into new pipes, alternatively re-using installation waste to produce new pipes. Funding for two years was granted from the Swedish Energy Agency in February 2019. [15]

4.3. Exclude and minimize usage of materials

There is a large potential in minimizing and excluding materials with fossil content or high climate impact. This is a relatively easy approach, possible to apply for any construction project, which in many cases also saves money and decrease emissions from transports. For Hoppet, for example these measures are discussed:

- Using integrated solar panels, which replaces the need of both installing roof tiles and solar panels,
- Avoiding toilet groups outside of the core of the building, which minimizes the pipe lengths,
- Using one combined technical system for lighting control, ventilation control and alarm system,
- Making more detailed solidity calculations to avoid unnecessary material in the framework.

4.4. Requirements for building products in a life cycle perspective

The results from the inventory of Byvädersgången show that it is vital to promote products with low climate impact in a life cycle perspective. A public organization, as The City of Gothenburg can do that by setting demands in the public procurement process and requesting data for greenhouse gas emissions verified by an EPD or similar. For Hoppet there will be a partnering collaboration with the contractor, to ensure that all measures are made to fulfill the goal of the project. In the procurement process all offers will be evaluated not only by financial performance, but also by cooperativeness and ability to contribute to the climate neutral goal in the Hoppet-project. Transportation of building products to the construction site also give rise to greenhouse gas emissions, but fossil free alternative biofuels are available at the market and will be required.

4.5. Fossil free construction site

The construction of a building is not the main source of climate impact in a life cycle of a building, but still have challenges to handle. For example, there are not a lot of working machines available on the market running on electricity or biobased fuels. The project group has recently started a collaboration with Business Region Gothenburg, responsible for business development in our region, to involve more actors to implement similar requirements to decrease climate impact from construction sites.

5. Concluding discussion

The assignment for Hoppet is to build a fossil free and climate neutral building. After searching the market for fossil free and climate neutral building products, the conclusion is that today it would be impossible to exchange all approximately 250 building products in an ordinary preschool to fossil free and climate neutral alternatives. Besides scouting for new materials and products, our work has been initiating research projects and trying to convert other actors and building owners to demand fossil free and climate neutral building products. However, we have found many companies that are starting to decrease their climate impact and to convert their products using fossil free or recycled materials. All promising, new and old products have to be evaluated and conscious decisions of what to use in Hoppet have to be made.

One initial goal was to create a general ranking method for material evaluation that could be used for comparing all different products or construction components. But after investigating the fossil content and making the climate assessment it became obvious that this would not favor innovation and development. Nor would it stimulate a change in attitude in the building sector. Instead, for Hoppet, decisions will be made on a case by case basis, evaluating product by product to include the potential for a product to be climate neutral in a long-term perspective. For some product groups, the fossil content can be the most challenging to replace. In that case it is most important to stimulate the development of a biobased alternative. For other products it might be the long transportation distances that have the largest climate impact. For those products it would make sense to promote them by purchasing them, resulting in stimulation of start-up of production sites closer to Gothenburg. The aim in Hoppet is to always choose products where all steps are fossil free and have the lowest possible climate impact, but when it is not possible to find such products the project aims to promote products with the possibility to be climate neutral in the future. During spring 2019, a more detailed system for product evaluation in the design process will be developed.

The benchmark is that the solutions, systems, products and materials we choose should meet all our requirements. The City of Gothenburg's Technical Requirements and Instructions for construction exist to ensure poison free environments, energy efficiency, moisture proofing, good indoor environment and the ability to efficiently manage and operate the properties. If a fossil free solution would contradict any of those requirements, there will be a discussion with the technical specialists on how to proceed.

The task is highly challenging, but in close collaboration with experts, researchers, innovators, entrepreneurs, suppliers and decision-makers we think it is possible to build fossil free. Maybe not for the first preschool, but in a long-time perspective. To inspire change and make a progressive development, an interest and understanding of the importance of fossil free materials and methods needs to be created in all stakeholders in the construction business (nationally and internationally). Hoppet, as the first fossil free demonstration project is an important part of this progress.

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Passive houses for active students – Providing knowledge about eco-efficient buildings

Jedliczka G

OeAD-Housing Office, Ebendorferstraße 7, 1010 Vienna

guenther.jedliczka@oead.at

Abstract. The OeAD-Housing Office is a non-profit organisation in the area of international cooperation in education, science and research in Austria. We cooperate with our parent company OeAD-GmbH as well as various Austrian student residences and partner universities worldwide. The main responsibility is accommodating international and national students in Austria's university towns. Our success story started with the construction of the first halls of residence built according to the passive house standards world-wide in Vienna in 2005. Since its completion, the OeAD-Guesthouse Molkereistraße has accommodated 280 international students and guest professors per semester. We are successful in managing a total of 8 student guesthouses in the passive house design constructed in Vienna, Graz and Leoben. This paper describes the benefits of passive houses and raising awareness for eco-efficient buildings. We focus on two OeAD-Guesthouses in Austria and highlight their design, architecture and what it is like to live in both of them. Upon request we are also able to propose the OeAD-Guesthouse PopUp dorms. As we want to share our knowledge with the rest of the world we initiated 2 summer universities which pay attention to ecological buildings and the financial and economic system. We also draw attention to several awards we have won during the past years.

1. More than 20 years of applied sustainability

The OeAD-Housing Office (=OeAD-WohnraumverwaltungsGmbH) is a non-profit organisation in the area of international cooperation in education, science and research in Austria [1]. It cooperates with its parent company OeAD-GmbH as well as various Austrian student residences and partner universities worldwide. Our main responsibility is the annual accommodation of over 12,000 international students and guest professors in Austria's university towns and since 2016 we also accommodate national students.

Mr. Günther Jedliczka became the CEO of the OeAD-Housing Office in 1998. He studied business and economics at the University of Economics and Business in Vienna. While pursuing his studies he spent two months in London and one month in Paris which helped improving his language skills and his personal growth. Back in 1999 Ernst Ulrich von Weizsäcker's book "factor4" served as inspiration to construct a passive house.

The starting point of this initiative was the construction of the first halls of residence built according to the passive house standards world-wide in Vienna in 2005. Since its completion, the OeAD-Guesthouse Molkereistraße, 1020 Vienna, has accommodated 280 international students and guest professors per semester. Since then we are successful in managing a total of 8 student guesthouses in the passive house design constructed in Vienna, Graz and Leoben. We have also expedited the construction of student dorms in the passive house design in Austria, as well as the retrofitting of existing dorms with photovoltaics systems, with the goal of reducing ecological impact both during construction and during the subsequent supply of energy.

The concept of a passive house is economically profitable in terms of energy expenses and benefits are evident within the company. By means of a regulated ventilation system a passive house creates a comfortable atmosphere and prevents stuffy air mold formation due to insufficient ventilation which helps reducing the operating costs.

Many students come into contact with the topic of eco-efficient building for the first time when they move to any of the OeAD-Guesthouses, while others chose one of our guesthouses because of the passive house standard. When moving in, each student receives information about the concept of the house and a basic manual with general instructions like airing or water saving. Suffice to say, staying in one of our passive houses is cozy, energy-saving and environmentally-friendly. According to today's state of the art technology it is the best and least expensive method to produce a comfortable room climate.

In each OeAD-Guesthouse the residents receive the information about the quality of the tap water and the importance of waste separation. In order to avoid the consumption of paper, the residence contracts are sent out only digitally (by email). The OeAD-Guesthouses as well as the OeAD-Housing Offices are centrally located in each university town and can easily be reached by public means of transportation. We also encourage students to use bicycles and provide storage places/rooms and even rent bicycles to them.

In the Housing-Offices fair trade coffee and fruits are provided. On a regular basis movie nights and panels are hosted to educate about the sustainable use of our planet (concerning fair fashion, climate change etc). The facility management also hosts training sessions about the ecological use of detergents.

In the OeAD-Guesthouses we provide fully furnished accommodations so the students do not have to purchase new bedding, dishes or kitchen ware during their (short term) stay. We also provide energy saving lamps in the residences.

There is a very high acceptance of the passive house concept by the residents. Due to the short dwell time of the students in the residence, between a few months (international students) up to some years, and the following change to other forms of living, most residents move out with the wish to continue living in a building with a passive house standard which helps to raise awareness for eco-efficient buildings. Especially students of technical studies, like constructional engineering or architecture, find a great interest in the concept of passive houses. International students popularize the building concept and a direct multiplier effect arises.

2. Highlighting two OeAD-Guesthouses

2.1. OeAD-Guesthouse GreenHouse in Lakeside Aspern [2]

Figure 1: Main facade - Sonnenallee

Back in the year 2005, there were first discussions with Mr. Christoph Chorherr (spokesman of the Green Party in Vienna), DI Josef Lueger (Federal Real Estate Company) and Mag. Günther Jedliczka (CEO of the OeAD-Housing Office) concerning the construction of a student residence in the seaside town of Aspern. An important prerequisite for the location of a new home in this largest urban development area of Vienna was the proximity to the subway and thus a connection to the universities within 30 minutes. After it had been ensured that there was a subway connection to Aspern during the construction phase, the OeAD-Housing Office was looking for partners for this pioneering project. In July 2010, 6 architecture firms were invited on the basis of a competition to present ideas for a student residence with the minimum standard passive house. The project was chosen by aap.architekten ZT-GmbH, which had developed a convincing concept with the goal of zero energy standards and were experienced in participatory processes and their knowledge in the field of ecological and energy-sufficient construction.

The OeAD-Housing Office, the Austrian Youth Movement (ÖJAB) and the Housing Association for Private Employees (WBV-GPA) jointly realized a forward-looking project in a new district – a highly efficient passive house for 313 international and Austrian students and the architecture should visualize this ambitious project.

Due to the three different home operators, an interesting mix of the residents and thus also an important impulse for the new district was developed. The WBV-GPA has also taken on the role of developer and installer.

At the time of its opening, GreenHouse was the world's first certified Passive House Plus (PHI) student residence, accompanied by a research project on electricity storage and monitoring energy consumption. In 15 reference rooms, 5 in each component, an extended monitoring with various measurements takes place. For precise control of the energy balance of the building, calibrated heat meters, energy meters, electricity meters and water meters, temperature sensors, window contacts, humidity sensors, etc. are used distributed throughout the building. The meters are equipped with bus modules and communicate directly with the building management system (BMS). The research project is being carried out by ASCR (Aspern Smart City Research) and Siemens.

The energy sources of the future for the urban development area are at the time of the design of solar energy, the energy from the air, which is recovered by the comfort ventilation with heat recovery in passive house construction and geothermal heat from the earth.

For economic reasons, the building had to be implemented in concrete construction with a full thermal protection facade. By an alternative development proposal, deviating from the original requirements of the master plan, a more compact structure could be implemented, which reduces the built-up area, at the same time ensures better tanning of the occupant rooms on the courtyard side and offers more living space and less development areas for the same area.

The compactness of the structures and the clear structural design grid across all floors, the use of semi-finished parts, prefabricated elements and floor slabs in the shell construction as well as the space-optimized development system allow for moderate construction costs despite high equipment quality and excellent energy values. Professional quality assurance and process support in the execution planning as well as in the construction work by the project management contributed significantly to the sustainability.

The rainwater is seeped through infiltration baskets in a core of the earth at the site. The water consumption is significantly reduced by flow restrictors and by fittings with extended cold water range, as the requirement for hot water in dormitories is above average. .
To achieve the zero energy standards, a centralized ventilation unit with 2 parallel rotary heat exchangers with heat and moisture recovery and special filters has been developed to reduce energy consumption. In the course of the research project, the ventilation could be carried out on demand and the energy consumption could be reduced. The residual heat requirement is covered by Fernwärme Wien.

SUMMARY

In dormitories, energy consumption is much greater than in classical residential buildings because of the large number of small apartments, each with its own kitchen. As a result, all components that consume electricity within the building must be optimized and extremely reduced. Reaching the Passive House Plus Standard under the given financial conditions (residential funding from the Community of Vienna, Passive House funding and research investments) required intensive collaboration among the building owners, the users and a team of architects, building physicists and building service technicians, who focused on this goal. The project received Gold ÖGNB (Österreichische Gesellschaft für Nachhaltiges Bauen, Austrian Sustainable Building Council) certification; a level of this certificate was required for all buildings in the district. In addition, the building owners and users chose to have the Passive House Institute certify GreenHouse.

From Passive House to Passive House Plus

The building was constructed as reinforced concrete with insulation in the façade upstairs and a curtain wall of boards as the façade on the ground floor and in parts of the floors upstairs. The U-value of the external walls is 0.10 W/(m^2K), while the U-value of the flat roofs with sloped insulation is 0.07 W/(m^2K). The wood-aluminium windows with triple glazing have a Uw-value of 0.80 W/(m^2K).

In 15 reference rooms (three in each building section), energy consumption, temperature, humidity, water consumption and window ventilation were extensively monitored. ASCR (Aspern Smart City Research) and Siemens conducted the research project.

Reducing energy demand

The following steps were taken to reduce the building's energy demand (Figure 2):

Central comfort ventilation (Figure 3) with parallel rotation heat exchangers (operation is based on CO2 levels) (Figure 4) and special bag and mini-pleat filters (F9) to reduce the ventilation system's flow resistance. A volume flow of 6,000 m^3/h per rotation exchanger. Heat recovery (EN308) 90.58 %, moisture recovery 73.14 %.

Daylighting in the first-storey common room and in the circulation areas.

LED lights throughout the building.

Motion detectors and light-dependent resistors in all common areas.

Optimisation components that consume power and avoidance of standby functions.

Elevator with energy recovery from the brakes.

Excellent insulation of distribution lines.

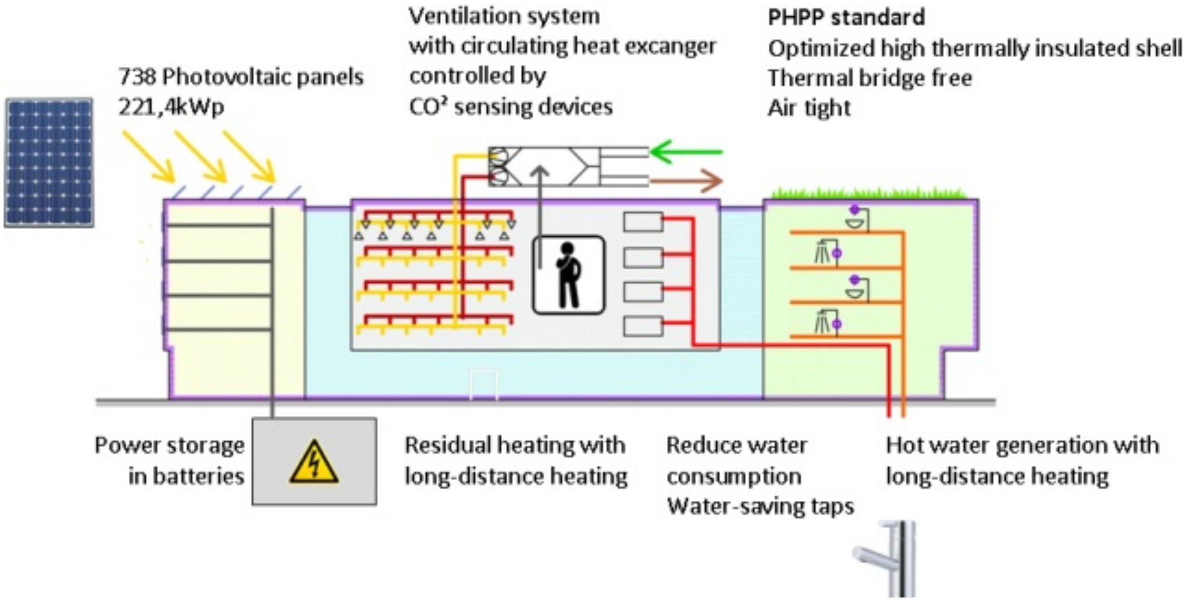


Figure 2: Building services

Figure 3: TROX X-CUBE ventilation system

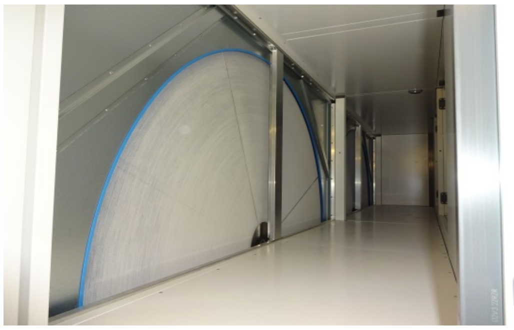


Figure 4: Rotation heat exchanger

Photovoltaic array

An essential component towards the Passive House Plus Standard is the photovoltaic array. 738 solar panels 300 Wp monocrystalline facing east and west were installed on the roof.

Total nominal output: 221.4 kW
Total production annually: 215,865 kWh
Total CO2 savings annually: 25,903.8 kg

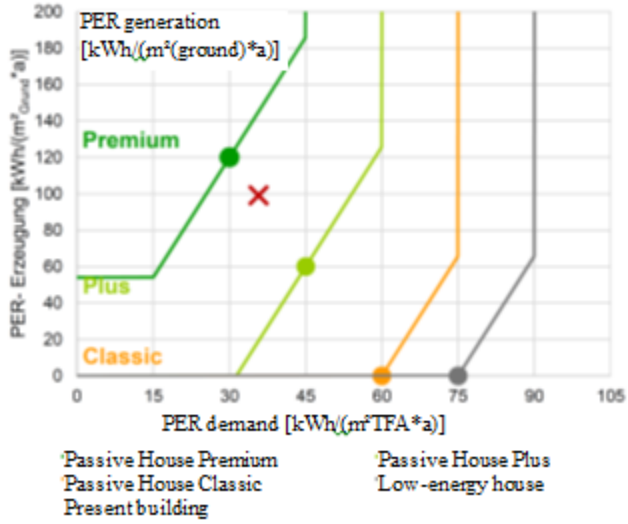
As part of a research project, excess electricity from the solar array is stored in batteries (Figure 4) for later consumption in the dorm:

Battery system, AC
Lithium-iron phosphate cells
Maximum constant output: 150 kW
Storage capacity: 170 kWh

Table 1. Building data OeAD-Guesthouse GreenHouse

Key data	
Plot area	3,820 m²
PHPP treated floor area	2,000 m²
Mean heating demand based on PHPP	11 kWh/(m²a)
Heating load based on PHPP	9 W/m²
Primary energy (PE) demand	101 kWh/(m²a)
Airtightness n_{50}	0.24/h

PER (primary energy, renewable) diagram



Graph 1: PER generation and demand
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2.2. OeAD-Guesthouse mineroom in Leoben [3]

Figure 6: Street façade – main entrance ©J.Konstantinov

The OeAD-Guesthouse mineroom was opened on October 1, 2016 after only 11 months of construction. This student residence is a contemporary home for 201 international students during their time in Leoben. The close connection of the region and the university to nature and its resources should be reflected in the building. Therefore, e.g. quotes from the mining sector, with which the city and the university have been connected for generations, can be found in the building.

This first global high-volume passive house was constructed as timber framed structure and is klima: aktiv GOLD certified. The certification by the Passive House Institute Darmstadt has also been carried out and the Passive House Plus Standard was achieved.

The building is located on Josef Heißl-Straße at a height of ground floor up to the 5th floor and set off to the north by one floor. Smooth facades form a clearly defined counterpoint to the subsequent demolished development structure. The facades are accentuated by colored frames around the large windows of the common rooms and by loggia-like recesses in front of the living areas of the residential communities in which plant troughs with kitchen herbs are arranged.

The structure was developed from a perimeter block development, which opens to the lower development in the west. Thus, courtyard and garden are protected from street noise. The components are staggered at the height of the ground floor up to the 5th floor and from the ground floor up to the 3rd floor and thus adapted to the smaller-scale development of the neighboring plots. By lowering the southern connecting tract, the tanning of the inner courtyard is optimized. On the southern facades, "green walls" of plant troughs were provided, which positively influenced the microclimate in the street and courtyard. The recessed and transparent ground floor zone provides an insight into student life as well as views into the courtyard and creates a weather-protected meeting zone in front of the building.

Inspired by the liveliness and the play of colors of the ore stone, the formally clear structures were covered with a plastic, multi-colored wooden formwork. The pre-grayed shuttered formwork, which repeatedly bursts out of the smooth, untreated larch wood formwork, runs vein-like over the building and will gradually discolor irregularly in various grays, browns and reds.

With the exception of the entrance area - the basement and the two staircases - the entire building was built in timber construction. The outer walls consist of a prefabricated, with mineral wool-finished timber frame construction, mostly having no supporting function. Horizontal bracing is provided by partition walls made of cross laminated timber wall elements in conjunction with glue laminated timber ceiling panels. About 1,900 m^3 of wood were used in the building for the supporting structure and the facade, thereby binding approx. 2,000 tons of CO_2. Partition walls and ceilings are fitted with plasterboard liners to meet the fire and sound insulation requirements. Beams and columns were over-dimensioned to burnup and could therefore be left visible.

The door cut-outs of the cross-laminated timber interior walls were turned into mobile furniture. Tables, benches, stools and sideboards bring the wood character back into the living and common areas. The house offers a wide range of residential and common areas. Single apartments, double rooms as well as shared apartments for 2-5 residents enable the students a differentiated housing offer. On each floor, so-called parlors offer individual retreat areas. There are common areas such as the extended living room, a launderette, music practice room, meeting and study rooms, gym and a multi-purpose room for chilling out and celebrating on the ground floor. In the courtyard, there is seating and table tennis, and in the garden wooden decks for lounging can be found.

Table 3 gives an indication of the key building data and building physics, with Figure 9 highlighting the measures taken with regards to the building equipment.

Additional to the building envelope, also power-consuming components have been optimized, whilst standby functions were avoided. The entire object was equipped with LED lighting, and the general areas are supplied with motion detectors and twilight switches. A space or empty piping for possible battery storage has already been provided and there is also the possibility to charge e-bikes and electric cars. The elevators are equipped with braking energy recovery.

By means of water saving, valves with an extended cold water range (cold water in the middle position), the hot water consumption, which is above average in the houses of the OeAD-Housing Office from experience, should be reduced. In line with that, the residual heat demand and hot water generation are covered by district heating (process waste heat from VOEST Alpine Stahl).

The ventilation system plays a big part in reduction of the overall energy demand. Here, the TROX X-Cube ventilation system (Figure 7) with 2 parallel rotary heat exchangers was used, which has an air volume flow of 4,500 m³/h per exchanger. Additionally, special pocket and pleated filters are used to reduce the flow resistance of the ventilation system. Further details to be highlighted are the re-heat number (EN308) of 90.58% and the moisture content of 73.14%.

Table 2. Performance indicators (PHPP)

OeAD-Guesthouse mineroom

Airtightness	n_{50} = 0.27/h
Heating demand	17.6 kWh/(m²a)
Building heating load	10 W/m²
Primary energy need	76 kWh/(m²a)
PER-demand	37 kWh/[m²a)
Producing renewable energy	87 kWh/(m²a)

Figure 7: TROX X-CUBE ventilation unit

Photovoltaic system:
Modules monocrystalline á 300 Wp with 3 inverters, 388 PV modules in east-west orientation
Total rated power 116 kWp
Total production per year: 105,000 kWh
Total savings CO2 per year: 12,600 kg

Figure 8: Photovoltaic panels – guesthouse mineroom

Table 3. Building data OeAD-Guesthouse mineroom

Building data		Building physics	
Plot area	3,214 m²	Exterior wall	0.104 kW/m²K
Built area	1,449 m²	Roof	0.067 W/m²K
Gross floor area	7,196 m²	Ceiling against unheated	0.091 W/m²K
Usable area home	5,900 m²	Windows/U_w	
Total number of homes	201		
Total accommodation	139		

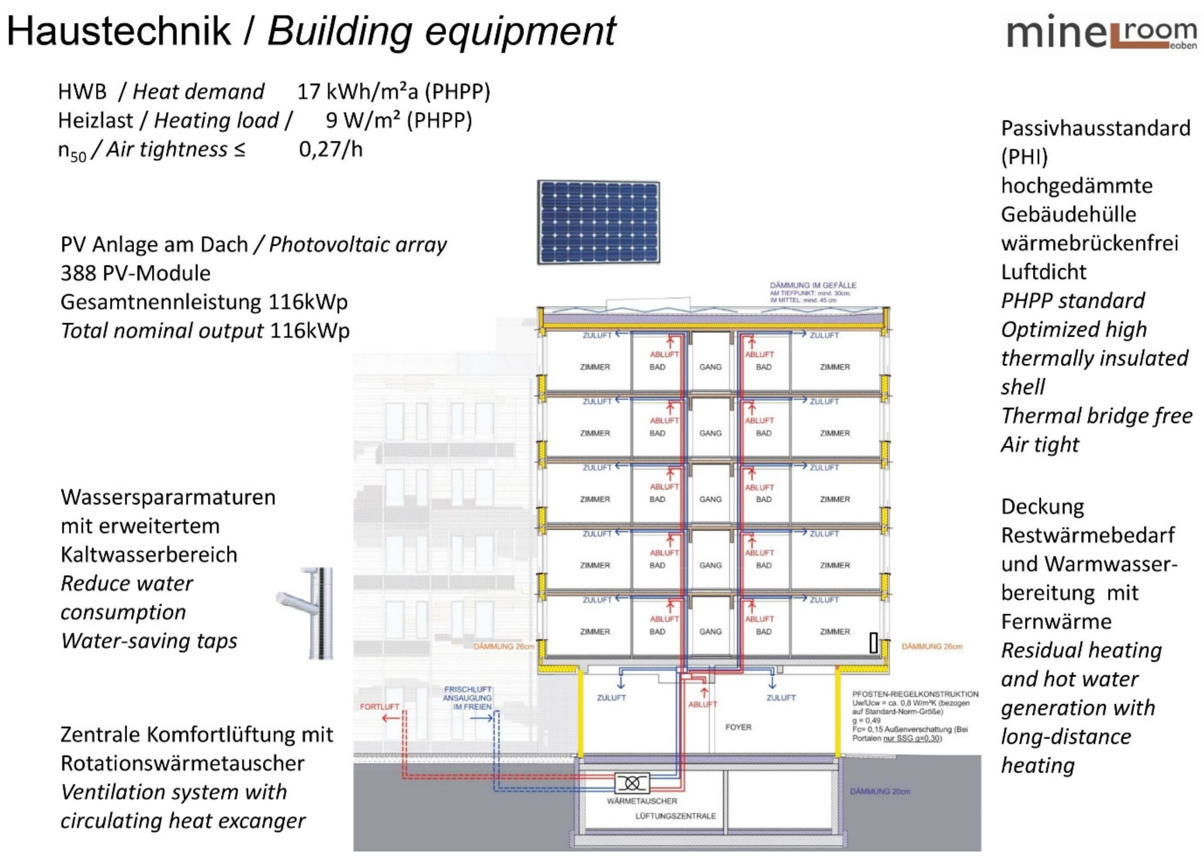


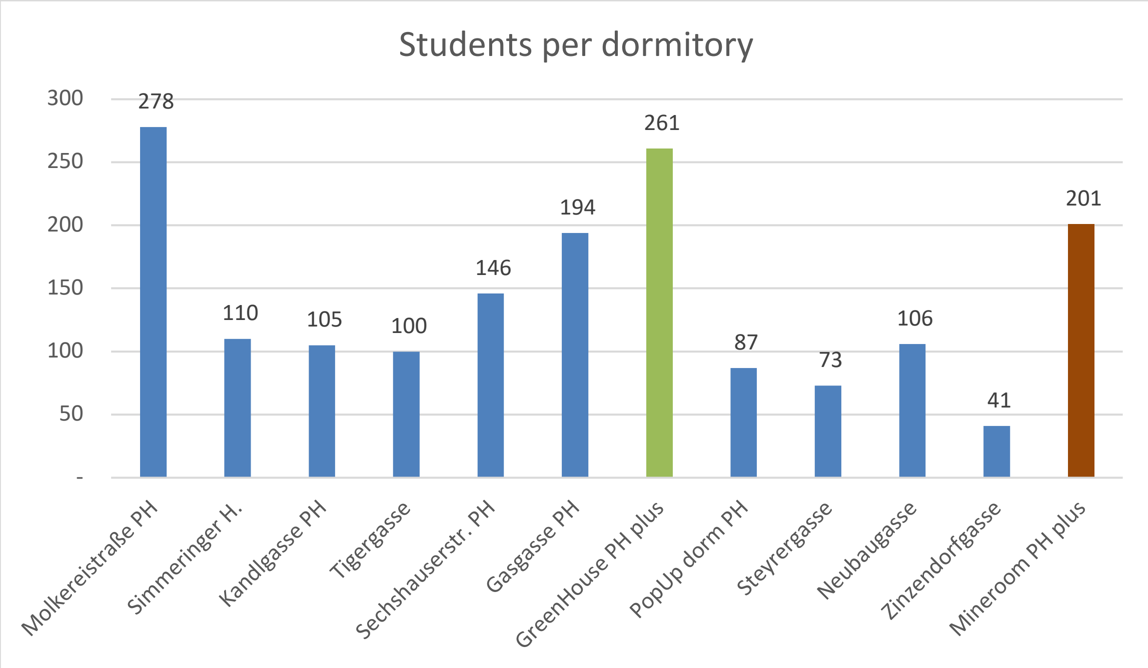
Figure 9: Overview building equipment guesthouse mineroom

3. Comparison of guesthouses of the OeAD-Housing Office

As visible from Table 4, most buildings use district heating for heating and hot water generation purposes. Out of the following 12 houses, 3 are situated in Styria (Steyrergasse and Zinzendorfgasse in Graz and Mineroom in Leoben), also, the passive house buildings Molkereistraße, GreenHouse and Mineroom accommodate the highest number of students (graph 2).

Table 4. Comparison of OeAD-Guesthouses

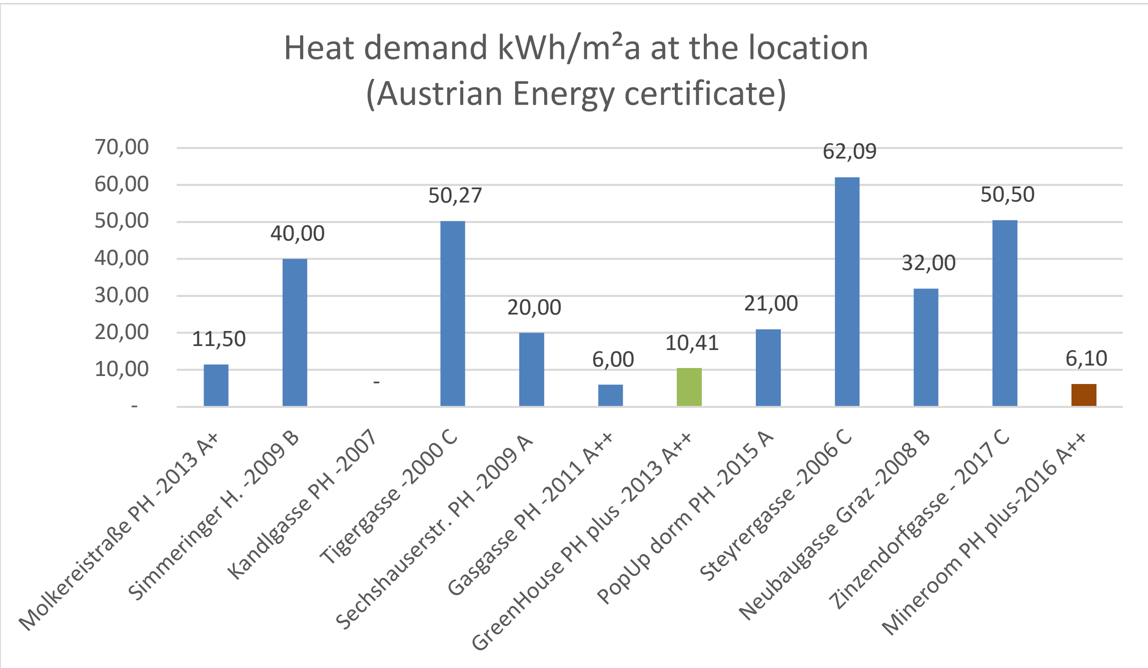
Object	Year of construction	Students	m²	Construction	Heating	Hot water generation	Ventilation system with heat recovery	PV [kWP]
Molkerei-straße	2013	278	6,338	Solid building	District heating	District heating	yes	n.d.
Simmer-inger H.	2009	110	2,778	Solid building	District heating	Local electric boiler	no	12.42
Kandl-gasse	2007	105	2,723	Solid building	District heating	District heating	yes	19.9
Tiger-gasse	2000	100	2,013	Solid building	District heating	District heating	no	16.7
Sechshaus-erstraße	2009	146	3,372	Solid building	Central heating	Central heating	yes	15.39
Gasgasse	2011	194	4,683	Solid building	District heating	District heating	yes	60.0
Green-House	2013	261	8,488	Solid building	District heating	District heating	yes	221.4
PopUp dorm	2015	87	2,028	Timber construction	Heat pump	Heat pump	yes	12.0
Steyrer-gasse	2006	73	1,337	Solid building	District heating	District heating	no	n.d.
Neubau-gasse	2008	106	2,009	Solid building	District heating	District heating	no	n.d.
Zinzendorf-gasse	2017	41	1,247	Retrofit	District heating	District heating	no	n.d.
Mineroom	2016	201	6,000	Timber construction	District heating	District heating	yes	116.4



Graph 2: Overview students per dormitory

Compared with the other guesthouses, the passive house buildings have a significantly lower heat demand – depending on the heating system in use. Graph 3 displays the heat demand for each of the 12 buildings for the year 2018, while also taking into account the energy category.

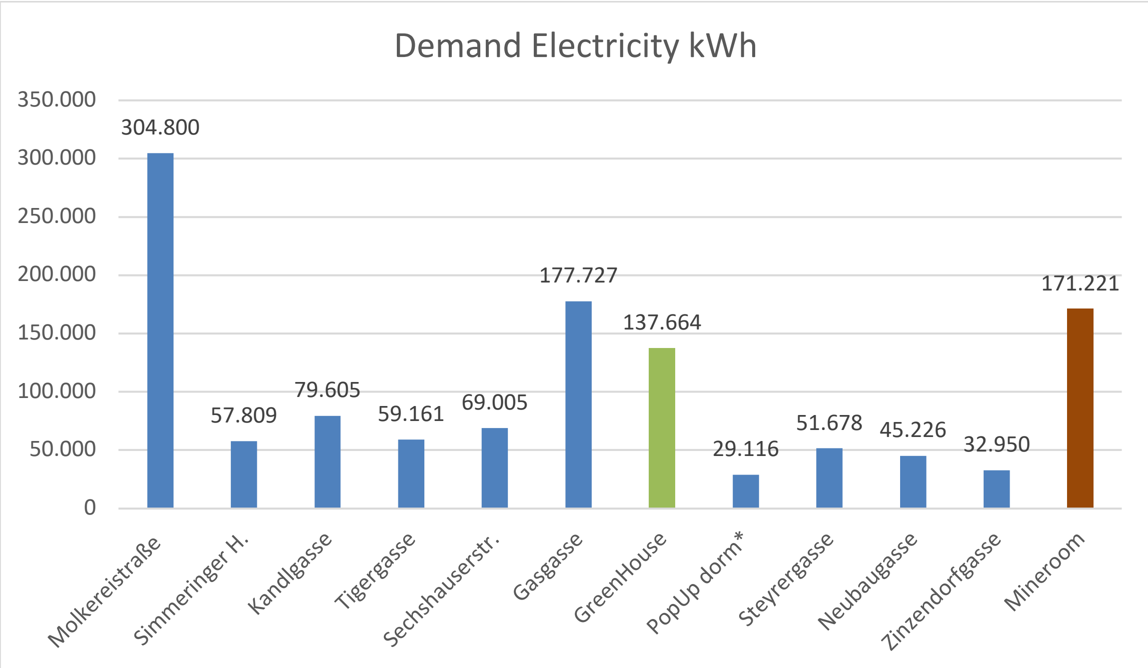
There was no data available for the guesthouse in Kandlgasse.



Graph 3: Heat demand per guesthouse [kWh/m²] – building names also indicate the resp. year of construction and energy category. Data are for the year 2018.

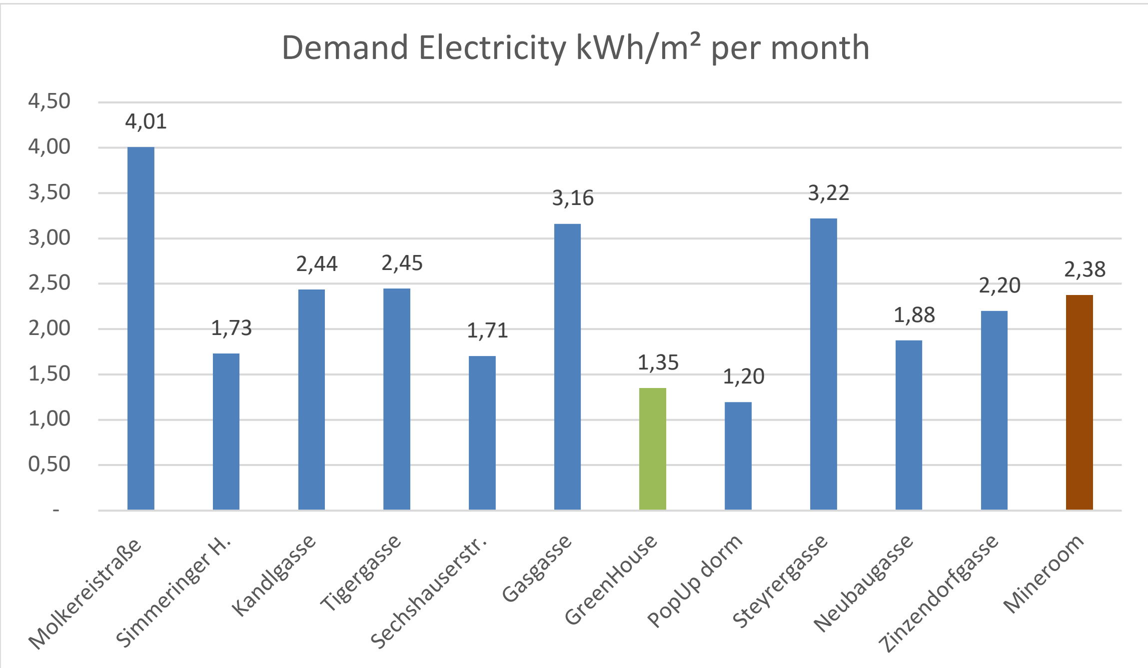
Surprisingly, for 2018, the electricity demand was higher in some of the passive houses than the other buildings (graph 4). This is in part due to some technical issue in the photovoltaic system of the guesthouse mineroom in 2018 – in line with that, the data shows a significantly lower electricity demand for 2017 (92.367 kWh). A further explanation probably lies in the behavior of the residents.

The electricity demand per m² and month (2018) was lowest in the passive houses, as is shown in graph 5.



Graph 4: Demand of electricity per guesthouse [kWh] – data for the year 2018

*PopUp dorms: Removable construction, size optimized for transportation. 250 m² common room as atrium – not conditioned, kitchen and laundrette in an oversea container.



Graph 5: Demand of electricity per guesthouse [kWh/m² per month] – data for the year 2018

4. Passive houses – active satisfaction

Striving towards reaching the highest possible standard of living with the lowest environmental impact, the contentment of OeAD-guesthouse residents is assessed once in a year via feedback questionnaires, which evaluate the overall satisfaction by looking at the different factors of room size, room quality and equipment. Residents rank the different buildings using grades ranging from 1 (very satisfying) to 4 (very unsatisfying). A system of 4 grades is used in order to put special emphasis on positive as well as negative critique.

The evaluation for 2018 shows an overall good ranking of OeAD-guesthouses within a range of 1.48 to 2.03, with the passive house-buildings GreenHouse (1.48) and Mineroom (1.52) providing the most satisfaction for residents. Also in 2017, GreenHouse and Mineroom were ranked best in contentment.

5. Sharing the knowledge with the world

Population growth, overuse of resources and environmental degradation are just a few of the big global challenges that we already face today. Too often, these developments are reigned by view that there is no alternative. However, there are many alternatives with some being already successfully implemented on a local scale. With the goal in mind to raise awareness, the OeAD-Housing Office initiated 2 summer universities: "Alternative Economic and Monetary Systems" (AEMS) in 2013 and "Green. Building. Solutions." (GBS) in 2011.

Both programmes attract highly qualified students and professionals from all around the globe and diverse backgrounds. In order to further foster diversity, there is also a system of scholarship support for those, who otherwise would not be able to cover the participation fee by themselves. This way 103 people from 50 nations and 5 continents could participate in AEMS and GBS in 2018.

5.1. The beginning of AEMS

11 years after the stock market crash, the world has not seen any substantial systemic changes. Neither economic textbooks nor incentives for financial actors to make one-sided bets have changed. The design of the financial and economic system basically remains the same, as does its inherent instability. There is overwhelming evidence that the current economic model based on everlasting economic growth is destroying the ecosystem of our planet, and thus the basis for the existence of humanity. However, dominant recipes for overcoming the current economic crisis still focus on restoring economic growth. AEMS sheds light on approaches and reforms that can make a difference.

The main intention behind the creation of the AEMS was to use a positive approach applied to the field of economic alternatives, asking if this apparently inherent economic instability might be reduced or avoided, and to show students chances for reforms. A great variety of possible approaches to economic reform has been proposed over the years proving that high demand for a new economic system exists.

A number of successful and promising concepts are presented to the students ranging from individual actions all the way up to fundamental reforms of global structures and institutions. This enables them to have a level-headed discussion of economic reform. The monetary system has its own intricate feedback loop with the economy; further emphasis on monetary reform is a natural choice.

AEMS offers room for critical thinking and the possibility to openly discuss and deconstruct ideas and concepts with distinguished experts from various scientific fields. The participants are able to move beyond the widespread limitations of higher education that lacks extensive exchange between scientific disciplines.

2018 saw the 5th installment of the summer school with 61 participants from 34 different countries.

5.2. Take care of your future

It is the aim of the OeAD-Housing Office to convey knowledge about eco-friendly building to future generations on the one hand, and to offer the highest possible standard of living with the lowest environmental impact on the other hand. To our minds, working sustainably does not only mean realizing eco-friendly projects, it also means creating awareness and knowledge, because nothing in this world is more sustainable than knowledge.

The GBS graduate-level summer program took place from July 21 to August 12, 2018 for the 8th time and 42 international students and professionals successfully completed the course. The GBS students primarily study architecture, urban planning, and engineering sciences; however, they worked alongside professionals and students from all faculties relating to the built environment.

The GBS takes up the central ecological, economic, technical, and social themes of sustainable design and construction to offer students the unique opportunity to study content focused on sustainable construction within an interdisciplinary framework, and also to experience the practical applications of sustainable concepts. The GBS provides knowledge that sharpens and deepens the students' competencies and understanding of sustainable planning, design, and construction. The participants belong to the generation that bears the brunt of the change from a postmodern industrial society to a circular-economy-oriented society. The participants therefore form a central target group that are sensitized to the environmentally conscious and responsible use of natural resources and need to be equipped with the appropriate knowledge to take action. The importance of the GBS Summer University is reinforced by ever-present evidence of more extreme climate change. The associated urgency to quickly reduce greenhouse gas emissions and resource consumption shows that the construction and building sectors are responsible for an enormous share of greenhouse gas emissions worldwide. The circular economy, urban mining, and the reduction of energy consumption in urban metropolises are indispensable measures which must be considered for sustainability in future urban planning, architecture, and construction sectors. Renewable energy production by new technologies and innovative ecological and sustainable building concepts and materials should therefore contribute to natural resource conservation and reducing greenhouse gas emissions.

Since 2018, both summer universities are supported by the Club of Rome.

6. Hard work pays off

All our efforts for an active ecologic contribution were honored with numerous awards (Table 3).

In November 2013 the OeAD-Housing Office was awarded with the Climate Protection Prize at the ORF climate protection awards in the category "Climate Protection in Companies". With more than 30,000 votes from the audience, the OeAD-Housing Office was chosen among 230 submissions.

The OeAD-Guesthouse mineroom in Leoben won the 2018 Blue & Green Award and the Styrian wood construction prize in the category large residential buildings in the year 2017.

In October 2018 the OeAD-Guesthouse PopUp dorms were awarded with the FIABCI Prix d' Excellence. It is an unique award given to real estate projects that embody innovation and economic sustainability. The OeAD-Guesthouse mineroom appeared as runner-up.

The OeAD-Guesthouse PopUp dorms was nominated for the climate protection award in 2016 and it was also awarded with the Green & Blue Building Award in 2015. Moreover the PopUp dorms were nominated for the 2018 City of Vienna Environmental Prize.

The OeAD-Guesthouse GreenHouse is the first award-winning Net-Positive Energy student residence in the world, winning the 2015 City of Vienna Environment Prize, with 1000 of 1000 points certified as a klima:aktiv gold building.

AEMS has won the "Bildung für nachhaltige Entwicklung - Best of Austria"-Award (Education for sustainable development – Best of Austria) in the category "political support" in 2016, while GBS was chosen by UNESCO Commission as UN Decade Project for Sustainable Education in 2013 and received the Green & Blue Building Award 2014 in the category Products / Services.

The OeAD-Housing Office and the University of Natural Resources and Life Sciences Vienna were runners-up for the Austrian TRIGOS Award 2015 in the category best partnership - for GBS and AEMS.

Table 3. List of awards and nominations

Nominee	Award	Year
OeAD-Guesthouse Gasgasse	state prize for architecture and sustainability	2012
OeAD-Guesthouse GreenHouse	winner klima:aktiv	2016
OeAD-Guesthouse mineroom	Green & Blue Building Award	2018
OeAD-Guesthouse mineroom	timber frame construction prize Styria	2017
OeAD-Guesthouse PopUp dorms	Green & Blue Building Award	2015
OeAD-Guesthouse PopUp dorms	winner FIABCI Prix d'Excellence	2018
OeAD-Housing Office	award Sustainable Development Goals	2018
OeAD-Housing Office	winner climate protection award	2013
OeAD-Housing Office	winner Austria's Leading Companies	2014
OeAD-Housing Office	winner innovative buildings	2016

In conclusion, the OeAD-Housing Office emphasizes Austria's leading role in relation to eco-friendly building and seeks to share knowledge with their international students and thus wants to carry the basic ideas of eco-friendly building out into the world. Moreover, our residents will always associate the comfort of their experience with eco-friendly building with Austria and will gladly return to the country - be it as tourists, university graduates or future business partners. Even if only a handful of our residents will be inspired by their positive experience with passive houses to build their own homes according to eco-friendly standards, or even launch an initiative similar to this one in their home countries, our goal of educating and inspiring people will have been reached and we will have contributed to a more responsible and intelligent use of resources.

Regarding the overall efficiency of the passive house buildings, it can be seen that the heat demand is significantly lower than in other guesthouses, while the picture for the electricity demand is not always as clear, since it is probably also influenced by other factors.

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Visual tool to integrate LCA and LCC in the early design stage of housing

Miyamoto A, Allacker K, De Troyer F

KU Leuven, Faculty of Engineering Science, Department of Architecture
Kasteelpark Arenberg 1 Bus-2431, 3001 Leuven, Belgium

ayu.miyamoto@kuleuven.be

Abstract. Over their whole life cycle, buildings are responsible for high environmental impacts and require critical financial resources. Decisions in the early design phase have a significant impact on both. This study aims to develop a visual decision support tool for architects in order to integrate an environmental and economic life cycle approach for dwellings. To evaluate the environmental impacts of the building design, the tool uses the Belgian LCA method, 'Environmental Profile of Building Elements'. This method translates 17 environmental indicators in environmental costs by considering the cost to avoid, reduce or compensate the effects to a level that is bearable. The tool allows to combine these life-cycle environmental costs (LCEC) with Life Cycle financial Cost (LCFC). To estimate the operational energy use of the building, the "dynamic Equivalent Heating Degree Day (dEHDD)" method is used. This method allows for fast and relatively accurate heating energy estimations in the early phase, based on a limited number of input data. The tool visualises the results in a graphical way which can be easily understood by architects. Even more, visualisation is seen as a powerful communication tool to share information and ideas with all stakeholders.

1. Introduction

As the built environment has been well-known as a crucial contributor to climate change [1,2], the 2010 European Directive on the Energy Performance of Buildings Directive (EPBD) requires EU Member States to improve the energy efficiency of new buildings to achieve the target of nearly Zero Energy Buildings (nZEBs) by 2020 [3]. In the same line, in November 2015, 174 countries signed an agreement to plan a drastic reduction in greenhouse gas (GHG) emission at the UN Conference on Climate Change in Paris. Design decisions in the early design stage significantly determine a building's life-cycle environmental and economic impacts [4,5]. However, due to the complexity of life-cycle cost (LCC) and life-cycle assessment (LCA) and the time constraints to consider those aspects in the early design phase, including those aspects, has remained a challenge especially for small scale project like dwellings [6]. As architects play a crucial role to reach the target, they must be better equipped to estimate influences of their decision on the impacts. In the constant feedback loop of designedly thinking, architects use mainly visual tools [7,8]. This paper proposes a visual design support tool for architects to design a sustainable dwelling based on LCA and LCC approaches. This paper is structured into five sections. The framework of the research is described in section 2. The calculation method is presented in section 3. The data visualisation in the tool is demonstrated in section 4. Results and discussion are described in section 5. Finally, conclusions are provided in section 6.

2. Framework for the approach

2.1. Goal

The objective of this study is to develop an approach to integrate life-cycle environmental and economic performance assessment in the early design stage to support architects when making their design decisions for a sustainable dwelling. The major hurdles for architects to integrate LCA and LCC in the early design stage are: time constraints, complexity of input and integration of dataset/results of the simulation. To overcome these difficulties, this study includes the following features:

- User-friendly input (no additional time and effort for input)
- Quick calculation method for estimating the heating energy in winter
- Graphical representation of results

In this study, the environmental impacts are monetised into a life-cycle environmental cost (LCEC). This monetisation enables to compare LCA and LCC in the same unit and to aggregate into a single figure. In addition, monetisation allows environmental taxation which is high on the EU political agenda [9] and has many advantages as highlighted by the organisation for economic co-operation and development (OECD) such as environmental effectiveness, economic efficiency, the ability to raise public revenue, transparency and addressing a wide range of issues [10]. As buildings have an effect on a wide range of issues such as energy, carbon, transport, waste, air and water pollution and resource through the life-cycle, LCEC can be used for the preparation of building life-cycle environmental taxes. The life-cycle total cost (LCTC) is defined as the sum of LCEC and life-cycle financial cost (LCFC). Both LCEC and LCFC can be divided into initial costs and in-use including the end of life costs (use+EOL) (Fig.1).

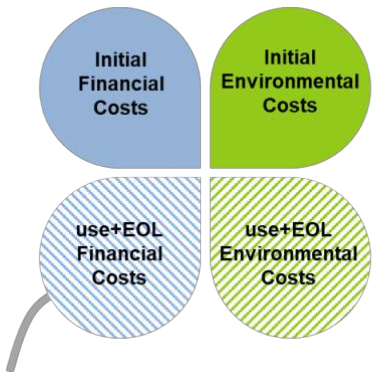

Figure 1: Four leaves clover diagram of LCTC

2.2. Workflow of the proposed approach

Figure 2 presents the hypothesis regarding the workflow of the design process considered in this research. The proposed tool, which is an Excel spreadsheet, consists of several input sheets, developed for each sub-stage: Brief-Form0, Form1 and Form2. Input parameters are classified into three categories: (1) geometry, (2) technical choices and (3) user behaviour. In the more advanced design stages, more detailed input parameters are required for each category. The user-friendly input and the calculation for estimating the heating energy in the tool are explained more details in [11]. Based on the input of these three categories, the tool provides a fast calculation of LCFC and LCEC. LCEC is based on 'Environmental Profile of Building Elements (MMG)'. Inputs of technical choice use a database of elements and materials from MMG. The database was extended with financial costs. The outputs are translated into two graphical representations: Sankey diagrams and parallel coordinate plots.

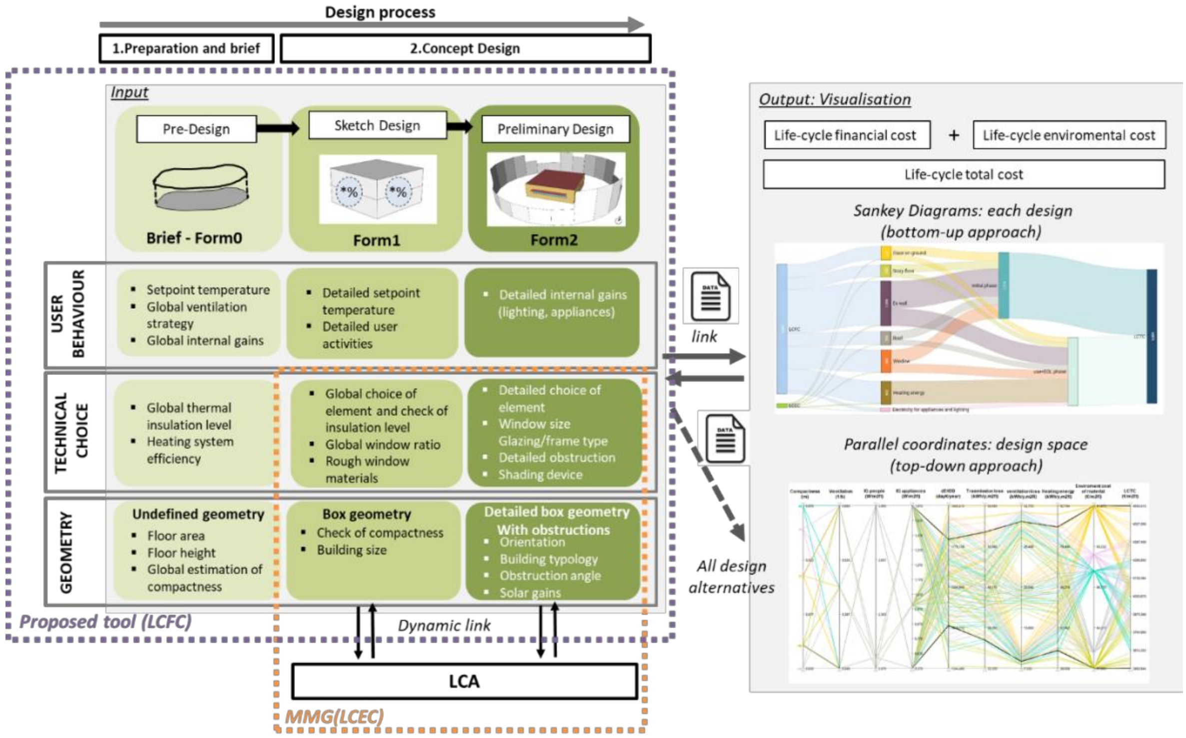

Figure 2: Considered workflow of the design process

3. Calculation method

3.1. Life-cycle financial costing (LCFC)

LCFC is based on the following formula [12]:

$$LCFC = IF + SPV(PF_0) + SPV(EOLF_0) \tag{1}$$

With:

- IF: initial financial cost (€)
- $SPV(PF_0)$: the sum of the present values of periodic financial cost (€)
- $SPV(EOLF_0)$: the sum of the present values of the EOL costs (€)

The present value of future costs is calculated as follows [12]:

$$PV[C_t] = C_0 \left(\frac{1+g/_{1+i}}{1+d/_{1+i}} \right)^t \tag{2}$$

With:

- $PV[C_t]$: present values of a cost (€)
- C_0: cost for a year of reference (€)
- g: nominal growth rate
- d: nominal discount rate
- i: inflation rate
- t: year of the cost (year)

In this study, the total financial cost is the sum of a construction cost, present values of future costs such as maintenance costs, heating costs, electricity cost for appliances and lighting and the EOL financial cost. A more detailed description can be found in [12].

3.2. Dynamic Equivalent Heating Degree Day (dEHDD) method to estimate operational heating energy

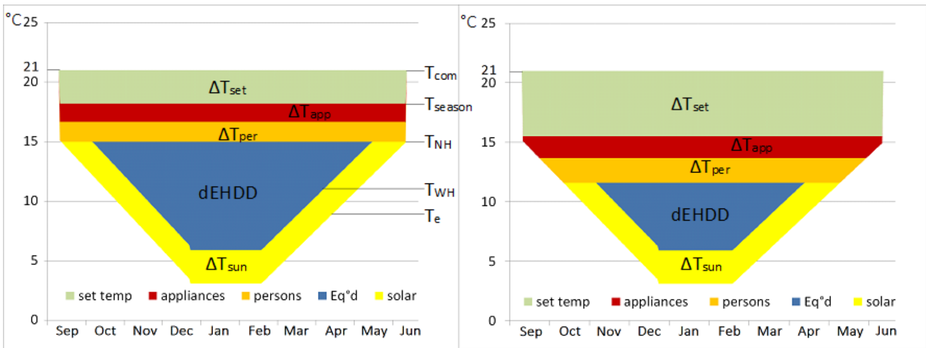

Figure 3: Representation of dEHDD for the temperate climate in Belgium and two different occupant behaviour profiles

The proposed tool uses a refinement of the Equivalent Heating Degree Days (EHDD) method to predict operational heating energy [13]. The Heating Degree Days (HDD) method predicts the yearly required energy for heating based on the number of days with a difference between the daily average outdoor and indoor temperature.

The EHDD takes into account the free solar and internal heat gains in a static way by a fixed reduction of the HDD [14]. In the dEHDD method, this reduction is calculated month by month for a better approximation of the solar gains and internal gains by occupant and appliances. The outdoor temperature (T_e) is obtained via linear regression of monthly temperature during autumn, winter and spring from Test Reference Years weather data (TRYs) [15]. The approach can be represented in a graphical way (Fig.3) with horizontally the number of days of the heating season and vertically the temperature. The number of dEHDDs is represented by the blue area in Fig.3. A more detailed description can be found in [13].

3.3. Life-cycle assessment (LCA) method: Environmental Profile of Building Elements (MMG)

In this study, the MMG method (the Belgian LCA method for buildings and elements developed for the Public Waste Agency of Flanders) is used to assess the life cycle environmental impacts and to monetise the environmental loads [16]. Seven environmental indicators “CEN” [17] in line with the European standard and ten additional environmental indicators “CEN+” from Belgian legislation [18] are taken into account. The method is described in more detail in [16]. This method monetises life cycle impacts as the cost to avoid, reduce and compensate environmental damage to a bearable level for the earth. The monetisation method in the MMG is described in [19].

4. Data visualisation in the tool

4.1. Sankey Diagram

Sankey Diagrams (SDs), initially developed by Riall Sankey to analyse the thermal efficiency of steam engines in 1898, are widely used to visualise quantitative flows in many fields of application. The width of the arrows is proportional to the size of flows. In this study, SDs are used to visualise the financial component of design decisions regarding elements. In the centre of Figure 4, the total cost for the different elements and costs for heating and electricity use by appliances and lighting are represented. The left flow (“flow (1)” in fig 4) visualises the relationship between elements and the sum total of LCFC and LCEC. The right flow (“flow (2)” in fig 4) visualises the relationship between elements and total initial cost and the cost during the use phase including the end of life (use+EOL). Several tools are available for SDs visualisation. “Sankey Diagram Generator v.1.2” [20] is used in this paper. Results of environmental cost are automatically collected from the MMG database to the proposed tool and the proposed tool automatically translates the dataset of LCFC and LCEC into a JavaScript code to visualise via the “Sankey Diagram Generator v.1.2”. Figure 4 and 5 show a representation of two design options. The useful feature for SDs is the possibility to visualise selected flows, e.g. in Fig.5 the inputs from the different elements of cost in “use+EOL phase”. SDs give architects insight into the impact of each design and help to evolve to a sustainable building.

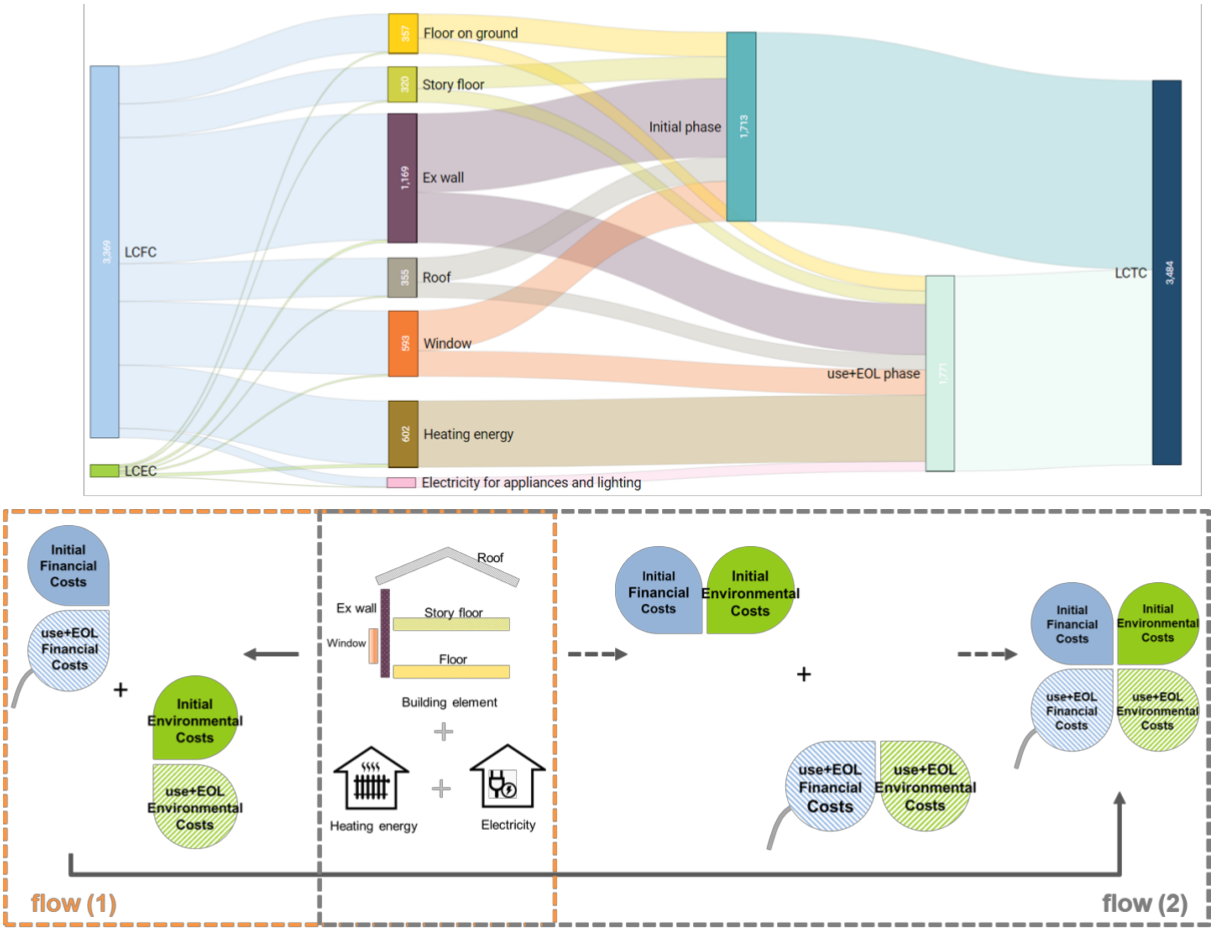

Figure 4: Representation of SDs for a design option (above) and diagram of flows (below)

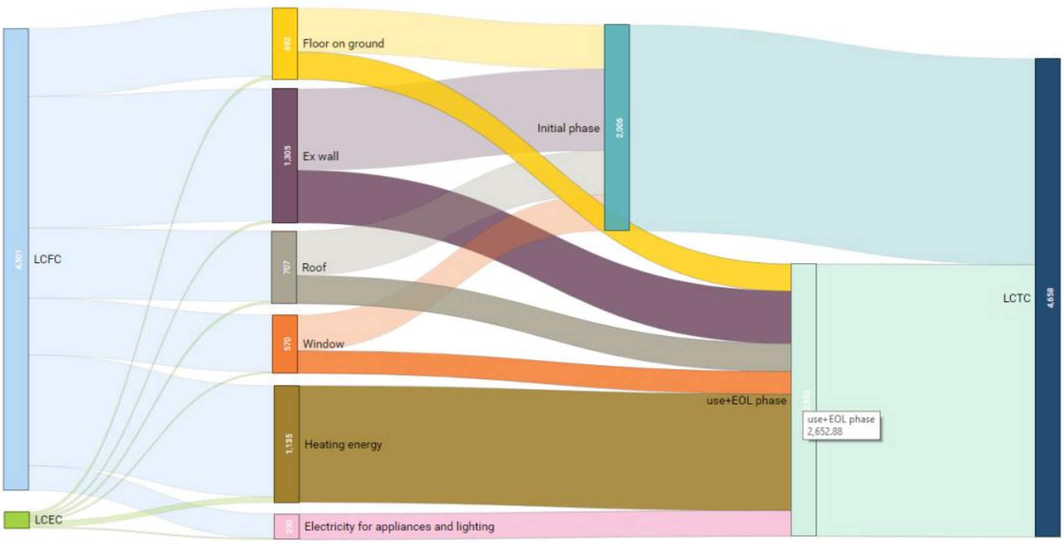

Figure 5: Representation for a design option and highlighting of “use+EOL phase” in SDs

4.2. Parallel coordinate plot for visualisation of design space

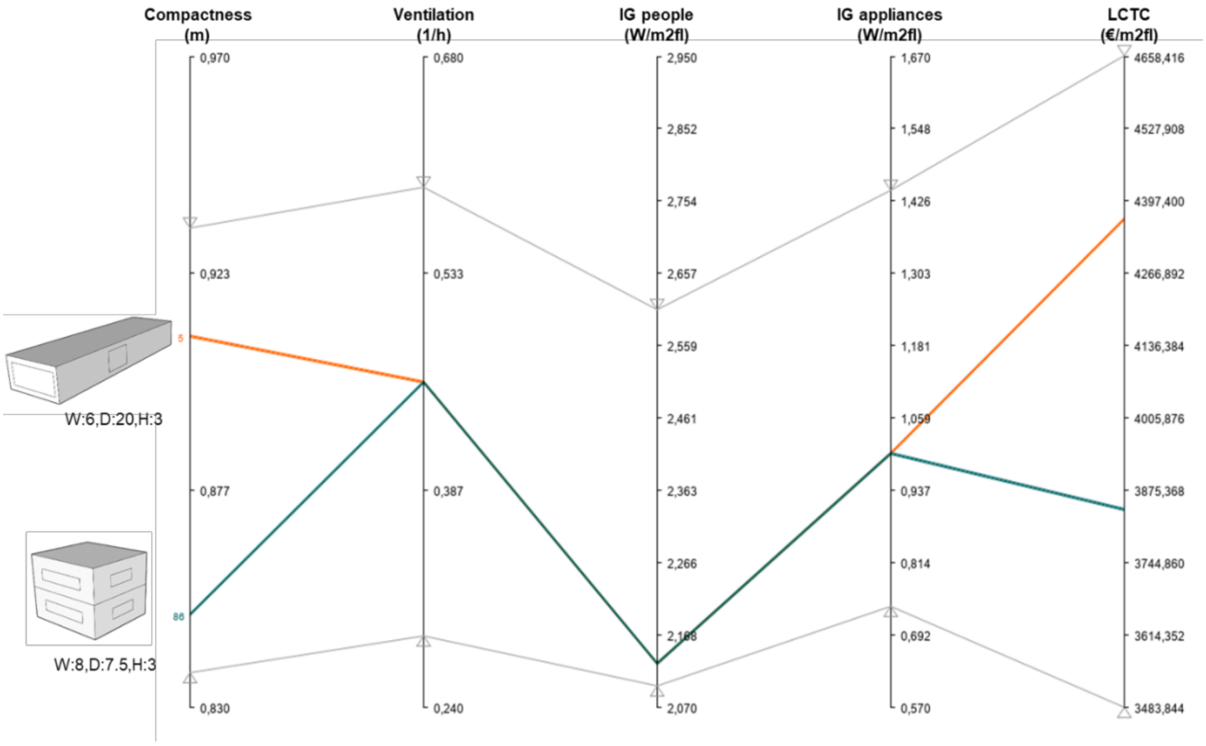

Figure 6: The representation of two design options (all axes with more extreme parameters then light grey being excluded)

Parallel coordinates are one of the most general techniques for representation and exploration of multidimensional problems. Parallel coordinate plots (PCPs) represent input and output parameters on parallel axes and all input and output values of one case are connected via lines. Hence, PCPs enable to represent an *n*-dimensional problem in a plane and allow to represent how a whole range of input parameters affect several outputs [21]. Several tools are available for visualisation via PCPs. For this paper “Xdat version 2.2” is used [22]. As highlighted by Siitola et al. [23], advantages of PCPs for architects in the early design phase are, firstly, an overview of the design space is easily grasped because PCPs itself is an overview. It enables architects via colouring and a selecting mechanism to understand the impacts of each parameter on the result quickly and to observe the relationship between parameters. Secondly, rearrangement operations such as changing the order of coordinate-lines, inverting the axis direction and so on, often give additional insights into the data set. Thirdly, architects can highlight the set of connections to facilitate comparisons between selected and non-selected lines. Fourthly, it is possible to display exact values per axis. It helps architects to discover design alternatives between certain limits, such as targets of LCTC and LCEC, investment cost, and so on. Figure 6 shows two design options (same total floor area but more or less compact buildings based on width, depth and number of floors) filtered so that only one value is considered for the ventilation rate, internal heat gains by people and appliances. The elaborated tool can automatically create a design space with user-defined parametric ranges and steps of each parameter. Figure 7 visualises the representation of a whole design space, applying different colours for each compactness and highlights design options of the smallest and the largest LCTC via a thick black line. It illustrates that the important feature of PCPs is its power to translate numerical data set into a visual representation and the ability to provide both an overview and detailed numeric values.

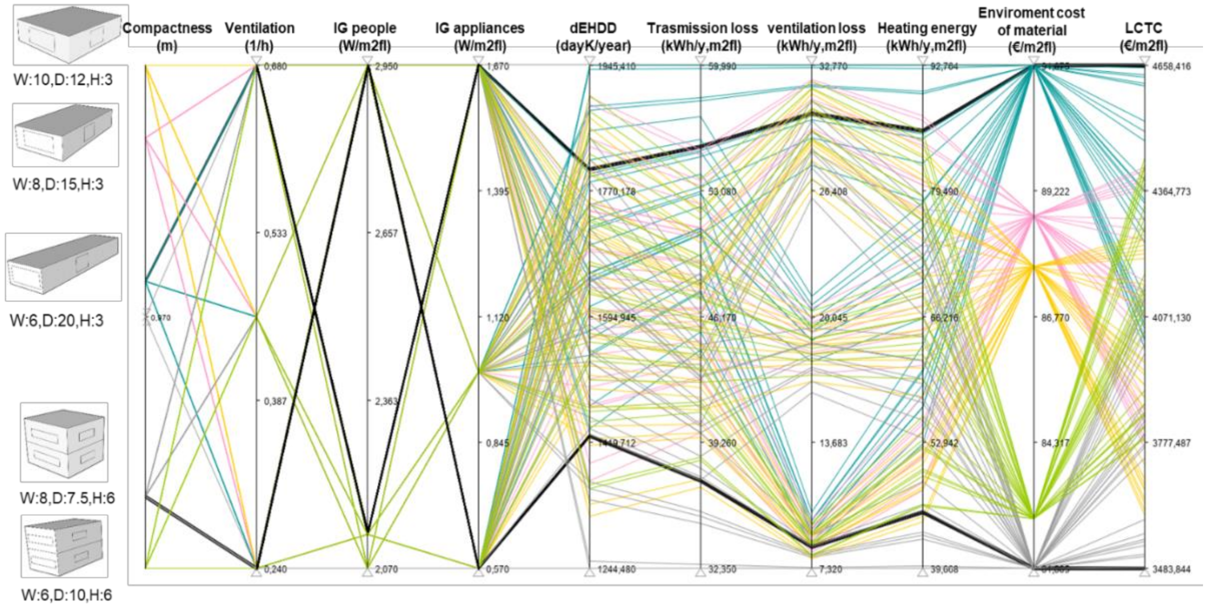

Figure 7: Representation of a design space and the lines representing highest and lowest LCTCs are highlighted in black

5. Discussion

This paper presents a tool to assess the life-cycle environmental and economic aspects for architects in an early design stage in order to support the design of sustainable dwellings. The tool proposed in this paper:

- Requires no additional effort to obtain LCFCs and LCECs of each design proposal than what architects already consider, such as orientation, location, geometry, materials, and so on. The proposed tool requires primary inputs categorised into (1) geometry, (2) technical choices and (3) user behaviour for energy estimation. A more detailed input can be provided along the design process if more detailed calculations are desired, typically evolving in level of detail from brief, sketch design and preliminary design.
- Enables fast and accurate estimations of the heating energy and electricity for appliances and lighting of each design option. This energy is translated into LCEC and LCFC. This quick estimation method enables architects to understand how their design decisions influence the environment and finance in a step by step process. As important design decisions are taken early in the design phase, this tool hence allows to assess the influence of these decisions at a crucial moment.
- Provides easily understandable output via monetisation of LCEC. Both environmental and economic impacts expressed in a single unit (€) and aggregated into a single figure enables to compare both easily.
- Demonstrates two types of visualisation of results: "Sankey Diagrams" (SDs) and "parallel coordinate plots" (PCPs) because architects often hesitate to deal with numerical datasets. SDs visualise the impacts of changing design parameters on LCEC and LCFC during a step by step design approach (bottom-up approach). PCPs generate an overview of the design space (top-down approach). However, since in the Sankey diagram the vertical scale is often adapted so that the sum of all costs of considered elements covers the whole screen vertically, the absolute differences between the design variants are not represented graphically but can only be read as a numerical value. To overcome this disadvantage, the tool allows to generate a design space by defining for each parameter a minimum value, a maximum value and a number of steps in between. This design space is visualised via parallel coordinates plots (PCPs). This plot can visualise the different costs on different axes. Analysing the effect of different design decisions becomes very graphical and allows an interactive iteration**.** Therefore, the combined use of these

two visualisation techniques enables architects to find better design solutions for sustainable buildings from an early design stage on. Even more, visualisation is a powerful communication tool for architects to share information and ideas with other architects, engineers, stakeholders and clients.

- Enables to use different climatic conditions with any Test Reference Years (TRYs) (also predicted future TRYs) for estimation of heating energy demands via dEHDD.

6. Conclusion

The advantages of the proposed approach are: (1) user-friendly limited inputs for the life-cycle financial cost (LCFC) and no extra effort to estimate in addition the life-cycle environmental cost (LCEC), (2) fast analysis of the importance of heating via LCEC and LCFC and (3) easy comprehensive visualisation. Via the tool, it is not a huge challenge anymore to integrate extra aspects (life-cycle environmental and economic) in the design processes as it does not require extra time and effort and it is easily interpretable via different graphical representations. This research is a starting point to assist architects in making decisions for sustainable nearly Zero Energy Buildings (nZEBs) from the sketch design stage onwards. Concerning further research, the usability test will be carried out by students and a workshop for architects will be organised to obtain feedback from practitioners. Furthermore, the tool will be extended to evaluate summer comfort/discomfort to avoid the need for active cooling.

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Life cycle environmental and cost evaluation of heating and hot water supply in social housing nZEBs

Hernandez P[1], Hernandez J[1], Urra I[1], Grisaleña D[2]

[1] TECNALIA Research & Innovation, Astondo Bidea, Edificio 700, Derio, 48160 Spain
[2] VISESA, Basque Country Public Housing Body, Portal de Gamarra 1A, 01013, Vitoria-Gasteiz, Spain

patxi.hernandez@tecnalia.com

Abstract. This paper presents a comparative analysis of different space heating and hot water systems for a social housing project in Santurtzi, Spain. The building, comprising 32 apartment units and currently under construction, has been designed to minimize thermal energy demand, while ensuring comfort and quality of the internal environment for the social housing occupiers. The selection of the heating and hot water energy systems has been carried considering a life cycle perspective both for environmental and economic impacts. Different alternatives have been analysed which compare conventional gas boiler installation, which has been the norm for this type of social housing for the last decades, with various options based on heat pump technology. Life cycle analysis of the environmental effects of electrification of the thermal energy demand through heat pumps show a potential for reducing life cycle CO_2 emissions. The economic evaluation done through life cycle costing, comparing investment, maintenance, replacement and operational costs of gas boiler with aerothermal and geothermal heat pump solutions, have shown however that gas heating solutions are still the most competitive economically. Increasing the overall efficiency of those heating and hot water systems that include heat pump technology, while reducing their uncertainty in operation is a key element to ensure competitiveness of heat pumps in the current market.

1. Introduction

In the last decades heating and hot water for residential buildings, and in particular for social housing, has been increasingly supplied in the Basque Country by the use of natural gas. Current construction standards, with reduced thermal energy demand, provide the opportunity to explore solutions that move away from natural gas, for example by electrification of thermal supply through the use of heat pumps. With a vision for an electricity mix that will progressively reduce its environmental impacts by utilising a larger share of renewable generation, and the potential for on-site renewable electricity generation which is becoming very affordable (mainly through PV panels), use of heat pumps is expected to grow in the coming years.

This paper studies alternatives for electrification of thermal energy loads through heat pumps in a case study of a nearly-Zero Energy Building, with particular attention to the evaluation of life cycle environmental and economic performance of different design alternatives for the installations.

2. Case Study

Alternative technologies for heating and hot water are studied in a new residential building, for social renting use, being VISESA the building developer (Basque Country Public Housing Body). The building is situated in Santurtzi (Bizkaia, North of Spain), with a temperate climate (Köppen-Geiger climate classification Cfb) and 1,023 Heating Degree Days (15 degree base temperature). It comprises 32 apartments in four floors, with a total of 2885 m^2 of useful floor area, and a North-South orientation. Construction is expected to be finished within autumn 2019.

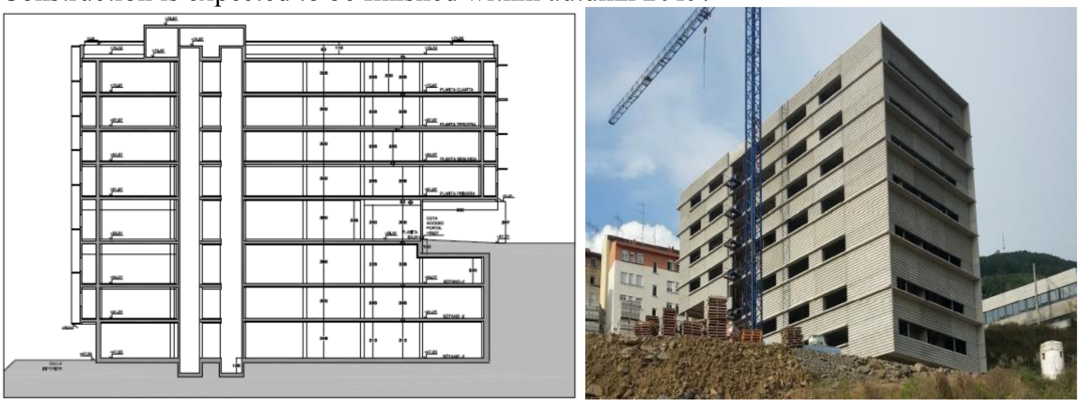

Figure 1. Section of the apartment building and current state of construction (December 2018).

The building has been designed to meet high energy – efficiency standards, beyond current building regulations in Spain, and even beyond future building regulations which are currently published as a draft, which is expected to require non-renewable primary energy use below 32 kWh/ m2·year, for new residential buildings in this location [1]. This is possible with a detailed design to reduce infiltration and thermal bridging, installation of mechanical ventilation with heat recovery, and the following thermal characteristics (transmittance U-values) for the building envelope:

- Windows: 1,20 W/m^2·K (Low emissivity, Argon filled, 4/16/3+3)
- Façade: 0,23 W/ m^2·K
- Roof: 0,21 W/ m^2·K

Calculated heating demand for a building of such characteristics in this climate is consequently very low, just 6 kWh/m^2*year, below the expected hot water demand which is 12 kWh/ m^2*year. No cooling systems are installed in residential buildings in this climate, as cooling demand is very low and natural ventilation, particularly night ventilation, is used to achieve comfort.

These low energy demands provide the opportunity to reconsider how energy supply is approached in buildings, as one of the main benefits of the gas supply, which is its ability to supply a large and instant power base, might not be longer needed for low energy buildings with correspondingly low peak power demands. Different options for utilization of heat pumps in this building have been therefore studied.

3. Different choices of energy systems for heating and DHW

Table 1 describes the different energy systems that have been considered for the building, which combine the use of the heat pump technology with different heat sources (air, ground, and mixed).

Table 1. Energy systems for heating and DHW considered in this study

	Installed Power	Efficiency
1- GAS + SOLAR (CENTRAL)	2 * 50 kW	102% (condensing boiler)
2- AIR-TO-WATER HEAT PUMP (CENTRAL)	2 * 47 kW	SCOP = 2,5

3- AIR TO WATER + GEOTHERMAL HEAT PUMPS (CENTRAL)	2 * 47 kW	SCOP = 3
4- GEOTHERMAL HEAT PUMPS (CENTRAL)	2 * 47 kW	SCOP = 4
5- AIR-TO-WATER HEAT PUMPS (INDIVIDUAL)	32 * 7 kW	SCOP = 2,5

Detailed design was carried for each of the options, with installation detail and budgeting as shown in Figure 2 as an example. Options 1, 2, 3 and 4 are centralized installations where heat is centrally generated and distributed to the 32 apartments. Option 5 refers to individual installations in each apartment.

The option 1 with gas, includes a solar thermal installation with 14 panels of 2.52 m^2 each, which covers 32% of the annual hot water demand, as this is requisite from the building regulations to comply with a minimum renewable energy contribution. Option 2 is an air to water heat pump, and option 4 a geothermal heat pump. Option 3 is a mixed solution which can combine both geothermal and air source heat pumps, depending on the temperature of the heat source (external air or ground). For all the heat pump cases, and with the estimated seasonal coefficients of performance (SCOPs) shown in Table 1, the requirements for contribution of renewable energy from current building regulations in Spain are fulfilled, as renewable energy from heat pumps is accounted as set out in the Renewable Energy Directive [2]. However, it is important to note that these SCOP values have a relatively large degree of uncertainty. The performance of the heat pump will depend on the performance of the actual installation, which includes various storage and buffer tanks (see figure 2), numerous pumps and heat exchangers, and a control logic that will be programmed. Real efficiency in operation will depend on the variations of both the heat source temperature (external air or ground) and the heating and hot water demands. Values for the seasonal performance of the heat pumps, which are provided by the manufacturers according to standard testing procedures such as EN 14825 [3], need therefore to be adjusted to real performance within this specific installation and expected demands. The values shown in Table 1 depart from the calculations made with the Spanish HULC energy certification tool [4], further adjusted for particularities which the software is not able to model, for example the losses through the different distribution and storage systems.

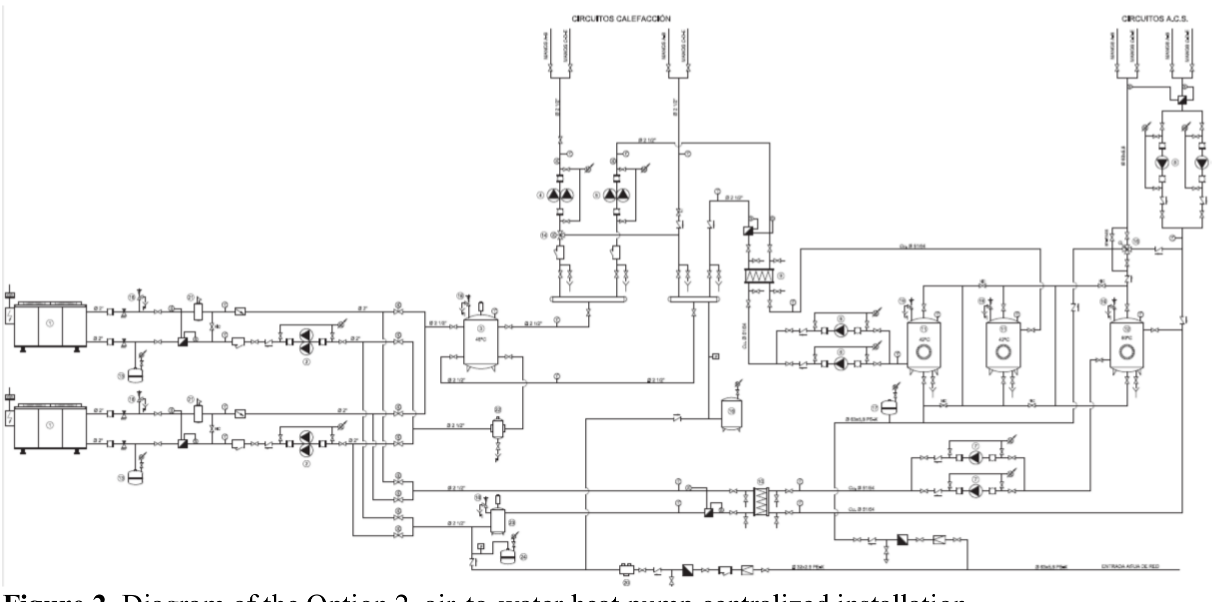

Figure 2. Diagram of the Option 2, air-to-water heat pump centralized installation

From these estimations about the energy performance of the different energy systems, heating and hot water final energy use for the building has been calculated and is presented in Table 2. This table does not add auxiliary energy use, which is very similar as core distribution system, which is quite standard in this type of buildings, has been maintained for all options.

Once the energy use of the different options has been calculated, an in order to assess economic and environmental performance of the heating and hot water system from a life cycle perspective, these results should be combined with the data on environmental and cost evaluation of other life cycle phases, such as the product manufacturing and installation, and the maintenance phases.

Table 2. Energy use for space heating and DHW for the different technologies.

	Gas [kWh/year]	Electricity [kWh/year]
1-GAS + SOLAR - CENTRAL	64701	0
2-AIR-TO-WATER HEAT PUMP - CENTRAL	0	36355
3-AIR TO WATER + GEOTHERMAL HEAT PUMPS – CENTRAL	0	30926
4-GEOTHERMAL HEAT PUMPS - CENTRAL	0	22722
5-AIR-TO-WATER HEAT PUMPS - INDIVIDUAL	0	30355

4. Results for life cycle environmental and economic performance evaluation

This study intends to serve as an example on how decisions on energy systems can take into account a life cycle perspective, and facilitate selection of options that have favorable economic performance over a period of study considering the whole life cycle cost, even if they correspond to different actors through that period (i.e.: building developer, building owner, building occupier/user).

Environmental and economic performance of the five technology options for heating and hot water supply have been evaluated from a life cycle perspective, following standard *'EN 15978:2011 – Sustainability of construction works – Assessment of environmental performance of buildings – Calculation methods for environmental evaluation' [5]*, and standard *'EN 16627:2015 – Sustainability of construction works – Assessment of economic performance of buildings – Calculation methods for the economic evaluation' [6]*. Evaluation considers the impacts of the products (manufacturing of the systems), on site installation processes, and the use stage (including operation and maintenance). End on life stage, as its impact is relatively very low for building energy installations, has been disregarded for this study. The study period for the assessment has been selected as 15 years, which is the expected service life for some of the key products in the analysis (such as the heat pumps).

The functional unit for the analysis has been selected as 1 kWh of heat delivered to the dwellings, for heating and domestic hot water. The environmental impacts and economic costs of delivering 1 kWh are quantified in the following sections.

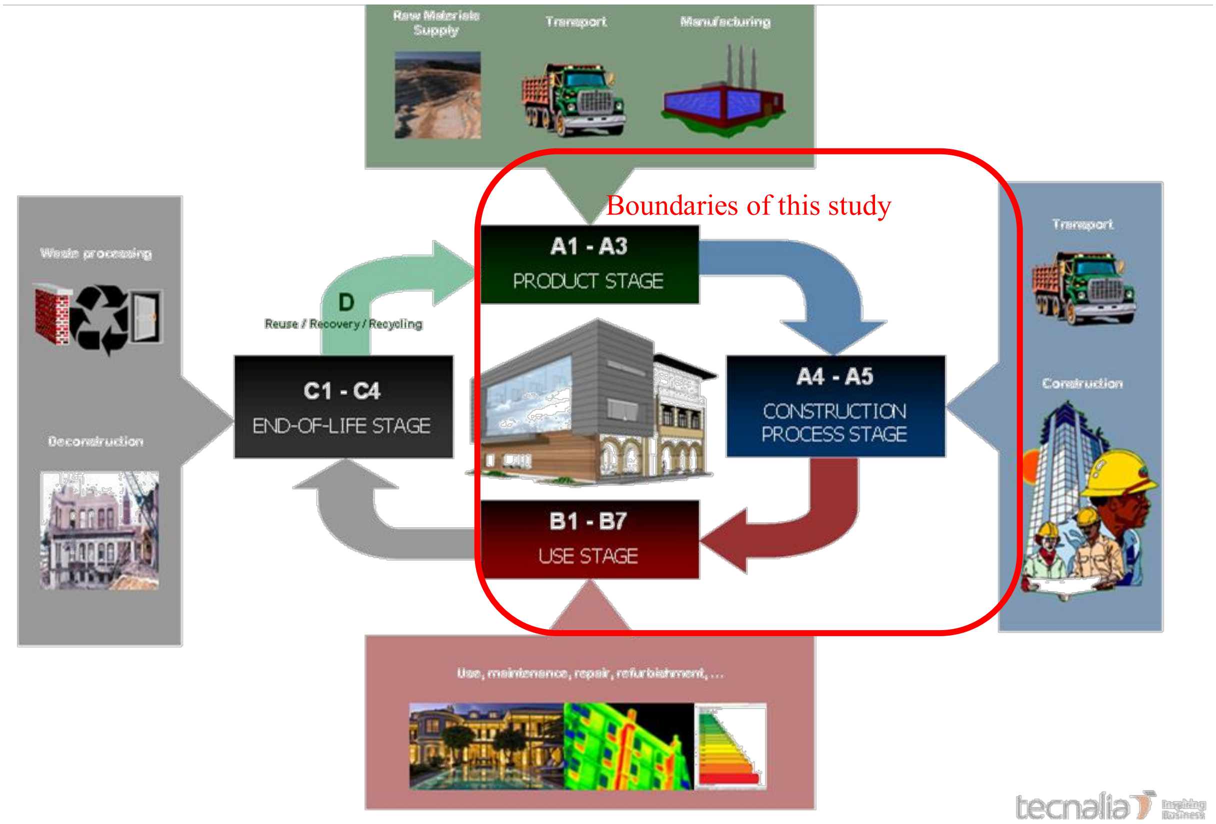

Figure 3. Description of the life cycle stages within EN 15978 and boundaries set for this study

4.1 Environmental performance evaluation

The Ecoinvent LCA database [7] has been used to attribute environmental impacts to the different products that conform the different installations, such as the gas boiler, solar panels, heat pumps, geothermal bore holes, storage tanks, etc.; as well as for the impacts related to electricity and gas usage. Different environmental indicators can be calculated according to EN 15978. Figure 4 shows the results for the global warming potential indicator.

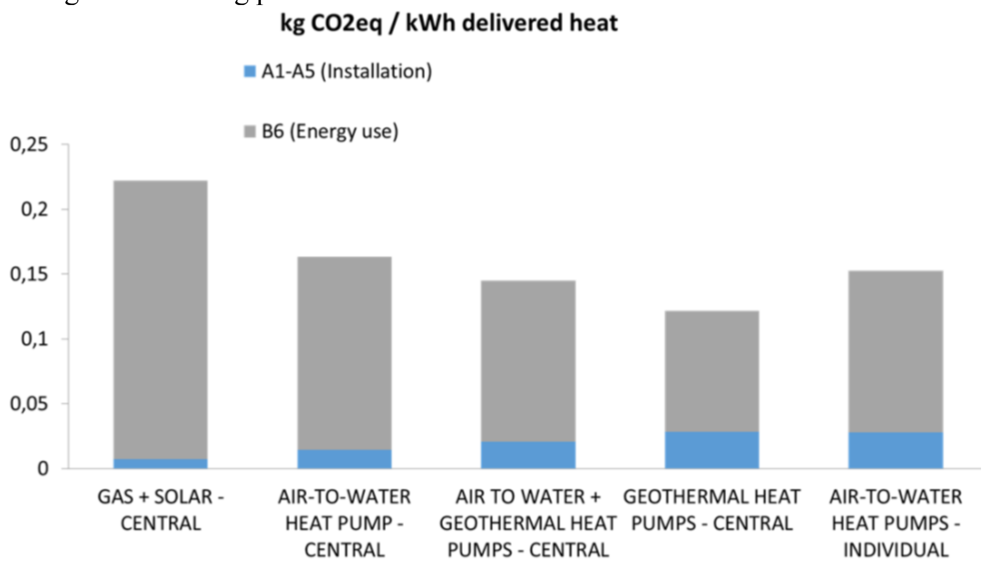

Figure 4. Global warming potential of delivered heat by the different energy systems

It can be observed that the main environmental impact is related, as it could be expected, to the actual energy usage in the operation stage (B6), and that the impact of the product stage (A1-A5) is relatively low. The solutions with heat pumps, even with the current electricity mix (which has been considered constant for the 15 years study period), are favorable to the heat pumps. Results range from 121 to 163 grams of CO_2eq per delivered kWh of heat delivered by the different solutions with heat pumps, compared to 222 grams of the conventional solution of gas boiler with solar water heating support.

4.2 Economic performance evaluation

To quantify the cost indicators over the study period, it is necessary to develop some scenarios and make certain assumptions on a few variables. This study considers a real discount rate of 3%, and conservative annual increases on prices of electricity of 0,5%, and 1% for gas. Costs of the different options are disaggregated and shown in table 3 (production and installations costs), and table 4 (maintenance costs).

Table 3. Cost of product and installation stages (A1-A5) for the different technologies

	1 -GAS + SOLAR	2- AEROT CENTRAL	3- GEOT+AEROT - CENTRAL	4- GEOT CENTRAL	5-AEROT – INDIVIDUAL
Total Generation + Distribución: Heating & DHW	**72.504,25 €**	**111.757,47 €**	**155.190,39 €**	**165.446,00 €**	**247.898,59 €**
Legal procedures	1.171,88 €	1.115,53 €	1.115,00 €	1.115,00 €	1.143,71 €
Generation and boiler room	27.453,93 €	69.347,62 €	71.866,81 €	70.089,00 €	237.920,00 €
Regulation and control	14.311,96 €	33.175,48 €	25.870,74 €	20.765,00 €	8.834,88 €
General distribution (not including internal for each apartment)	8.832,44 €	8.118,84 €	8.118,84 €	8.118,00 €	
Solar installation	20.734,04 €				
Bore holes			39.533,00 €	56.400,00 €	
Thermal Response Testing (TRT) & commissioning			8.686,00 €	8.959,00 €	

Table 4. Cost of maintenance stage (B2) for the different technologies

	Annual maintenance costs [kWh/year]
1-GAS + SOLAR - CENTRAL	1,700 €/year
2-AIR-TO-WATER HEAT PUMP - CENTRAL	1,700 €/year
3-AIR TO WATER + GEOTHERMAL HEAT PUMPS – CENTRAL	1,500 €/year
4-GEOTHERMAL HEAT PUMPS - CENTRAL	1,000 €/year
5-AIR-TO-WATER HEAT PUMPS - INDIVIDUAL	2,560 €/year

Operational energy costs are more complex to calculate. For centralized heat pump installations, the costs for contracting electricity power capacity for different time periods during the day need to be considered. For geothermal installations, lower contracted power is one of the economic advantages, as due to the more constant temperature of the ground used as heat source, a good coefficient of performance (COP) is maintained even in cold periods. On the contrary, air source heat pumps lower their efficiency during periods with low external temperatures, and therefore need to draw more power from electricity grid to deliver the necessary heat supply. Centralized installation with air to water heat pump need to contract an estimated power of 45kW for the peak power periods, compared to 25kW contracted power for centralized geothermal heat pump installations. As for individual heat pump installations, each apartment would need to contract additional power capacity, which has been estimated as additional 3kW, which largely increase the fixed costs of the operation for the users. Gas installations do have the advantage of very low fixed costs. Figure 4 shows results of the overall operational costs for the considered options, showing fixed costs and variable (energy) costs, for each delivered kWh of heat.

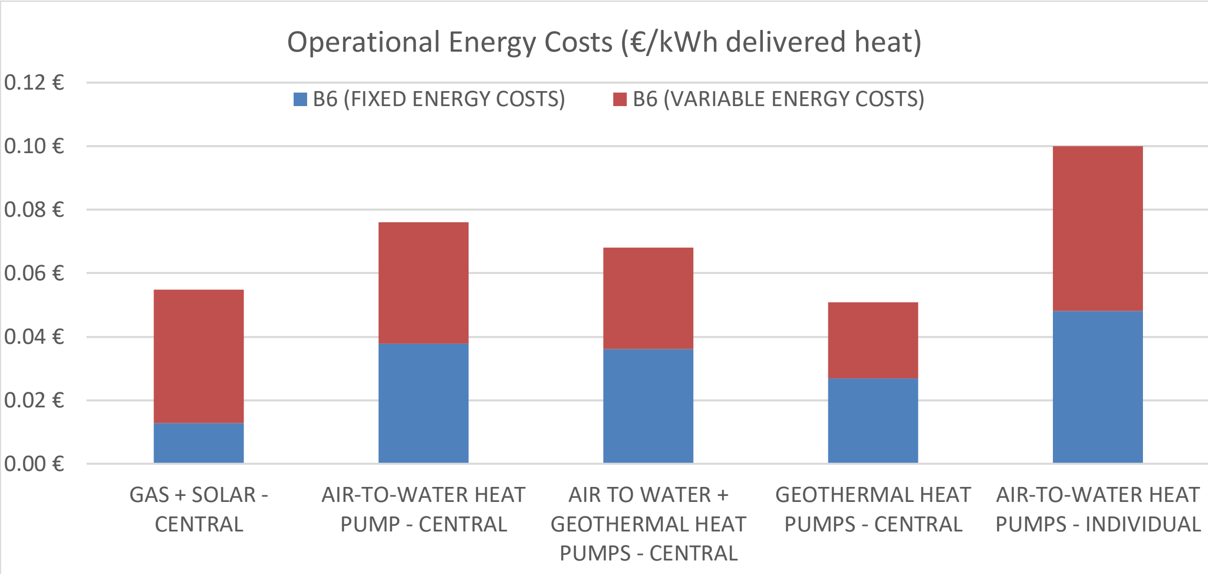

Figure 5. Operational energy costs for the different energy systems.

It can be observed that the low fixed costs of the gas installations make them a very interesting option from an operational energy cost perspective, only after the centralized geothermal installation. Individual heat pumps, due to both variable and fixed costs, are the most expensive solution in this case.

To be able to compare all the technologies for the selected study period of 15 years, costs of the other life cycle stages need to be added to the operational energy costs. Figure 6 shows the results of adding the initial costs for the installation and maintenance costs for the five technological options considered in this study.

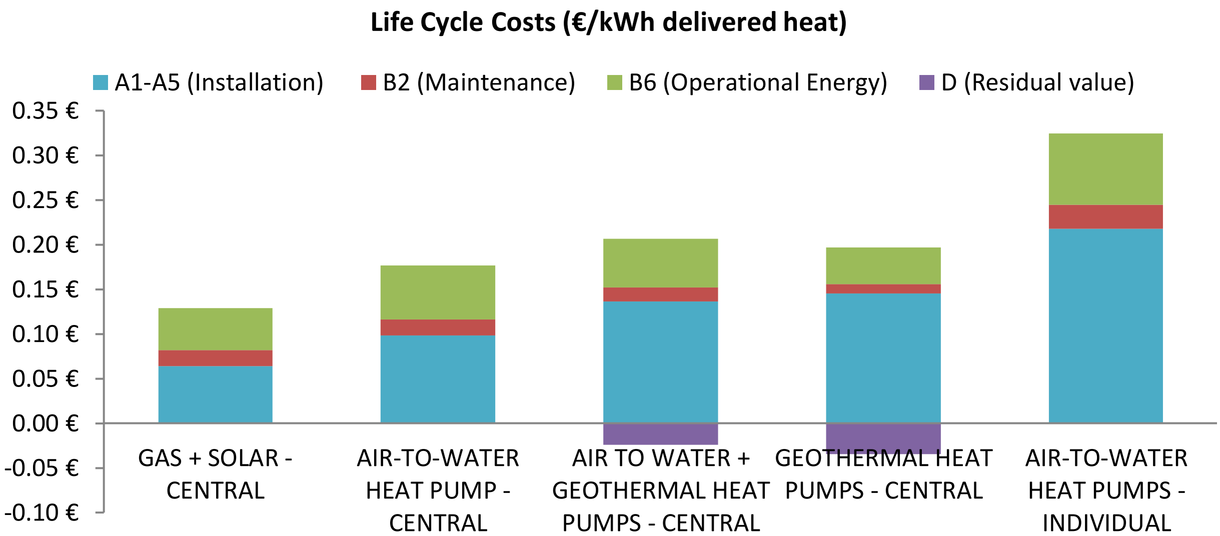

Figure 6. Life cycle costs for the different energy systems considered in the study. Residual value considering value of components (particularly geothermal borehole) after the 15 year study period.

Due to the lower initial investment and a competitive operational cost, gas installations backed with solar water heating systems are currently the most economically favourable solution for this case study building.

Geothermal installations offer the lowest operational costs in energy, and the lowest cost for the users considering also maintenance, but larger initial investment costs mean that overall life cycle costs are higher than both gas and air to water centralized installations. It must be noted that if we would consider the residual value of the borehole in geothermal installation, as will have an estimated service life of 50 years, much larger than the study period of 15 years, life cycle cost results would be similar to air to water centralized heat pump installations.

Air to water individual installations are the most expensive solution for this building within all cost categories (installation, maintenance, and operation).

5. Discussion and conclusions

The building sector is aiming for a progressive reduction of the energy use, and decarbonisation of the energy supply. A first step to achieve this goal is the drastic reduction of the energy needs for buildings, and a second step should be the study of the optimal technologies and energy systems to supply those energy needs.

This study has compared solutions for heat pump installations which could substitute the common gas installation, in a 32-apartment building designed for very low energy use for heating and hot water.

Most of the life cycle impacts of delivering heat to the building occur during the operation phase due to the energy use. Even for a building as the studied with very low energy use in operation, the manufacturing and installation of the actual heating energy systems represents a relatively small percentage of the total life cycle environmental impacts. Only for geothermal installations, where significant environmental impacts occur in the installation mostly due to the borehole drilling, and for the individual heat pump installations, the share of total life cycle CO2 emissions that can be attributed to the manufacturing and installation of the systems is above 10%.

Total life cycle CO2 emissions have shown that natural gas, which has been frequently cited as a ‘low-carbon’ and ‘transition’ fuel and is still the most common heating fuel in Spain, has larger CO2 emissions than alternative solutions based on heat pump technology, even with the current electricity mix.

Studying life cycle costs for the presented technology options, for a period of study of 15 years and including costs for investment, operation and maintenance, gives however a very different result. The gas installation, which is backed with a solar water heating system, is still the most cost-efficient option for providing heating and hot water to the case study building. The low initial investment, and operational energy costs only challenged by the most efficient geothermal heat pump solutions, means that solely in cost terms it is still difficult to compete with this standard solution. Comparing within the heat pumps, centralized air to water heat pumps is the most competitive, mainly because lower initial investment. If the period of study will be extended (e.g. 50 years), geothermal solutions could become competitive in cost terms, as their major investment cost (borehole heat exchanger) has a service life of 50 years. Individual heat pumps are the most expensive option, due to higher initial investment and higher operational costs, in part due to higher needs for contracting electricity power for the apartment occupiers.

As a final conclusion, heat pumps can be a good solution to reduce CO2 emissions, particularly as they offer the possibility of using increasingly renewable electricity, also from on-site renewable energy sources. Although economically they still have strong competition from the gas energy supply, overall life cycle costs are close and could be matched in the near future. Improving the overall performance of heat pump installations in operation will be of key importance to reduce life cycle costs of heat delivered by heat pumps. The large sources of uncertainty that were found when calculating seasonal performance of installations using heat pump technology, also highlighted the need for thorough commissioning, measurement and verification procedures for buildings including heat pump technology, procedures which have already been implemented in the described case study building.

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A case-based study on the use of life cycle assessment and life cycle costing in the building industry

Collin C, Olesen G G H, Qvist Secher A

Ramboll, Hannemanns Allé 53, 2300 Copenhagen, Denmark
Ramboll, Olof Palmes Allé 22, 8200 Aarhus N, Denmark

chc@ramboll.dk

Abstract. The environmental impact of human activities has been a concern for engineers and architects for centuries, from limitation of energy and raw materials to predicting future energy and resource demands. This review demonstrates how life cycle assessment (LCA) and life cycle costing (LCC) tools can be used to support design decisions in the building industry throughout the design process. The study is primarily based on DGNB certification projects in Denmark conducted by the engineering consultancy company Ramboll and focuses on how LCA and LCC tools can be used in the early design stages to quantify decision making and how tools are used in the final stages of a certification process to verify the building geometry with regard to life cycle costs and environmental impacts.

1. Introduction

In accordance with the Danish Construction Association only 4% of all building projects in 2018 were considered sustainable in Denmark, counting buildings with sustainability certifications, meet the voluntary Danish low energy class or additional sustainability measures exceeding the Danish building regulations [1]. In Ramboll Denmark approximately 6.5 % of the projects within the building industry are described as sustainable in the project database, half of these are certification projects like DGNB, LEED and BREEAM[1]. Looking at all Ramboll's projects within the building industry globally there has been an exponential growth in projects described as sustainable over the last 10 years.

The Danish building regulation has tightened the requirements to energy consumption of buildings over the last decades, but has yet to finalize the currently developing voluntary sustainability class, which will contain a requirement for LCA and LCC estimates for major building components. In the long term, specific requirements for a building's total energy and resource consumption over its life time may be implemented [2]. With lack of interest and demand for sustainable buildings and a lack in regulations it is crucial that engineers, architects, developers and contractors have entrepreneurial spirits when it comes to sustainable building design and informing the clients and developers of the possibilities and value propositions herein.

The aim of this paper is to increase awareness of design driven by life cycle methods through case studies in the engineering and design company Ramboll [3]. The case studies focus on different

[1] Deutsche Gesellshaft für Nachhaltiges Bauen (DGNB), Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM)

methodologies utilising life cycle engineering[2] as a driver for design decisions and the paper will present the potentials and boundaries in both early design stages as well as detailed design stages.

2. Life Cycle Engineering Screening Approach

A common design constraint is limited time and budget for a project. To enhance informed decision making and promote sustainable solutions it is important to have tools which provide quick feedback to the designers and client. This section will explain the Ramboll sustainability screening methodology through theory and examples. This approach can be used both in early design stages as well as very late design stages and even during construction. The methodology has been developed to qualify the answer to one of the most common questions posed by clients; *what is the most sustainable material/product for a given function?*

2.1. Sustainability Screening of Building Materials and Products

To enhance informed decision making and promote sustainable solutions a screening tool as seen in figure 1 can be used. The screening tool can be used to compare functional equivalent products or materials which means the primary functions and services must be equivalent. They are compared on a variety of parameters which includes the life cycle and both social, economic and environmental qualities.

Functional equivalent product group		Sustainability Parameters		
		Social	Economic	Environmental
Life Cycle Stages	Production			
	Construction			
	Use			
	End of Life			

Figure 1. *Scheme for sustainability screening of building materials or products*

The use of this scheme will enable the designer to compare products over the entire life cycle of a building and on all three sustainability parameters; social, economic and environmental. This method can be adapted to all project phases. In the early design stages, it is possible to compare different materials, products or systems based on experience and generic data. Environmental data is accessible through the free online database *oekobau* [5], whereas costs can be found in the Danish cost tool *molio price data* [6]. Social data can be both descriptive and specific. A descriptive parameter could be aesthetic and cultural quality and a specific material property could be light reflectance which will influence the daylight in a room and thereby also the users, thus some parameters are easy to quantify whereas other are subjective.

The scheme can also be used to specify material qualities in a tender through requirements for e.g. enclosure of environmental data and building sustainability certifications. In a later design stage, the scheme can be used to compare specific building components or products against each other on a chosen set of parameters. The data will primarily be derived from the manufacturer's websites combined with generic data when needed e.g. for life span, maintenance and cleaning cost.

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[2] *Life cycle engineering enables informed decision making by evaluating environmental, economic and social impacts of products, buildings or cities in a life cycle perspective. The Life Cycle Engineering methodology presents results clearly and enhance transparency to create a solid basis for decision makers* [4].

Table 1 gives an example of what parameters can be chosen when comparing different ceiling products on their sustainability in the early design stage. The method helps the practitioner identify comparable measures and can be used to ensure equal focus on both social, economic and environmental aspects in a life cycle perspective. In figure 2 the final visual presented to the client is seen. The purpose of the visual is to quickly enable the client to make a decision based on both social, economic and environmental data in a life cycle perspective.

Table 1. *Example of a sustainability screening for comparing different ceiling products*

Comparison of ceiling products		Sustainability Parameters		
		Social	**Economic**	**Environmental**
Life Cycle Stages	Production (A1-A3)	FSC Certification & Cradle2Cradle	Building Component Cost [EUR/m2]	Global Warming Potential (kg CO2e/kg) & Recycled content
	Use (B1-B7)	Aesthetic, Light reflectance & Off-gassing	Maintenance [EUR/m2/year] Life Span (years)	Maintenance and cleaning Life Span (years)
	End of Life (C1-C4)	-	-	Global Warming Potential (kg CO2e/kg) Cradle2Cradle

Acoustic ceiling panels	Environmental Impact [kg CO2 eq]	Lifetime [years]	Price [kr/m2]	Maintenance friendly	Recycled Material Content [%]	Toxicity and degassing [mg/m3]	Product Certification	Aesthetics
Ceiling Panel 1	0,43 kg CO2 eq	50 years	130 kr/m2	**Yes** Possible de- and remounting for easy accessibility	0%	0,02mg/m3	FSC/ PEFC	The solution does **not** meet the requirement for a "uniform ceiling surface"
Ceiling Panel 2	1,87 kg CO2 eq	30 years	296 kr/m2	**Yes** Possible de- and remounting for easy accessibility	71%	<0,5mg/m3	C2C	The solution meets the requirement for a "uniform ceiling surface"
Ceiling Panel 3	1,20 kg CO2 eq	50 years	225 kr/m2	**Yes** Possible de- and remounting for easy accessibility	52%	0,01mg/m3	?	The solution meets the requirement for a "uniform ceiling surface"

Figure 2 Example of a sustainability screening of different ceiling products as it is visualised to the client

2.2. Potentials and barriers related to the simplified life cycle approach; Sustainability screening

The simplified life cycle approach has shown the potential to enhance designers and clients to make more informed and thereby more sustainable design decisions. The method can be tailored to the specific client needs and context, but is also vulnerable as it depends on the consultant's competences and experience. This method requires the practitioner to have a basic understanding of the functional unit of environmental impact data to ensure data comparability and knowledge of product certifications.

Even though this simplified method is faster than conducting environmental and economic life cycle assessments it has shown to be time consuming in data gathering. The data needed can be found in various databases and from manufacturers directly, but currently no common database that can create this overview exists. A database requires continuous maintenance in securing accurate and updated data, hence the manufacturers should see the benefit of reporting and updating their data.

A potential flaw to this method is the risk of making comparisons based on too few parameters and thereby neglecting important issues which might lead to taking wrong decisions. As both qualitative and quantitative data can be used to describe materials or products it can result in a subjective weighting of the variants. A common understanding in the industry of the minimum requirements for a comparison is important in order to not neglect important issues or parameters.

A common barrier for the specific product comparison is the lack of data on the manufacturers' websites and the lack of specific environmental product declarations in Denmark. The lack of data limits the design space and may result in the same few products being used repeatedly. Some manufacturers do not disclose their product content online which could make the designer choose another brand where the data is easy to access. This might leave new and innovative products out of the comparison, as they often have not declared their product through environmental declarations (EPD) or have certifications and labels like *Cradle to Cradle* or the Danish indoor climate label etc. This approach could then make it even harder for new and potentially more sustainable products to penetrate the market.

3. LCA and LCC comparison studies of building elements

This section describes the process of conducting LCA and LCC comparison studies during a design phase. What building components or design solutions should be compared will depend on the specific context and should thus always be evaluated to ensure that design solutions with substantial impact are chosen.

3.1. LCA and LCC comparison studies of building elements

Often various solutions are explored and discussed and poses questions like; *which solution is more sustainable, solution A or solution B?* In this case it is possible for the sustainability consultant to utilize the Danish LCA and LCC tools; LCAByg [7] and LCCByg [8] developed by the Danish Building Research Institute to visualize the environmental and economic impacts over the life span of the given building to enhance transparency of environmental and economical sustainability impact. Comparison studies requires a stringent methodology and a common understanding on how to define prerequisites and set up assumptions. To conduct LCAs and LCCs the right data needs to be at hand, an overview of the different data needed can be seen in **Table 2**.

Table 2. *Data Requirements for calculation LCA and LCC*

	Data Requirements	**Where do we get the data from?**
Life cycle stages	Quantities	Estimates, 2D or 3D design models e.g. Sketch Up, Revit
Production (A1-A3)	Cost	Estimates, Molio cost database, Contractor's *list of products*
	Environmental impact	Oekobau, EPDs or Proxy data
Use phase (B1-B7)	Energy consumption	Be18 calculation
	Maintenance & Cleaning	Molio cost database, Danish Facility Management (office), The Danish social housing sector (social housing), Manufacturers maintenance & cleaning guidelines
End-of-life (C1-C4)	Life Span	Oekobau, EPDs or Proxy data
	Environmental impact	SBI 2013:30 Industry Guidance on life span, Levetider.dk (A Danish database of building component life span)

Financing data like inflation and discount rate is already implemented in the Danish *LCCByg* tool and national standards for CO_2 emissions related to energy production is already implemented in the Danish *LCAByg*. Figure 3 shows an example a comparison of the life cycle cost of three different possible solutions to a façade renovation. The different alternatives were discussed with the building owner, the project team and the facility manager and then modeled and compared via the Danish *LCCByg* tool. The price data for the different processes in the renovation solutions were found in the *Molio cost database*, where it is possible to find the related cost per area for pressure washing of the existing façade, repair and re-painting, etc. The three different renovation solutions over a 50 year life span are depicted in

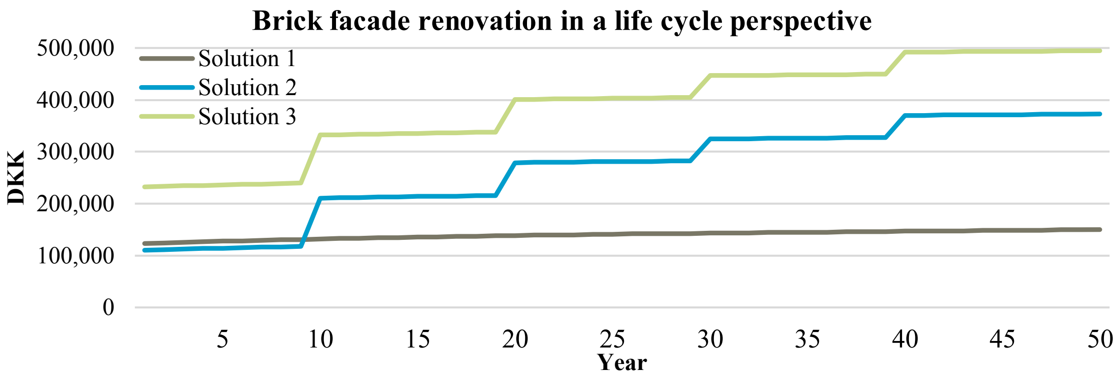

Figure 3.

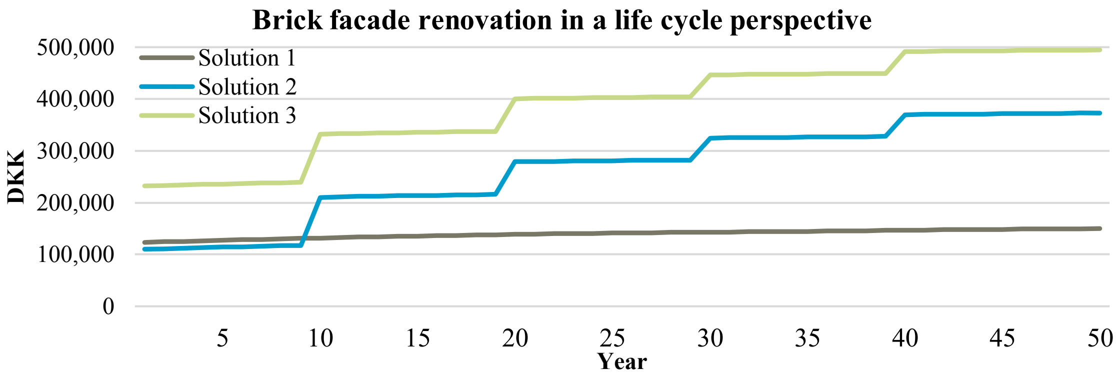

***Figure 3**. Life cycle cost of 3 brick wall renovation solutions. Solution 1: Revert to raw brick wall by cleansing the façade. Solution 2: Clean the façade, re-plaster and repaint. Solution 3: Repair the cracked façade with new plaster and repaint.*

3.2. LCA and LCC comparison studies including whole building simulations

LCA and LCC comparison studies can be integrated into engineers' and architects' design explorations. As an example, a client wanted to explore different solar shading systems and the related energy and daylight performance. The life cycle cost comparison of a fixed and a dynamic solar shading system can be seen in figure 4. Here the yearly energy consumption, daylight levels and heating and cooling demands are accounted for as well as the construction and maintenance cost. This life cycle cost assessment not only compares the performance of the two systems 1:1, but also sees the systems in the relation they are in, within the building. The energy and daylight simulation data were retrieved from a whole building simulation model by the indoor climate engineer and the cost data were provided by the contractor on the project as well as the specific product manufacturers. Maintenance and cleaning data were derived from the DGNB manual.

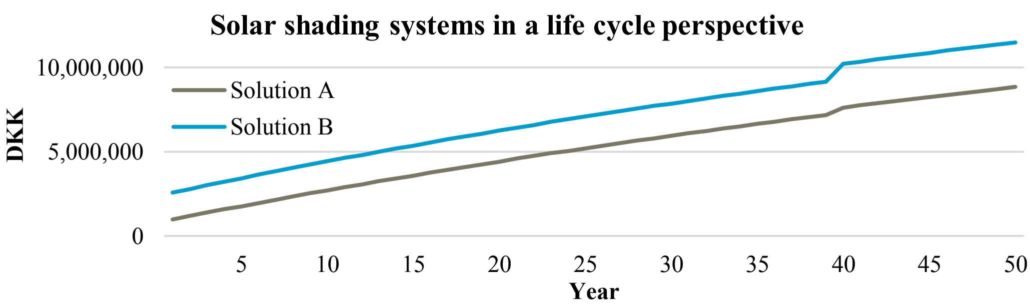

***Figure 4.** Life Cycle Cost of a fixed (solution A) and a dynamic (solution B) solar shading system*

3.3. Potentials and barriers related to the LCA and LCC comparison studies

The LCA and LCC comparison studies provide a quantified overview of consequences and is a useful tool in a decision-making process. Even stronger arguments and more holistic decision making would be obtainable by conducting LCAs and LCCs simultaneously. An integration possibility between the two tools would ensure consistency in data and enhance the use of both assessments.

Numerous barriers prevent the utilization of LCA and LCC as decision making tools e.g. limited time which is often related to limited knowledge and experience of the consultants or project managers. The building industry is rather conservative and tends to go on with a "business as usual" approach, thus not allowing time for comparative studies like the examples above. Other barriers can be the data gathering, and discussion on how simplified a comparison can be without leading to wrong decision making. This dilemma of LCA and LCC is related to the nature of the design process. Early design choices are responsible for a significant amount of the total environmental impacts and costs, but conducting LCAs and LCCs during this stage is based on assumptions and incomplete data [9].

Another limitation during the design process is the many different stakeholders that need to be involved to give input to the calculation. Often different companies need to be involved as well as facility managers and contractors, which often are not included in the early design stages. It is crucial to find the right balance between involving the needed stakeholders and not spending too much time.

As the data and information needed to perform the LCA and LCCs come from many different sources it is important to have standardized methods of e.g. modelling, to allow for easy quantity take offs and calculations.

4. Whole building LCA and LCC

Most of the whole building LCA and LCCs conducted in Ramboll has up until now been conducted at the end of the design process, during construction or even by the time of handover. This approach has mainly been due to the lack of experience within these early stage analyses in the market and the complexity and large amount of information required as well as due to time constraints. The reasoning has been to conduct the LCA as late as possible where the exact data is at hand and time can be saved as no design changes will occur. This approach will only be useful for benchmarking and help the client get a sustainability certification (DGNB) and does not utilize the potential of LCA and LCC as a design tool in the early stages to improve economic and environmental sustainability. The importance of life cycle calculations of both environmental and economic aspects is the ability to visualize the impact over the entire building life cycle for the client and not only the construction cost and impact. In current DGNB projects LCA and LCC studies are initiated during conceptual or schematic design on the largest building components and will be finalized during the construction stage with exact data from the contractor. **Figure 5** visualises the distribution of global warming potential (GWP) or carbon emissions between building components in a large office building in Denmark.

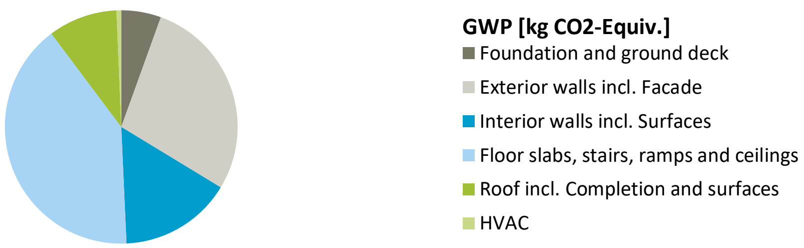

Figure 5. *Life Cycle Assessment result visualising the global warming potential (GWP) related to the building components for a large office building in Denmark.*

4.1. Potentials and barriers related to the whole building LCA and LCC

Even though the use of LCA and LCCs as design decision tools are not currently an integrated part of the design phase, the potential of it is being recognized. This has initiated an internal global development in the company. As seen in **Figure 5** the LCA can help the designer understand where the largest optimization possibilities are. Conducting a related LCC assessment will help visualize the business perspective and cost optimization possibilities.

LCA and LCC is currently not implemented in the early design, which may be due to the lack of BIM integrated tools [10]. The lack of integration between BIM and LCA/LCC tools means that design changes must be imported manually, re-calculated and exported back into the models. The manual work is time consuming and prone to human error. However, during the testing of several BIM integrated LCA tools in Ramboll the problem occurred to be the lack of standardization of the models, which can be difficult to change when collaborating with external stakeholders. Another lack within the BIM-integrated LCA and LCC tools were the fact that the 3D models may only be available at schematic or detailed design, when design changes become increasingly difficult to make. Utilizing LCA and LCC as drivers for the entire building design in the early design phases is currently difficult due to the vast design space of interrelated data and parameters to consider. On the other hand, LCA and LCC can no longer successfully be used as a decision-making tool in late design stages because proposed design changes likely will require large costs [9]. For certification purposes an as-built model with adequate detailing is necessary for the BIM integrated design tools to give the exact quantities. These models are, however often the responsibility of the contractor and are thus not as detailed as is needed for the certification purpose. An example is that the rebar in the reinforced concrete is not modelled in 3D and the actual amount will have to be retrieved from delivery notes from the building site. Another reason to why LCA and LCCs are not integrated design tools may be due to the lack of professionals and training courses within life cycle assessments and life cycle costing [11].

5. Conclusion

Life cycle calculations for buildings are receiving increased attention from national building regulations like the environmental ministry of Finland announcing that building LCA will become mandatory by law in 2025 at the latest [11]. Similarly, the number of DGNB certified buildings in Denmark is increasing and thus pushing the market. The increased experience with LCA and LCCs will impact the industry to develop methodologies adapted to the different design stages, but to see an even faster transition in the industry, legislation is needed. Since 2006 it has been mandatory to calculate the overall demand for primary energy in all new buildings in Denmark, with a continuously increasing threshold. This regulation has resulted in early design simulations as an integrated part of the design process today, whereas in the beginning the calculations were made at the end of the design or during construction only. Through regulation on LCA and LCC similar changes in the industry may occur. The industry needs access to comprehensive national databases with both product specific EPDs and generic country specific data as well as regulation pushing for LCA and LCC for new buildings.

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Whole-Life Costing of a French Single-Family House Refurbishment: the "Bat-Eco2" case study

C Colli[1], A Bataille[1], E Antczak[1]

[1]Laboratory of Civil Engineering and Environment, LGCgE, Université d'Artois, Pôle de Béthune, Faculté des Sciences Appliquées, Technoparc Futura, 62 400 Béthune, France

carolina_darochacolli@ens.univ-artois.fr

Abstract. Bat-Eco 2 is a research project on building refurbishment life cyle assessment (LCA) and whole-life costing (WLC). The project's goal is to contribute to the development of a tool to help decision-making on refurbishment solutions, considering the environmental aspects along with the economic ones. This project has been split in four steps: (i) LCA of a standard single-family house refurbishment built in 1939 and located in Libercourt, Hauts-de-France; (ii) WLC of the same case study; (iii) crossing of LCA results with WLC ones; (iv) simplified tool specification in agreement with these results. This paper presents the WLC methodological choices and the corresponding WLC results. The WLC methodology complies with the ISO 15686-5. It details the refurbishment life cycle stages in compliance with the EN 15 978. The main choices are presented, i.e. system boundaries, economic rates, present costs for each life cycle stage, building residual value. Results enable to enumerate economic hotspots for the case study of this single-family house refurbishment. The whole-life costing is calculated using excel sheets, considering economic data from the social landlord Maison & Cités, house owner of the study case.

1. Introduction

The French building stock is composed of more than 65% of buildings constructed before 1975[1], hence following no thermal regulation. According to the recent plan of thermal refurbishment in France[2], 500 000 housings per year must be refurbished.

The refurbishments, basically, consider the investment costs in order to help decision makers[3]. However, this investment costs are not representative of the whole building life costing. Still, there are many studies considering economic sustainability[4–8], but without taking into account the whole-life costing (WLC) of a building (products, construction or refurbishment, services during lifetime and end-of-life). The whole-life costing is the sole methodology which considers all costs along the building lifetime, and thus it is more pertinent to represent the economic aspect of a building[9].

2. Goal and Scope

The current work uses specific methodological choices concerning indicators, economic parameters, system boundaries and rates. The goal of this paper is to present and to discuss the WLC results. A sensitivity analysis of the WLC assessment will supplement the analysis. This investigation was carried out on a typical single-family semi-detached house refurbishment located in the North of France.

This project takes into account the cost of financing the investment, as well as the externalities associated to (i) the tenant solvency and (ii) the vacancy rate. This corresponds to a WLC approach. The income is not considered in the study

This work is part of the Bat-Eco2 project, a regional project aiming at specifying a tool in order to support decision-making for different refurbishment choices, combining environmental and economic criteria.

3. Method

The economic assessment used in the present work is the WLC applied to a dwelling refurbishment. It takes into consideration all the costs of a building period of analysis. This methodology includes the life cycle costing (LCC) plus the externalities, the non-construction costs and the income. For a building, the LCC sums up the costs of construction, the operation costs, the maintenance costs and the end-of-life costs[3]. The methodology follows the standard ISO 15 686-5:2008[10] and the boundaries are represented in Fig. 1.

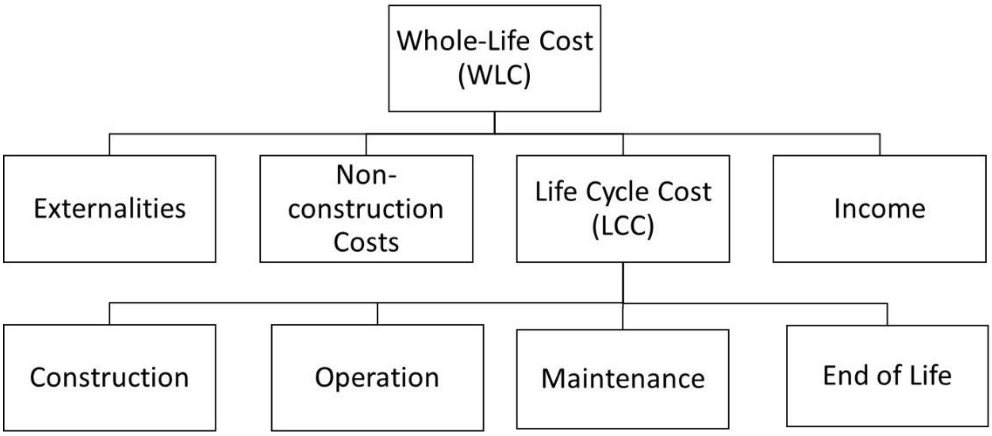

Figure 1: System Boundaries
Source: ISO 15 686-5

The "Construction" aspect corresponds here to the refurbishment and its initial investment. The operation consists of the rents, the insurances, the energy and water consumptions and the living taxes. The maintenance is composed of the replacements during the building period of analysis and the expected/planned maintenances. The end-of-life costs represent (i) demolition or deconstruction, (ii) waste transport; (iii) products and equipment treatment or disposal.

The WLC methodology is quite similar to that of life cycle assessment (LCA). After defining the goals and the system boundaries, an inventory is established with the detailed costs for each step as mentioned before. The results are then summed up.

The income is not considered in this analysis. Regarding the non-construction costs, only the cost of financing the investment is taken into account; and regarding the externalities, only the vacancy and unpaid rent rates are taken into account.

The environmental cost impacts are not taken into account on the operation step. This study focus only on the economic assessment, an environmental assessment has already been done. The interaction between environmental and economic assessments is under work.

4. Case Study and Methodological Choices

This paper presents the WLC of a refurbishment operation of a single-family house from 1939 located in Libercourt, North of France. The house is a semi-detached dwelling on a area of 300 square meters. The living area after refurbishment operation is 59 square meters.

The dwelling is composed of two bedrooms, one living room, one kitchen, one toilet, one bathroom and one small cellar.

The case study is part of the social landlord Maisons & Cités Soginorpa. It is one of their typical energy efficiency refurbishment.

This study is presented as part of the Bat-Eco2 research project, aiming at supporting decision-making on different refurbishment choices.

The partners of this project are Artois University, Lille 1 University, CD2E (Centre de Développement des Eco-Entreprises, a public agency), CIRAIG (Centre international de référence sur le cycle de vie des produits, procédés et services, a Canadian Research Center on Life Cycle Assessment), CROA (Conseil Régional de l'Ordre des Architectes), NJC Economie (a French firm dealing with economics in building) and the landlord Maisons & Cités Soginorpa.

The WLC methodological choices are presented hereafter.

4.1. Period of Analysis

The economic period of analysis depends on the profitable time of the building[3]. If the estimated period of analysis of the building during a life cycle assessment (LCA) is of 50 years, the one used in the WLCs is normally lower. The standard ISO 15 686-5 suggests not exceeding a 100-year period of analysis for WLC.

However, many studies consider a lower period: between 25 and 40 years[11], arguing that any future costs after year 40 are insignificant. Another explanation is the increasing uncertainty linked to the extension of a considered period.[12] The longer the considered period, the more uncertain the evolution of economic taxes and rates. As a matter of consequence, the reliability of economic results decreases as the considered period of analysis increases. For this case study, the considered French building period of analysis is usually 50 years nowadays. Taking into account this duration, the period of analysis is also of 50 years for the present WLC. This complies with the requirement given by the standard, i.e. less than 100 years.

4.2. Real versus Nominal Value

In economic terms, the values can be expressed in two different ways, due to the existence of a monetary value fluctuation in time due to the inflation rate. Thus the economic assessment results can be expressed in real or nominal values. The real one presents the values without inflation effects. The nominal one considers inflation effects and stands for the current value of products.

Considering real or nominal values, it is fundamental to define a reference year in order to calculate the present value according to the future values using real or nominal discount rates, respectively. For this case study, the real value has been chosen in order not to take into account the fluctuations in product costs.

4.3. Inflation Rate

The inflation rate indicates the variation in product prices. This rate is normally computed from observed variations of previous years. However, price fluctuation of previous years is not necessarily helpful to predict the future ones. Thus, the results obtained for the inflation rate can be highly debatable.

In terms of economic assessments, it must be defined whether one chooses to express the results in real value or in nominal one. According to the choice, the inflation rate is not taken into account.

4.4. Discount Rate

The discount rate is the expression of present value preference instead of future value. This discount rate can be drawn, as the inflation rate, from previous year variations.

In order to lower the uncertainties of this study, a set of different real discount rates were allocated such as replacements discount rate, maintenance discount rate and living tax discount rates.

4.5. Economic Data
The economic data related to the construction products and equipment, as well as the data regarding the energy and water prices, maintenance and replacements, end-of-life must be considered in the whole-life costing approach.

These data can be generic ones, possessing a degree of uncertainty, but, if available, they are specific data. In the French context, there is a generic economic database named Batiprix [13]. It is updated each year and contains data related to prices of each construction product and of each equipment, as well as prices of implementation.

For this case study, specific data were collected from the project team social landlord.

4.6. System Boundaries
The analysis considered the externalities, non-construction costs and the LCC, according to the standard ISO 15686-5 [10]. The LCC phases have been fully considered. However, no cost spent by the tenant is computed, meaning no energy and no water consumption costs during the use phase. Indeed, this case study is analysed in order to produce data to help the decision-making before refurbishment operation.

The costs included in this WLC are rent; externalities due to unpaid rent and vacancy rates; initial investment; cost of financing; planned replacements; planned maintenances; property taxes and end-of-life.

4.7. Economic Indicators
The standard ISO 15686-5 proposes the use of the net present value (NPV) or net present cost (NPC). This net present value represents the sum of all costs discounted for a reference year. The equation of NPV is presented below.

$$X_{NPV} = \sum_{n=1}^{p} \frac{C_n}{(1+d)^n}$$

Where
C is the cost of year n, q is the discount rate, d is the real discount rate per year, n is the number of years between the reference year and the occurrence of the cost, and p is the period of analysis.

Many studies consider the NPV as the economic indicator [5–7,14,15], but there is also some dealing with the future value [11,16].

The economic indicator used in this WLC is the NPV and the discounted payback time.

The discounted payback time is the time to recover the costs of investment in present values. In this paper, the payback time is calculated as the ratio between the initial investment and the net cash flow per period.

5. Results
The economic results computed from the case study details and methodology are shown in Fig. 2.

The values presented in Fig. 2 are relative values, for the sake of the landlord economic data confidentiality. The percentages are calculated considering the total rent as 100% and the corresponding percentage debts for initial investment, replacement, maintenance, property tax and end-of-life.

The whole-life costing includes the entire costs during the building period of analysis. Thus, some important economic hotspots are highlighted, such as, the maintenance and replacements costs, which represent 17% of the expenses altogether.

The costs associated with the end-of-life are very low, thus not clearly visible in Fig. 2. These costs regroup the aspects of demolition, transport and waste disposal at the end of the period of analysis, i.e. 50 years.

In order to complete the current analysis, a sensitivity analysis has been carried out and is presented hereafter.

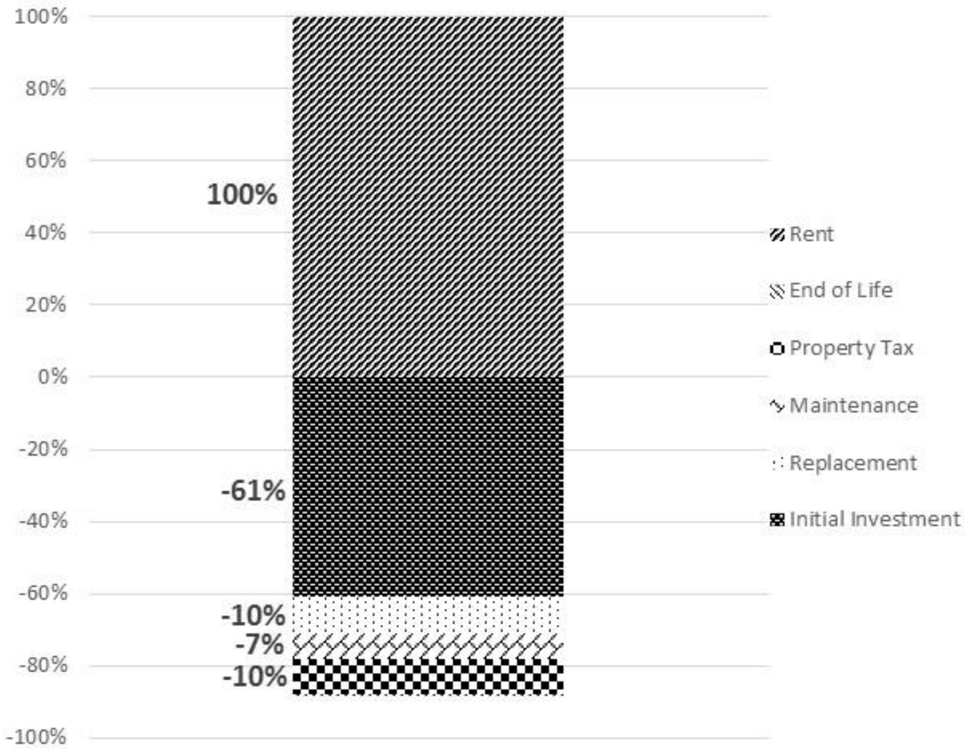

Figure 2: Relative Net Present Value according to different steps on the case study lifecycle (relative results are presented from top to bottom according to the legend)

6. Sensitivity Analysis

6.1. Period of Analysis

The building period of analysis for this case study is 50 years. In order to analyse the sensitivity of the results to this information, two other periods were considered: 30 and 80 years. All maintenances and replacements were then taken into account. No other extended new refurbishment was considered for the longer period. The results of this analysis are shown in Table 1. The relative values are all given in relation to the reference scenario (50-year-period).

Table 1. Analysis Results according to building period of analysis (reference period of 50 years)

Period of analysis (years)	NPV (%)	Discounted Payback time
30	-53 %	-
50	100%	41
80	180%	41

The 2nd result is as the reference and the others were calculated in accordance. The NPV of 30 years building period is negative and thus, the percentage is equal to (-) 53% of the reference scenario with 50 years building period of analysis.

The payback time is of 41 years for both 50 and 80 years periods. This 41 years payback-time is out of reach when the period of analysis is of 30 years.

6.2. Loan period

The variation of the loan period does not give very different NPV as can be seen from Table 2. The payback time varies from 35 to 45 years, depending on the loan period.

Table 2. Analysis Results according to Loan Period

Loan Period	NPV (%)	Discounted Payback time
15	137 %	35
20	100 %	41
25	61 %	45

6.3. Discount Rates
Discount rates estimations are drawn from past values. These rates are one of the keys to the assessment reliability. The sensitivity analysis considers variations of the following rates: loan, maintenance, replacement, property tax and rent. The results are shown in Table 3.

Table 3. Analysis Results according to Discount Rates

Discount Rate Values	NPV	Discounted Payback time
Loan Discount Rate		
2%	175 %	33
4.10%	100 %	41
6%	25 %	48
Maintenance Discount Rate		
0.5%	76 %	43
1.6%	100 %	41
3%	121 %	37
Replacement Discount Rate		
0.5%	54 %	45
1.8%	100 %	41
3.1%	131 %	37
Property Tax Discount Rate		
1.2%	79 %	43
2.2%	100 %	41
3.2%	116 %	37
Rent Discount Rate		
1%	329 %	31
2%	100 %	41
3%	-68 %	-

6.4. Rental vacancy and unpaid rent rates
For this case study, a rental vacancy rate and an unpaid rent rate of respectively 1.1% and 0.9% are considered. These rates are related to the attractiveness of the houses and the capacity to pay the rent. The house used in this case study is part of the stock of Maisons & Cités, which is composed of social houses and are occupied by modest families. The thermal refurbishments in the entire house stock are of importance to reduce the energy costs as much as possible. Indeed, the energy and water consumption costs are essential to determine these two rates

The results of these taxes variations are given in Table 4. A variation of +/- 0.5% gives a difference of +/-5% of NPV, but the payback time is almost identical.

Table 4. Analysis Results according to Rental vacancy and unpaid rent rates

Rate	NPV	ROI time
	Rental Vacancy	
0.6%	105 %	41
1.1%	100 %	41
1.6%	95 %	42
	Unpaid Rent	
0.4%	105 %	41
0.9%	100 %	41
1.4%	95 %	42

7. Discussion

One can notice the economic importance of the initial investment in this WLC. If initial investment was only considered as a matter of expense in the WLC, the social landlord will obtain almost 40% of the benefits from this operation. Contrariwise, if the whole-life costs are to be taken into account, this refurbishment operation project provides a benefit of about 13% of the rents in NPV.

The degree of uncertainty is higher for longer periods of analysis. Hence, the chosen period for economic assessment is not usually beyond 50 years. It could be observed that the discounted payback time is very important in this analysis, showing a beneficial situation or a non-beneficial one depending on the considered period of analysis. Considering 30-year-period, the building does not reach any payback on investment. On the contrary, for an 80-year-period, the payback time is equal to the one of 50-year-period. However, the NPV reaches 180%. The graph of cumulated NPV is presented in Fig. 3.

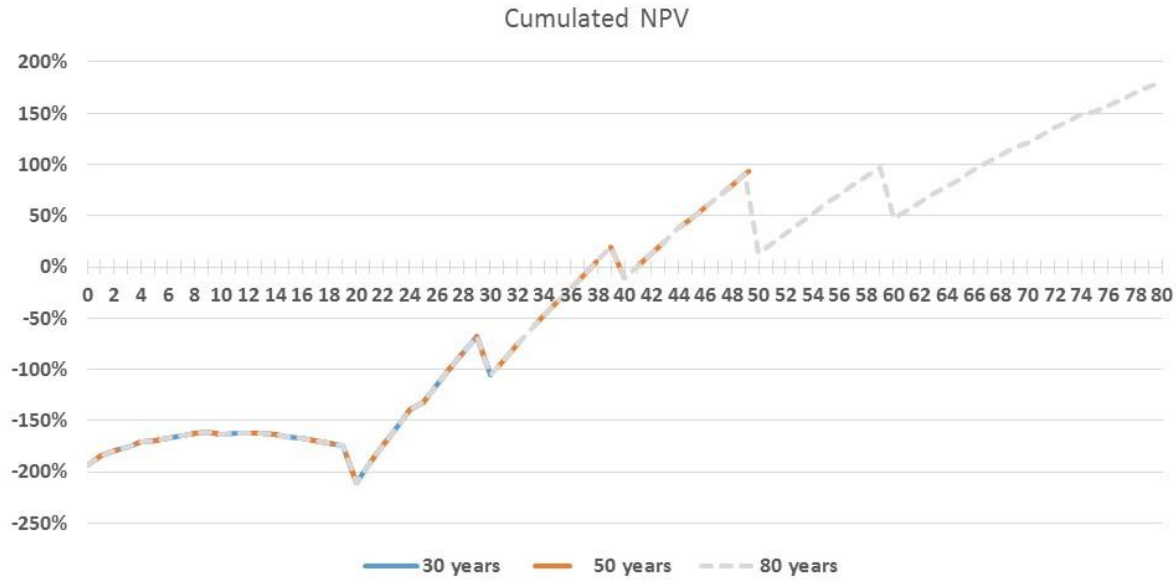

Figure 3: Cumulated NPV for 30, 50 and 80 years of period of analysis

The cumulated NPV presented in Fig. 3 is calculated as a percentage of 50 years cumulated NPV. Thus, for 50 years cumulated NPV it reaches 100% and for 30 and 80 years, the cumulated NPV is obtained according to the reference value.

Interestingly, it is more profitable for the social landlord to consider either a period of 50 years or a period much longer than 66 years. Indeed, the cumulated NPV after a period of 66 years equals the one reached after a period of 50 years. This is related to the planned replacements.

The sensitivity analysis highlights the importance of the rent discount rate. A decrease of 1% can result in + 200% of NPV results. On the contrary, an increase of 1% can result in no return on investment at all. Another important discount rate is the loan one. The fluctuation of this rate can result in a variation of + 75 % or - 75% of the NPV. The payback time varies accordingly. Hence those different rates must be chosen very knowingly.

8. Conclusion

This study discusses some methodological choices for building whole-life costing. It presents economic results of a typical refurbishment operation. It compares the results of WLC with the initial investment. Furthermore, it analyses the sensitivity of these economic results.

The corresponding results show the importance of considering the building whole-life costing instead of just the initial investment. While considering only the initial investment would give a very profitable operation, a whole-life costing presents lower returns on investment.

According to the sensitivity assessment, the dominating discount rate is the rent one. Its chosen value has the greater influence on the operation profit. The loan discount rate is important too. The results variation reached +/- 75%.

Attention must be paid to the choices of the different discount rates, as well as of loan period and lifetime period.

Next step of this project is investigating the case study eco-efficiency, based on those WLC results along with the corresponding LCA results.

Acknowledgements

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A survey of private landlords in Karlsruhe and their perception of deep energy retrofit

Naber E[1], Lützkendorf T[2], Volk R[1], Schultmann F[1]

[1] Institute for Industrial Production, Karlsruhe Institute of Technology, Karlsruhe, Germany
[2] Centre for Real Estate, Karlsruhe Institute of Technology, Karlsruhe, Germany

elias.naber@kit.edu

Abstract. Energy use related to buildings accounts for 35.3% of Germany's final energy consumption and nearly a third of greenhouse gas emissions. Thus, deep energy retrofit (DER) has a substantial role in the German energy efficiency strategy. Although many DER measures are economically viable, the pace of DER is below expectations and target value. A few studies investigated this phenomenon and conducted surveys mostly among owner-occupiers. However, 54% of the 40.5 million apartments in Germany are rented and a total of 15 million are let by private (not professional) landlords. Therefore, this investigation focuses on private landlords to find out what drives or constrains them to do deep energy retrofitting. A survey was conducted in a quarter of Karlsruhe, a large city in Germany with an above-average demand-driven real estate market. In this quarter, 83.2% or 8464 apartments are rented. 85 private landlords who own 10% of the rented residential buildings in the quarter responded and gave insight into their perception of DER. The results show that the buildings of the respondents originate from a construction period with large saving potential. Main strategies for investments in DERs are conservation of economic value of the property and the compliance with legal requirements. The main trigger is required maintenance. Despite an eco-friendly attitude, ecological criteria have a minor part in the DER decision. Finally, policy recommendations are made.

1. Introduction

In the strategic plans of the German government, the national building stock has a major role in achieving the goals of the German energy transition [1, 2]. These plans include several national milestones until 2050. Main goal for the national building stock is to reach nearly climate neutrality in 2050, which means a reduction of its primary energy demand by at least 80% compared to 2008 [2]. Currently, the energy use in the building stock is responsible for 35.3% of Germany's final energy consumption and most of the consumption originates from residential buildings (22.1% of Germany's final energy consumption) [3]. The latest monitoring report of the German energy transition, published mid-2018, states that the weather-adjusted final energy consumption in buildings increased by 4.3% from 2015 to 2016 [4]. However, since 2008 it has decreased by an average of 0.8% p.a. In order to meet the reduction targets, it needs to decrease much faster in the remaining years. Hence, further efforts are required in order to achieve the energy transition targets as quickly as possible [4]. The main challenge is the transformation of the existing building stock, as most of the residential buildings were constructed before first thermal requirements came into force in 1977/1978. Moreover, the pace of deep energy retrofit (DER) is below expectations and target value. Latter can be explained, as private owners have decision-making sovereignty over the majority of the building stock and many of them do not invest into deep energy retrofitting, despite many retrofit measures are technically feasible, increase comfort, can be economically profitable, contribute to other tangible and intangible factors positively [5, 6]. In order to tackle the challenge, generating knowledge about the perceptions, preferences and the respective decision-making processes is of high importance. These findings support policy makers in determining strategies to increase the DER rate. However, owners can have multiple roles at the same time (see section 2). For owner-occupiers many studies about the perception of DER exist (see section 3). Therefore, this study aims to relate the perception of DER to a given role. The focus group of this investigation of the perception of DER are private ("amateur") landlords. This focus distinguishes this study from others and forms the original contribution of this paper.

Furthermore, in the *Urban transition lab 131* research project (*www.iip.kit.edu/english/1064_2827.php*) the citizens of the Oststadt quarter of the German city Karlsruhe demanded an investigation of their building stock, its owners and tenants. Subsequently, several surveys and field studies were carried out in this quarter. A survey of private landlords forms the basis of this paper.

2. Brief overview of ownership structure and deep energy retrofit in Germany

Owners pursue multiple aims concerning their properties and have different capabilities. Furthermore, they can be owner-occupier and/or landlords of a property. Then, landlords can be subdivided into professionals and "amateurs" [7]. The importance of considering roles is illustrated for Germany in the following. According to census data from 2011, the ownership structure and the type of use of apartments in Germany is shown in figure 1 [8]. A closer look into the statistics discloses that about 54% of a total of 40.55 million apartments in the German residential building stock are rented. Thereof, 15 million are let by private ("amateur") landlords (for comparison in the EU about 30% of the apartments are rented [9]). Furthermore, the results of EU-SILC survey [10] indicate that the household ownership rate has a slightly decreasing trend or seems to remain static in Germany (e.g. the EU household ownership rate was at about 70% in 2017 [10]). Another investigation predicts an increase of ownership rate from about 45% to 50% by 2030 for Germany [11]. However, on a granular level the German statistics show considerable regional differences. Besides ownership structure, the apartment age or building construction period is of high interest for the analysis of DER [12, 13]. A comparison of the frequency distribution of construction periods of residential buildings and apartments shows little discrepancies [14, 15]. In the period 1949-1978 the average number of apartments per building is higher than in other periods [14, 15]. Which indicates that more and bigger multifamily houses were built in that period. The micro census of 2014 reveals that rented apartments are on average older than owner-occupied apartments [16], e.g. in Baden-Württemberg (the state of the investigation area) rented apartments are on average 4.5 years older than owner-occupied apartments and about 74% of the rented residential building stock was built before thermal and heating system regulations came into force (1978). That is about 10% more than owner-occupied apartments. These figures show the significance of considering the roles and for the case of Germany the importance to conduct private landlord focused research.

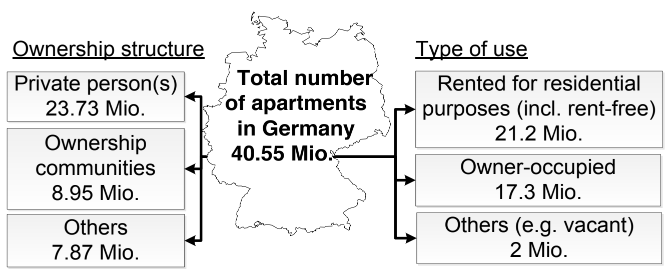

Figure 1 Ownership structure and the type of use of apartments in Germany (according to [8])

For assessing the progress in deep energy retrofitting, the respective annual rate is determined. The determination of this rate is complex, and approaches differ from each other. For Germany, the most cited studies compute insulation rate between 0.99% and 1.43% p.a. for the past 15 years for the building cohort built until 1978 and replacement rate of heating systems between 3.1% and 3.27% p.a. for the past 15 years for the same cohort [14, 15]. Nevertheless, the retrofit activity is limping behind the target values, which are twice as high. Besides favorable circumstances such as low interest rates and current real estate market conditions, other stimuli are set by the government to promote DER in the entire building stock. For new buildings, high requirements towards thermal insulation and heating systems are in force. For existing buildings, DER of certain building parts are mandatory and financial incentives are offered, as well as legal frameworks to mitigate burdens and drawbacks. Additionally, the replacement of heating systems with renewable heating sources is promoted via subsidies and requirements. Furthermore, informational instruments such as energy performance certificates (EPC) are used to raise awareness.

3. Brief literature review of decision-making of deep energy retrofit

The decision-making process and perception of DER has been investigated in several studies. Among others Friege & Chappin [17], Stengel [7] and Steinbach [18] present comprehensive reviews on modeling decisions of retrofit of buildings in the context of energy efficiency. Friege & Chappin [17] conducted a review using bibliometrics. Stengel [7] and Steinbach [18] reviewed relevant literature as part of their dissertation. These authors show that the parent topics are: technical options, modeling/simulation, policy/incentive instruments and understanding decisions. The following subsections briefly summarize three areas of interest, which partly complement the mentioned reviews.

3.1. Survey based studies of deep energy retrofit

More than 50 scientific survey-based publications can be found, which are related to energy efficiency measures in residential buildings and were published after the year 2000 (found via analyzing the Scopus query which yielded more than 620 results: TITLE-ABS-KEY(("Homeowner*" OR "Landlord* "OR "House Owner*" OR "Building Owner*" OR "Dwelling Owner*" OR "Apartment Owner*") AND ("Renovation*" OR "Retrofit*" OR "Refurbishment*" OR "Renovating" OR "Retrofitting*" OR "Refurbishing"))). The surveys have diverse approaches to study the subject matter. Some use official panel and survey data. However, due to limited consideration of items and attributes concerning retrofit, renovation or refurbishment of homes, many conducted own surveys. Most of them focus on owner-occupiers. Many of the reviewed surveys use convenience or random samples, which show a high heterogeneity of socio-demographic characteristics among the owner-occupiers and private landlords. For more insight please refer to [7, 17, 18] and to the query. As communality, most studies conclude that economic aspects are very important but not sole driver of DER decisions. The observed depth of DER activity is mainly based on economic trade-offs. For Germany, Albrecht et al. [19] created persona types of owner occupiers which are well established, often used and modified. More recent studies aim at combining survey results with agent-based models [20, 21].

3.2. Deep energy retrofit and landlords

Landlords are much less addressed than owner-occupiers. A reason could lay in the assumption of economic rational behavior, which seems likely. Another reason related to this void could be the challenge of surveying them. Official data about landlords is rare. Then, reaching them is not trivial and neither framing the survey. Many landlords do not reside in the rented building or in the vicinity of it. Therefore, questionnaires can fail to reach them. Additionally, the surveys need to isolate the behavior towards the building used by a third party. Otherwise, they can end up merging the general attitude with the specific attitude towards the rented object. Hence, generic surveys have pitfalls when considering multiple roles. Schätz et al. [22] conducted a survey among 1,354 landlords in Germany (2005-2006). According to them, the level of professionality can be determined by the quantity of owned apartments. They assume that landlords with more than 15 apartments are professional, who then act more rationally and economically effective (a similar differentiation is made by [23] for so called “micro”-landlords who own up to 20 apartments). Interestingly, 73% of their sample manage their apartments themselves or with the help of family members [22]. The most prominent motive for apartment acquisition is retirement provision and asset formation. In a subsample with landlords of buildings older than 1990, more than half of them rate their assets as in excellent condition (without any renovation needs). However, only half of the respondents are aware of energy efficiency requirements and nearly 70% will only make investments if absolutely necessary. In 2015 Renz & Hacke [24] interviewed 18 private landlords in order to verify several hypotheses and combinations of motives. Among others, a significant barrier to implement DER is the principal-agent dilemma. Concerning this dilemma, the legally permitted modernization allocation is regarded as a not realizable option. Another interview of 18 private landlords in Germany [25] provides insight in the investment behavior in DER in the context of low demand housing markets. The interviewees show a lack of knowledge concerning energy efficiency of buildings and have limited access to good-practice examples. In contrast they were well acquainted with negative reporting of DER. Investments are made to fix small problems/maintenance and can be triggered, if an increase of finding new tenants or keeping long-standing tenants happy can be expected. Accordingly, the interviewees stated that investments are driven by social responsibility and by an emotional relationship with the building or the neighborhood, rather than due to increasing profit. However, energy efficiency is not regarded are an essential asset or benefit [25]. A survey of >2,000 private landlords and members of a German homeowner association conducted by the association itself in 2017 states that the top four barriers for investments in their assets are: rent cap, tax burden, lack of subsidies and bureaucracy [26]. In contrast to the other surveys, this survey was not analyzed scientifically by its authors. However, it is the only one which covers private landlords which are part of an organized network. The variety of surveys show some commonalties, especially the lack of knowledge about DER and the principal-agent dilemma seems to be a main issue for landlords both in low demand housing markets or in well-organized landlord associations.

3.3. Principal-agent dilemma and deep energy retrofit

The principal-agent dilemma is a problem, which occurs when agents make decisions and take actions based on their interests, which impacts principals with contrary interests. For the real estate rental market this dilemma is called landlord-tenant dilemma. It can occur in several situations. Only the DER triggered problem will be presented. This problem forms a major difference between owner-occupiers and landlords and forms a main economic barrier for the latter. Alike other countries, in Germany tenants pay for their energy consumption. The energy consumption for space heating and cooling is dependent on the composition and quality of the building. Therefore, landlords have little incentive to invest into DER as they do not profit from lower energy bills, unless they raise the rent level which is not in the interest of the tenant. This makes it plausible that investments are mainly dedicated for value conservation or maintenance. In theory, there are many possibilities to overcome this problem [27, 28]. In practice, landlords in Germany profit from financial subsidies such as low interest loans and grants to mitigate the financial burden and the landlord-tenant dilemma. Then, rental laws allow for modernization allocations, which enable landlords to increase rents after DER. An important influence on the dilemma are the real estate market conditions. The profitability of an investment depends on the enforceable rent increase and low rent levels represent an obstacle. However despite currently expectable profitability, retrofit activities appear to be stagnating and only a moderate increase is expected [29]. Survey results show that private landlords are not familiar in solving this problem. For example, they do not bail out the legal possibilities of rent increase as professionals do and are not acquainted with DER [24, 30, 31]. Testorf et al. [31] conducted a survey (2009-2010) among owners who received support from subsidy programs and had a total of 5,797 respondents. 251 of them were enterprises and about 13.2% of the remaining private owners were landlords. In their study, they compared landlords’ rent level increase after DER. Professional landlords increased the rent on average by 27% whereas private landlords increased it by 10%. With respect to the specific investment per m^2, the increase is again considerably different between professionals (median is 18%) and amateurs (median is 2.5%). As causes for the discrepancies Testorf et al. identified legal uncertainties and market conditions [31].

4. Survey design and data

A series of paper-based, online questionnaires and experiments was conducted in the quarter of the "urban transition lab 131". The investigation area has a population of about 21,000 who live in 10,173 apartments (83.2% or 8,464 apartments are rented). The quarter features an above-average demand-driven real estate market, mixed use areas and mixed construction periods, but most buildings are built before 1978 (85%). For this paper, the main questionnaire of private ("amateur") landlords is presented. This questionnaire had two forms: paper-based and online. Depending on the number of assets in the quarter the questionnaire was designed to be completed in 30-60 minutes. For the purpose of this study, the share of private landlords in the sample is maximized. Hence, a variant of snowball and convenience sampling as nonprobability sampling strategy was chosen in order to acquire an adequate sample. Requirement for participants was being a landlord with at least one asset in the investigation area rented by a third party. Therefore, the largest local homeowner association was approached in order to ask for referrals to private landlords in their network. Finally, the questionnaire was distributed by mail to 655 private landlords who met the criteria and were members of the association. The questionnaire was scheduled from 20th May 2016 to 25th July 2016. 20 questionnaires were undeliverable. Additionally, 34 responded in order to inform that they did not match the criteria. A reconsideration of the sample by the association assumed that about 120-230 of the 655 private landlords would not match the criteria as they suspect an error in address pre-processing. Therefore, population size is assumed to be 450.

5. Results

The analyzed sample contains 85 fully complete responses of landlords. The online survey yielded 11 complete and 34 uncomplete questionnaires which can be interpreted as a quit rate of about 77%. The number of uncompleted paper-based questionnaires which were handed in is 11. Two of them commented on the uncomplete questionnaire (rough translation): "…that local agencies and politics are to blame for the unattractiveness of DER…" and "…that landlords are discriminated by the legal framework... ". 20 landlords have assets which they partly occupy themselves and rent out the rest. The remaining 65 completely rent out their apartments/buildings. The 85 landlords own 419 apartments in 93 buildings in the investigation area. 54 of the buildings are solely owned by the respective landlords. The remaining belong to an ownership community. The residence of about one third of respondents lays in the investigation area, about one third in the city Karlsruhe and about one third elsewhere.

5.1. Age, asset management and identification of basic environmental perception

70% of the sample are older than 55 and 37% are at least 66 years old. Gender is mixed. Concerning the responsibility for asset management, 63% manage their apartments themselves, 32% hand the management over to third parties and 5% hand it over to friends or extended relatives. A cluster of Likert scale questions concerning attitudes and other questions about ecologic commitments (such as donations and other ecology related activities) aimed at identifying the basic environmental perception. In a comparative analysis, milieus and lifestyles are assigned according to the range of observations in the sample. This analysis is based on the official environmental awareness survey of 2010 [32]. On the social scale of Sinus-Milieus the landlords in the sample range between mid and upper class. On the fundamental orientation scale the landlords range across all three classes (traditional, modern/ individualized and reoriented)[32]. A more granular analysis shows a good degree of conformity to several items in three Sinus-Milieus/lifestyles (Traditional, Social Ecological, Intellectual Milieu)[32].

5.2. Funding and investment planning

For maintenance and repairs, 54% of the landlords allocate funds in sinking funds or other similar dedicated reserves. The others fund maintenance and repairs from their general savings or with loans. 60% of the respondents do not dedicate any funds for DER related investments. The remainder dedicate savings in some extent, but only 11 consult experts for determining the amount. A hierarchical cluster analysis of the responses reveals a group of 25 landlords who do not use any particular financial performance indicator for evaluating investments in their property. The remaining 60 landlords form 16 clusters which can be assigned to two main groups. The first group focuses on tax-based evaluation of investments and the other on amortization assessment/recapitalization.

5.3. Motives, occasions, barriers
A total of 19 motives gathered from literature and interviews of landlords were tested in a Likert scale. Similarly, 14 occasions and causes for DER and 20 barriers were tested. Figure 2 summarizes the results of the three areas. For each area, results with the three highest and three lowest approvals are presented. For challenging the perception, some items were compared to objective data, e.g. energy performance certificate (EPC) values were compared to the perception of the energy performance of their building. In this case, the landlords highly overestimated the performance of their property.

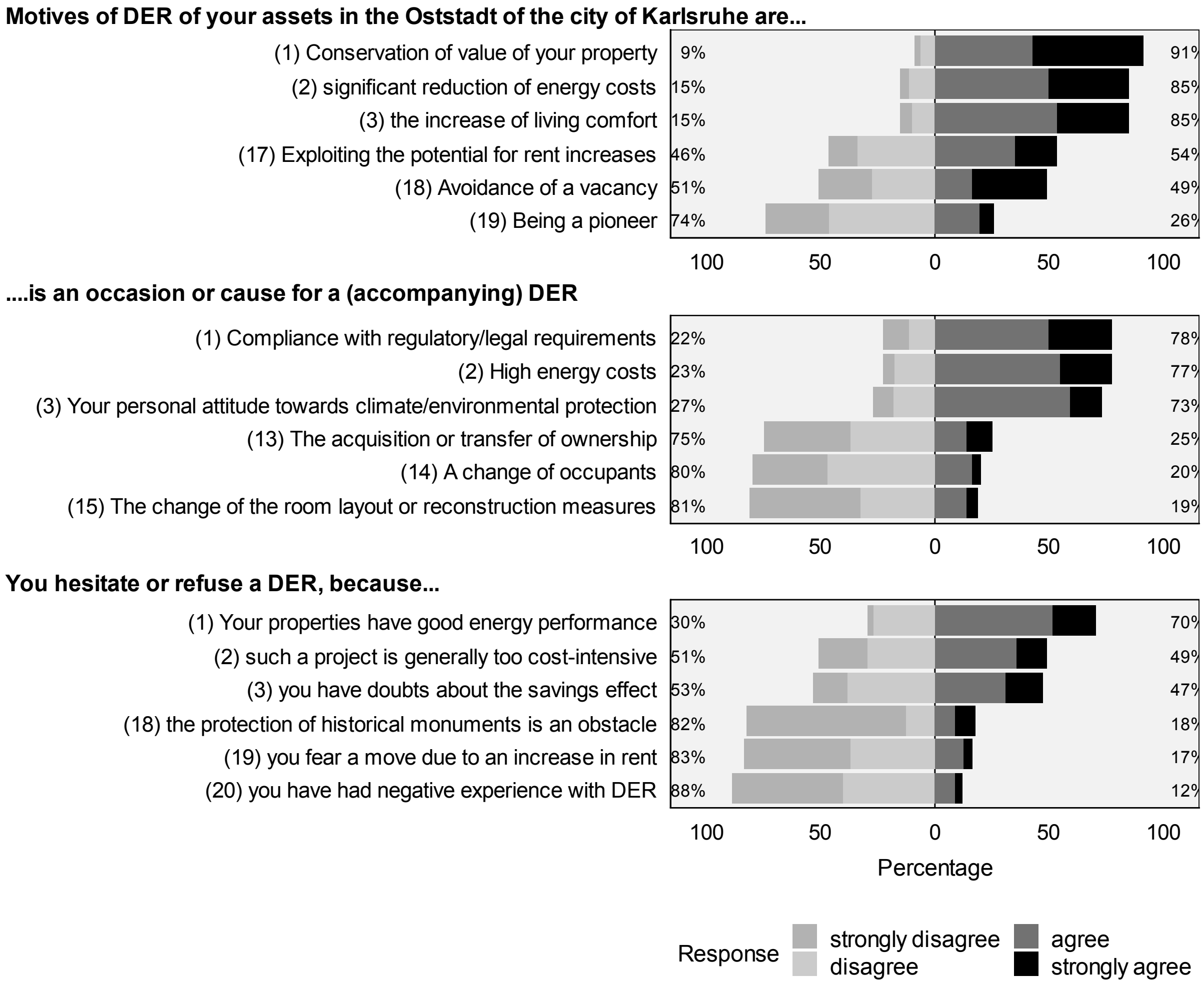

Figure 2 Approval of motives, occasions, barriers. Respectively, the items with the three highest and three lowest approvals are presented. N=85; top: motives; middle: occasions; bottom: barriers.

5.4. Experience with previous deep energy retrofit
More than half of the landlords made some experiences in the context of DER. The experience was assessed with four values: no experience, positive, negative and neutral. Figure 3 summarizes the results.

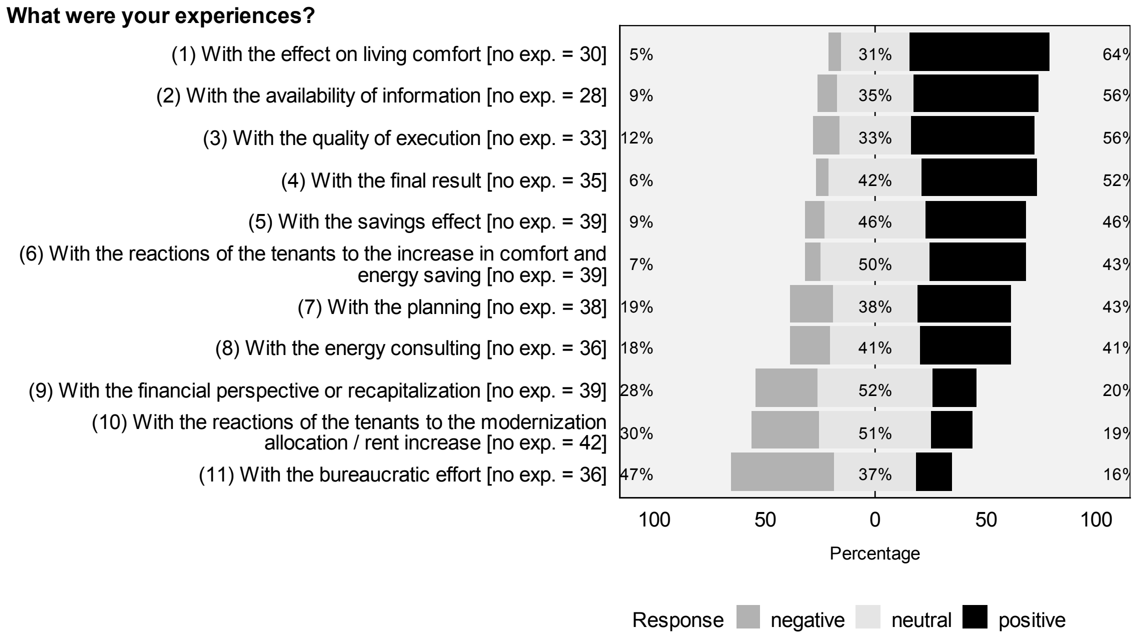

Figure 3 Experience with DER. N=85; no exp.= number of respondents without experience.

5.5. Channels of advice and information

The participants were asked who they seek advice from concerning their property on legal, financial issues and DER. They could choose multiple sources from a total of 25 predefined options. Figure 4 shows the sources with 30 and more mentions. Concerning legal advice, most of the respondents consult their homeowner association (who are professional lawyers). For financial advice, most landlords approach banks. For DER, no clear main information channel is used. The most frequently chosen channel is technical press. Internet sources and DER consultants are second. Real estate agents, neighbors and consumer advice centers belong to the least considered sources for advice.

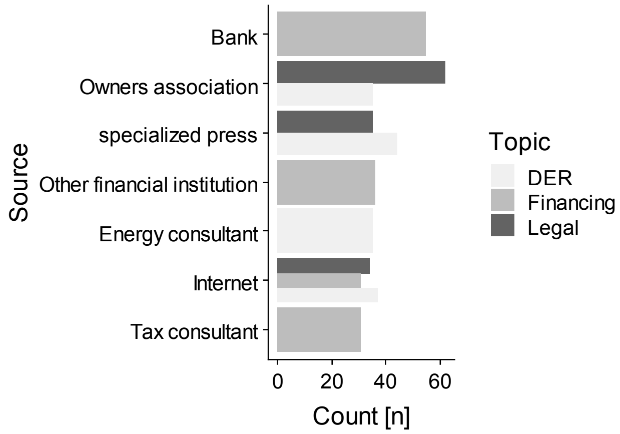

Figure 4 Sources of advice and information for the three topics of DER, financing and legal. The bars present and groupe different topics if a source has 30 and more mentions of the respective topic.

6. Discussion of the results

Despite the bias created by the sampling method, the interpretation of the results has some generic elements. Additionally, the design yields some specific findings about organized private landlords in demand-driven rental markets. A cluster-based analysis of presented and other results yielded six profiles. The communalities are aggregated to form a generic profile (cf. section 7). Concerning the demographics of the sample, the age spread and distribution is in accordance with other studies (e.g. [22]). Acceptable correlation between age and DER was not found, which is in accordance to Kastner

& Stern [33], who did not discover a clear pattern of correlation across several studies. In general, the sample has a positive attitude towards environment and climate protection. However, the identified milieus/lifestyles (personal attitudes) seem to have limited transferability to decision making behavior of DER of not self-occupied buildings, as ecological criteria have a minor part in the decision (cf. 5.1.-5.3.). The share of self-managed properties is comparable to the share determined in other surveys [22]. Those who transfer the management to professionals have a clear link between finance planning and maintenance-dedicated funds. This can be explained by the condominium act, which regulates administration and forming funds. In comparison to the survey on low demand rental markets [30], the motives and barriers shift as expected (figure 2), which emphasize the importance of considering the market conditions. The barriers for DER are mainly related to doubts about DER effectivity and to overestimation of the buildings' energy performance (figure 3). However, landlords should be sufficiently informed due to the mandatory generation of EPC. This indicates that EPC fail to achieve the informative purpose. The motive to exploit rent level increase potential by DER has one of the lowest approvals, which is in accordance with the observations of rent level increase after DER made by Testorf et al. [31]. This can be coupled to the legal framework, e.g. rent caps and uncertainty of enforceability, or to social responsibility or low familiarity and utilization of financial indicators (cf. 5.2-5.3). Noteworthy are the mainly positive and non-economic experiences after DER (figure 3 items 1, 3, 4, 6). The experiences made in preparation phase of DER (figure 3 items 2, 7, 8) show a split field. Landlord specific experiences which relate to the relationship to the tenants and the economic aspects show a considerably less positive experience. Overall, the experiences are mainly neutral or positive, which promises a potential to invalidate some barriers related to DER. The survey revealed a considerable deficit related to the information sources/access. For legal and financial issues, the information channels have a distinct expertise and the majority uses these as main sources. Specialists on DER are much less approached and most information on DER are compiled from technical press and the internet. This causes considerable issues concerning the perception of DER and energy performance, as two of the three most utilized channels for DER can be characterized as passive and not individualized.

7. Conclusion and policy implications

For reaching climate neutrality in the building stock, the importance of considering private landlords is evident. Despite good circumstances, DER implementation is behind expectations. The conducted survey revealed insights into private landlords in an above average demand rental market. In general, private landlords are characterized by their interest in climate and environment topics. They are motivated to save energy and convinced of the ecological advantages of DER. However, they doubt the promised energy savings. The main strategy for investments is conservation of property value and compliance with legal requirements. The main trigger for DER is maintenance. The building performance is often overestimated. Despite an ecofriendly attitude, ecological criteria have a minor part in the DER decision. Financial subsidies are the preferred type of financial incentives. In summary, four areas of policy improvement can be identified: economic incentives, markets, enforcement, lack of knowledge and awareness. For economic incentives, private landlords prefer grants more than subsidized loans. A large part of them focuses on tax-based economic evaluation. Even though tax deductibility of DER is possible, a combination with other economic incentives is not. Then, real estate markets are not reflecting the energy performance sufficiently. EPC fail their informative purpose and DER has no strong association with property value conservation. Adequate access to data about prices, rent levels and energy performance could improve this. Some DER measures are mandatory. However, these requirements are merely enforced. A stricter enforcement would raise awareness, responsibility and place DER higher on the agenda of legal and financial advice. In parts, simplifying bureaucracy could solve some issues of applying for subsidies or receiving professional advice. Concerning the lack of knowledge and awareness, better access to good-practice and DER roadmaps/EPC information could yield significant improvements, as well as the enhancement of public contact points and sources of information with dedicated DER experts. Finally, a higher focus of campaigns on landlords' and tenants' perspectives could raise awareness and mitigate the landlord-tenant dilemma.

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New business models to support sustainable development: The case of energy-efficiency measures in buildings

Honold A[1], Lützkendorf T[2]
[1] Institute of Information Systems and Marketing, Karlsruhe Institute of Technology
[2] Centre for Real Estate, Karlsruhe Institute of Technology

anika.honold@kit.edu

Abstract. The German government has set ambitious climate-protection targets to limit global warming. The aim is to achieve an energy-efficient and almost climate-neutral building stock by 2050. This applies particularly to buildings, responsible for more than 20% of CO_2 emissions. The aim is to reduce the primary energy demand of buildings by 80% by the end of 2050. Achieving a nearly climate-neutral building stock requires targeted modernization measures that contribute to increasing energy efficiency. Barriers confronting the implementation of energy-efficient measures include lack of knowledge due to inadequate provision of information, lack of trust, and problems regarding financing possibilities. Therefore, solutions are needed for holistic concepts that make energy-efficient building and modernization more attractive. In addition to traditional business models (BM), measures that accelerate the implementation of energy-efficiency and BM that support the sustainable development of potential customers are sought. Expert knowledge must be shared to close information gaps; savings guarantees must be considered to build trust, and finally, financing possibilities must be available to support implementing sustainable measures. The research focuses on a modification of BM under the aspect of increasing energy efficiency in buildings for customers. This approach considers specific functions, effects, and benefits of BM. The aim of this extension is to create a basis for systematizing existing BM on the one hand, and on the other, to extend the proposed methodology. Finally, the developed guide supports startups designing new BM.

1. Introduction

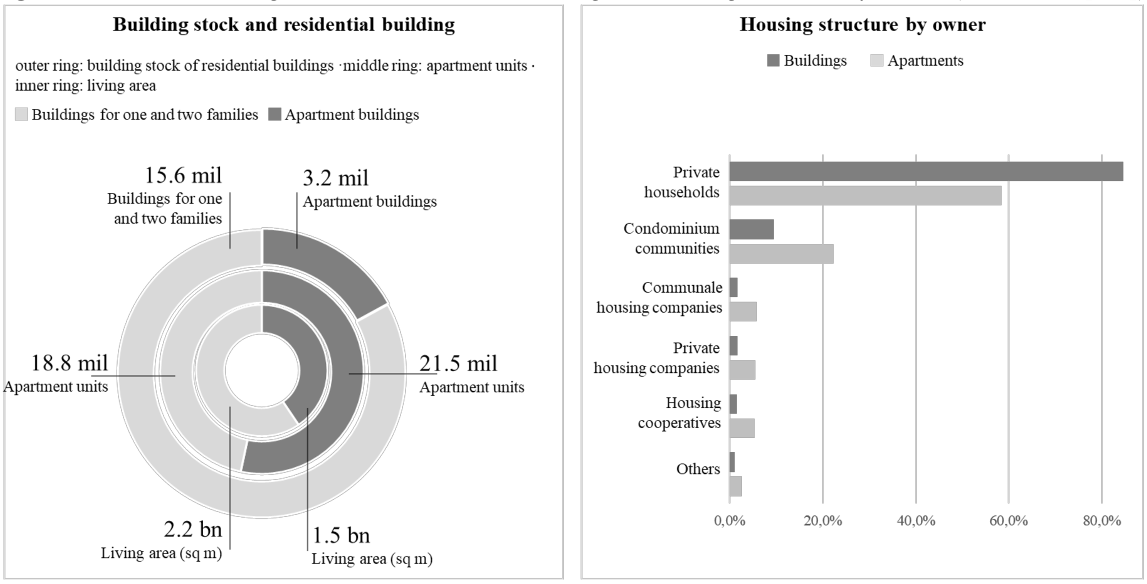
Today, the development of strategies for sustainable development is based on generally accepted goals, specifically, the Sustainable Development Goals (SDGs) [1]. One essential goal is the protection of the climate in ways that contribute to the conservation of natural livelihoods (SDG 13). With the goal of influencing production and consumption patterns (SDG 12), a solution applicable in the area of construction and urban development (SDG 11) is presented. Several countries are currently developing national strategies to improve climate protection. In 2016, Germany presented the Climate Action Plan 2050 [2]. It establishes the principles and targets for conserving resources by saving primary energy and reducing greenhouse-gas (GHG) emissions. Proposed solutions include reducing energy demand, improving efficiency, increasing the use of renewable energy, optimizing operations, using new products and technologies, improving methods and tools for design, and questioning demand (sufficiency). In addition to identifying areas of action—Energy Sector, Transport, Industry, and Agriculture—the plan formulates reduction targets for GHG emissions particularly for the area of action designated as Buildings. By 2030, GHG emissions in buildings are to be reduced from 1990 levels by 67%. For this action area, a budget of 70 million metric tons of CO_2-equivalent will be available in 2030. For the year 2050, Germany is targeting an almost climate-neutral building stock [2]. In order to achieve these medium- and long-term goals, the energy performance of existing buildings must be improved. Although an annual renovation rate of 2% is targeted, recent IPCC publications show that an average renovation rate of up to 5% is required to achieve the goal of limiting global warming to below 1.5 degrees [3]. In Germany, an annual renovation rate of less than 1% is currently being achieved in the field of energy-efficient modernization of residential buildings [4]. However, such data are controversial; clear definitions and survey methods for refurbishment and modernization rates are missing. Modernization rates for individual building components or parts of buildings are available in the literature [5]. It appears that current efforts are not sufficient to achieve the defined objectives, so possibilities must be sought to identify and overcome existing barriers to significantly improving energy efficiency in buildings. Private and institutional building owners currently do not have sufficient scope or willingness to take action that will speed up the modernization of existing buildings to improve energy efficiency. This raises the question of whether and to what extent additional incentives and/or complementary approaches should be pursued. One possible approach is the establishment and extension of new business models to improve energy efficiency in buildings. The authors of this contribution have undertaken a research project to investigate the potential for new business models, focusing on the following questions: (1) What is the condition of existing buildings in Germany with regard to their energy quality, and what is their ownership structure? (2) What barriers can be identified and assigned to actor groups? (3) What business model requirements can be formulated, and what approach to the systematization of business models can be derived from this (best needed)? (4) Which business models already exist, and how can their approaches be generalized or reused (best available)? Which hints and recommendations should business startups receive when they would like to contribute to the improvement of energy efficiency in the building sector with new business models? How can achievable economic effects be estimated? This article presents the first preliminary results in answer to these questions. Section 3 discusses major barriers; sections 4 and 5 present approaches for a typology and analyze existing BM. Section 6 provides information for startups. The basis for the article is a literature review, the authors' professional experience, and the results of discussions with experts.

2. Overview of the building stock of residential buildings and ownership structure in Germany

In Germany, the building stock is divided into 18.8 million residential buildings and 2.7 million nonresidential buildings (excluding industry). Nonresidential buildings account for 37 percent of total building energy consumption, while residential buildings account for the remainder. Figure 1 (left) shows the building stock of residential buildings. Those built before 1979, when the 1st Thermal Insulation Ordinance came into force, are of special interest. In fact, this applies to 62 percent of residential buildings and 66 percent of residential units, whose share of final energy consumption is 68 percent [6]. The energy requirements of new and renovated residential buildings are significantly lower. The legal requirements for building construction before 1979 were significantly lower than after 1979. In addition, the current energy consumption of these buildings cannot be determined exactly, due to partial, complete, and multiple modernizations in the meantime. While the members of the organization *Bundesverband der Deutschen Wohnungs- Immobiliengesellschaften* refurbished two-thirds of its building stock (28.9% partially, 37.3% completely) in terms of energy efficiency, the documentation of modernization measures for the private housing stock is fragmentary [7]. The progress in energetic retrofitting of individual building components also varies considerably [5], substantially complicating the analysis of the energy consumption of these buildings.

The “Destatis report” of the Federal Office of Statistics in Germany on the stock of buildings and apartments shows that the supply of housing in 2011 is predominantly in private ownership (Figure 1). More precisely, private households possess 84.6 percent of residential buildings and 58.4 percent of apartments [8]. Private households are grouped as *owner-occupiers,* who use their residential property for their own needs, and *private landlords* (also known in Germany as “amateurs”). The share of homeowners is the proportion of owner-occupied residential units to all residential units. In 2014, this share was around 46 percent in Germany. Conversely, 54 percent of private households own apartments that they do not occupy, assigning this proportion to the group of private landlords. The second most common form of ownership is condominium communities (9.5 percent of buildings, 22.4 percent of apartments). These are owner-occupied properties and apartments eligible for allocation to the rental-housing market. Together, condominiums account for almost a quarter of the total housing stock. The remaining parts of the residential space fall into three forms of ownership: communal and private-sector housing companies and housing cooperatives (building share < 2 percent, residential share between 5 and 6 percent [4]).

Figure 1. German building stock and residential building and housing structure by owner (based on [6], [8]).



3. Overview of the barriers related to energy retrofit

Barriers are unwanted factors that slow down, hinder, or block a decision-making process. Various studies have already investigated the circumstances of the matter, subjecting influencing factors to refurbishment decisions and removing barriers that arise during energy-related refurbishment (cf. [9-17]). Table 1 shows the identified barriers (see lines A-K), whereas columns 3-10 check whether a barrier could be confirmed in the literature [10-17]. The most frequently occurring obstructions are explained as examples here. Often, financial factors (barrier type A) prevent an energetic refurbishment. For example, those affected by an alleged refurbishment measure may encounter limited financial possibilities [9], insufficient financial support, or an uneconomical refurbishment [10]. Limited financial possibilities imply a postponement of measures to improve energy efficiency [11,12]. Insufficient knowledge (barrier type B) results in those affected, on the one hand, not knowing about the need for renovation of their property [9,13]; and, on the other hand, being insufficiently informed about possible savings (e.g., heating costs, energy, CO_2) after a refurbishment. This is usually due to a lack of consciousness with regard to the issue of environmental protection, which often has the consequence that other aspects (e.g., economic efficiency, aesthetics, living area) have a greater impact on refurbishment design than energy-related aspects [13]. Time-related factors (barrier type E) also have an influence, whether because of the long period of un-inhabitability of the property [14] or the complexity and associated strain of various time aspects on the design and coordination effort [15]. The principle of the landlord/tenant dilemma (barrier type K) describes the interest of landlords in protecting their investments over the long term, but possible unwillingness to finance short-term costs. In addition, the tenant is reluctant to bear short-term costs, despite benefiting directly from the refurbishment and lower energy costs [11,12,18]. However, the investor could levy a modernization charge and a rent increase after an energetic retrofit, a potential disadvantage for the tenant if a disproportionate increase in rental costs to offset the additional expenditure is significantly higher than the energy costs saved.

Different strategies for select appropriate solutions to address the barriers may include government incentives, counseling programs, and regulations, as well as new technologies, which can be used to overcome them. Another approach is either existing or newly developed business models. This research paper examines business models as a solution to identified problems. Prospective business models could possibly contribute to achieving a modernization rate of more than 2 percent per year.

Table 1. Barriers confirmed in literature.

Barriers	confirmed in literature							
	Friedrich et al. (2007)	Jakob (2007)	Kesternich (2010)	Stieß et al. (2010)	Beilan et al. (2011)	Meyer et al. (2014)	Renz/Hack e (2014)	Vögele et al. (2017)
A Financing problems (e.g. no money, no monetary incentives, uneconomical)	✓	✓	✓	✓			✓	✓
B Insufficient knowledge (e.g. about possible savings and energetic condition)	✓	✓	✓	✓	✓	✓	✓	✓
C No discussion of the topic of energetic refurbishment (e.g. lack of knowledge about possible solutions)			✓	✓	✓	✓	✓	✓
D Lack of knowledge in the operating phase and operational optimization (lack of problem awareness, no need to refurbish)	✓	✓		✓	✓		✓	
E Time factors (uninhabitability of the apartment, lack of time for planning and coordination, etc.)	✓	✓	✓	✓	✓		✓	✓
F Underestimation or doubt of savings potential	✓						✓	
G Missing technical and satisfactory solution (e.g. loss of comfort, no holistic solution)							✓	
H Missing planning tools								
I Lack of reason for renovation (e.g. low price level of fossil energies)		✓		✓			✓	✓
J Architectural and constructional reasons (e.g. restriction by monument protection and other technical factors)		✓	✓	✓			✓	
K Investor-user-dilemma	✓	✓	✓	✓		✓	✓	✓

It is now possible to apply this table to the identified actors in the housing sector (see section 2). Then the question can be answered: which stakeholders are affected by which barriers? In essence, private households (amateur landlords, owner-occupiers) and communities of homeowners provide the most reasons for a lack of modernization measures and have major deficits in knowledge, financing, and trust.

4. Business Model—Basics, trends and typology

4.1. Basics and scientific trends of business models

The term "business model" is not clearly defined in literature. Where Osterwalder and Pigneur [19] describe a business model as the "rationale of how an organization creates, delivers, and captures values," Margretta [20] combines business models with the fundamental questions of a company (i.e., how a company can earn money with its business). Bieger and Reinhold [21] see a business model as the result of an analysis of existing and new combinations of business-model elements. Network-centric approaches to business models aim to link different types of stakeholders into a coherent system. This includes all types of stakeholders (e. g., customers, investors, employees, suppliers, partners) and, in particular, society and the environment [22,23].

Companies still have some uncertainties with regard to environmentally friendly strategies. However, research shows that the sustainability factor implies technological and organizational innovations that positively influence sales and profits [24]. In addition, there are positive side effects, such as environmentally friendly production, less use of resources, less CO_2 emissions, and more innovations [25]. The current literature contains numerous papers dealing with business models in the context of sustainable development [25-37]. An excerpt from that discussion can be found in Nidumolu et al. (2009), who describe the path to business models that support sustainable development. They outline in five steps the challenges a company faces on the way to a holistic sustainable strategy. Sustainable business models are the result of exploring new paths that can include ecological services, but also the restructuring of established paths that require modernization [25-27]. Concretely, concepts such as *Green Economy* or *Green Growth* emphasize the sustainable use of resources [28]. A similar aspect is taken up by the *Green* [29,30] or *Sustainability Business Model* [22,31]. Such models include the establishment of lower environmental impacts and a promising platform for innovation. Their focal point is a change of core business strategy (e.g., from selling products to selling service systems containing the product). Somewhat less specific but still relevant are general recommendations for business models on redesigning systems (e.g., minimizing consumption, maximizing the society's benefits, and avoiding waste, cf. [32]). These aspects are considered and classified into so-called archetypes. Different archetypes include different approaches (e.g., maximizing material/energy efficiency; adding value from waste; replacing renewable energy and natural processes; and providing functionality instead of ownership. Detailed descriptions can be found in [29,30,33,34]).

Economically successful technological innovation requires business-model design and implementation combined with careful strategic analysis [26]. Canvas—a business model by Osterwalder and Pigneur [19]—takes this aspect into account. It provides every business with a simple tool to describe and think through its processes. This architecture of business models typically contains and connects different dimensions—for example, in relation to customers, benefits, added value, partners, and finances. While previous research has generated concepts that include the ecological aspect in Canvas (e.g. [30] or *Value Mapping Tool* [34]), the *Triple Layered Business Model Canvas* (TLBMC) is a specific tool that is an extension of Canvas, combining topics such as innovation of business models, as well as sustainable and green business models [33, 35-37]. This extension adds an ecological and a social dimension to the model, the ecological extension of the TLBMC based on a life-cycle perspective on environmental impacts and benefits of products and services. Environmental impacts contain ecological costs based on performance indicators (e.g., GHG emission). Environmental benefits extend the aspect of value creation. Essentially, innovations are sought that reduce (increase) negative (positive) environmental and social impacts [30,33,37].

Although the current literature aims to integrate sustainable development into business models, it is essentially focused on the optimization of internal and organizational processes. Therefore, an approach is sought that aims to optimize customers' processes in order to create added value for customers, ecology, and welfare. A first approach links the sustainable business model to user-driven innovation. The development of a sustainable value proposition constitutes the core of a sustainable business model [38]. However, to this aspect, the externality of the business models can be added. The research approach in this paper follows one that defines business models in the context of supporting sustainable development (in this specific case, an energy-efficiency strategy) for the customer.

4.2. Functions, effects, benefits of business models to improve energy efficiency in buildings (EEiB)

The main function of an EEiB-business model (as defined by the authors) is to increase the energy efficiency of a building. Hence, in order to eliminate barriers that arise during energetic refurbishment, a business model requires certain functions that imply effects and benefits for the customer and for society. Table 2 shows the identified functions (A), effects (B), and benefits (C).

Functions of business models represent their basis. This could be the provision of innovative products and services, but also the development of concepts for the design and implementation of renovation measures, or approaches for the optimization of existing HVAC systems. The effect describes the result a business model can produce. With regard to a potential refurbishment investment, this characteristic represents the time-related advantage of an investment, the identification of savings potentials or guarantees, or the provision of knowledge. The benefit of a business model refers to ecological circumstances that the business model causes (e.g., saving GHG emissions or primary energy and the associated costs). The benefits essentially reflect environmental circumstances. The conceptual step that follows is the development of benefits around social and economic aspects (e.g., reduction of externalities, creation of jobs and partnerships, or integration of companies with different interest groups). Thus, a business model can be evaluated from environmental, social, and economic points of view. Together, these components represent the future value proposition of a company's range of products and services to its customers.

4.3. Introduction of specific business models

The range of business models that contribute to the improvement of energy efficiency in the housing and real-estate sector is constantly increasing. In fact, a recent evaluation of the accompanying research "Energiewendebauen" commissioned by Project Management Jülich indicates that the number of projects (PRJs) dealing with business models has more than doubled from 2018 to 2019. Accompanying research includes projects on contracting (28 PRJs), prosumer models (16 PRJs), and leasing (8 PRJs), but also on approaches such as crowdfunding or sharing economy (in total, 9 PRJs). In Table 2, five business models (partly based on the mentioned projects) are presented.

The selected examples show the approaches to complementary research mentioned above and set different priorities. While in Case 1, the EEiB business model focuses on a financing concept, other business models are based on product service systems or prosumer approaches. Finally, these business models are classified according to the systematization described in Chapter 4.2.

Table 2. Examples of EEiB business models

Case 1 EPC [39]: Energy performance contracting is based on a contract between an owner of a building and a service provider, which contains a guaranteed savings goal in relation to energy consumption or energy costs before the contract is concluded. The service provider receives a regular payment that the client can often finance from the saved energy costs. The contractor controls, optimizes, and maintains the systems with regard to the highest possible energy efficiency. Planning and operational optimization for lighting, cooling, ventilation, and/or heating installations remain in the contractor's hands.
Case 2 RRA [40]: The leasing of roof areas with simultaneous roof renovation is an example of sharing concepts. This model enables a refurbishment measure with a significant increase in the value of the property. The operator of the photovoltaic system receives possible subsidies and the current feed-in tariff by feeding the generated electricity into the grid of the local grid operator. In exchange, the owner of the roof area receives the agreed-upon payment from the operator. The amount of the payment for the roof is determined individually. In addition, a complete renovation of the roof is carried out for owners of large roof areas, such as large production halls and warehouses, commercial enterprises, and public facilities.
Case 3 SW [41,42]: The leasing of software includes the aspect that the supplier often retains ownership of the physical product. This is a subscription-based service that, depending on the rate, offers services in addition to basic applications. Software for operating and building technology may enable energy management of buildings. Efficiency potentials in highly complex building operation can be identified, and energy-saving measures can be implemented and controlled. Corresponding software service packages also provide online diagnostics, updates, cloud applications, or maintenance.
Case 4 FSM [43]: Full-service renovation packages include consulting, design, energy testing, renovation, quality control, commissioning, and financing. The concept of serial modernization of buildings differs fundamentally from previous refurbishment offers, in terms of lower costs, short refurbishment duration, attractive design, and functional and savings guarantees. This is implemented with elements such as 3D scans of the building, pre-assembly of all components, and quality control to achieve the Net-Zero standard.
Case 5 MS [44]: The decentralized generation of electricity from renewable sources or in a combined heat and power plant, often in combination with a tenantable-electricity approach (*Mieterstrom)*, is based on a prosumer approach (i.e., an energy consumer like a building also acts as an energy producer). Energy is preferably fed into the house network of the building and either directly covers the current energy consumption of the tenants living in it or charges a battery store. Only when the energy produced on site cannot be consumed is the excess electricity fed into the public grid. For owners of apartment buildings, these models offer the opportunity to reduce ancillary costs, become less dependent on electricity price trends, increase property value, and generate additional revenue. Tenant savings of energy costs is another advantage.

5. Classification and analysis

The classification and analysis aims to identify business models that increase energy efficiency in the construction sector and contribute to the reduction of greenhouse-gas emissions. The developed systematization refers to the identified barriers. The evaluation in Table 3 regarding functions, effects, and ecological benefits is based on the personal assessment of the authors. Development of the systematization with regard to further functions, effects, and benefits shown in Table 3 is possible. In the future, the list should be extended in both horizontal and vertical directions, with the aim of clustering similar models and uncovering future potential for new business models.

Table 3. Systematization of business models

	1) EPC	2) RRA	3) SW	4) FSM	5) MS	Addressed barriers*
A) Function	✓	✓		✓	✓	B, C, E, F
A1 Building inspection and energy audit	✓	✓		✓	✓	B, C, E, F
A2 Approvals from local authorities and applications for grants and subsidies		✓		✓	✓	A, B, J
A3 Analysis and diagnosis (energetic analysis)	✓	✓	✓	✓	✓	B, C, H, I, F
A4 Consulting, development, and selection of solutions and energy concepts			✓	✓		B, G, I, J
A5 Economic efficiency calculations	✓			✓	✓	A, B, F, K
A6 Financing concepts and aids	✓	✓		✓	✓	A, B
A7 Project planning				✓	✓	E, J
A7 Project implementation and renovation work	✓		✓	✓	✓	E, J
A8 Project management				✓	✓	E, J
A9 Quality control	✓		✓	✓	✓	B, D, F
A10 Operating the plant/facilities	✓	✓	✓		✓	B, D
B) Effect						
B1 Energy saving potentials	✓	✓	✓	✓	✓	
B2 Savings guarantees	✓		✓	✓	✓	
B4 Investment priority	✓	✓		✓	✓	
B4 Provision of information	✓	✓	✓	✓	✓	
C) Ecological benefits						
C1 Primary energy saving	✓	✓	✓	✓	✓	
C2 Reduction of greenhouse gas emissions	✓	✓	✓	✓	✓	
C3 Comfort gains for customers		✓		✓		
C4 Cost saving for customers	✓	✓	✓	✓	✓	
C5 Reduction of resource consumption	✓	✓	✓	✓	✓	
C6 Motivation to deal with the life cycle of a product/service	✓	✓			✓	
C7 Improved longevity and durability of products (upgradeability and repairability)	✓		✓			
C8 Recycling of materials						
C9 Change in consumer behaviour			✓			
C10 Active development and maintenance of existing value creation networks				✓		
C11 Promotion of efficiency	✓		✓	✓	✓	

*Barriers: A) Financing problem, B) Insufficient knowledge, C) No discussion of the topic of energetic refurbishment, D) Lack of knowledge in the operating phase and operational optimization, E) Time factors, F) Underestimation or doubt of savings potential, G) Missing technical solution, H) Missing planning tools, I) Lack of reason for renovation, J) Architectural and constructional reasons, K) Effort without direct benefit

6. Guide for Startups: Turning an Idea into a Business Model

If the development of business models seems complicated and ambiguous at first sight, a guide serves to develop and help in business-model selection. The path from an idea to a business model that improves the customer's sustainable process includes the key points summarized in Table 4. Ideally, when searching for and selecting a suitable business model, startups must consider four steps. In step 1, ecological, technological, and social developments result from the named techniques. These trends call for business models that support the energetic-refurbishment measures. Step 2 analyses the market and its participants. The focus includes identification of a suitable target group. For example, using the building and ownership structure from Chapter 2 for this study enables identifying the target group of private landlords. Subsequently, assessing for the focal target group the barriers confronting customers becomes possible (cf. chap. 3). Essentially, private landlords and owner-occupiers show considerable deficits in terms of knowledge, financing, and trust (e.g., [11]). A potential business model must take this into account. After designing a business model with the tools of Canvas or TLBMC, the business model must be specified (step 3). In addition, the functions, effects, and benefits of business models (see chapter 5) must be considered in order to counteract the barriers identified in Step 2. After identifying potential business opportunities, the business model with the greatest potential for overcoming the barriers must be selected. Finally, further steps (such as the preparation of a business plan and its implementation) must be initiated [45].

Table 4. Turning an Idea into a Business Model.

	To do	In detail
1	Have an idea or search for upcoming trends	Generate ideas using creativity techniques (e.g. brainstorming, mindmapping) and trend analyses regarding current developments in society, culture, state, law, politics, economy, technology, and ecology
2	Analyze all conditions and elaborate the idea	Analysis regarding market, competition, market potential, market trends; customers as well as their needs and barriers; strength-weakness analysis of all market participants
3	Identify potential business models	Model a business model using Canvas and TLBMC; take into account the functions, effects and benefits of business model
4	Select business models	Select a suitable business model and initiate the next steps (business plan, implementation, controlling, monitoring, and, if necessary, adaptation of the business model)

7. Discussion and outlook

Through the proposed systematization of business models, this paper offers an approach to linking the theoretical concept of (sustainable) business models with the problem of the barriers that arise during the energetic refurbishment. In addition, the identified functions, effects, and benefits have the potential to represent future value-proposition formulations for the customer. Companies and startups can use combinations of the identified systematization to design their own business model. A guideline for startups is also provided, to help startups on their way from an idea to an economical and ecological business model. Business models that focus on sustainable process improvement for the customer contribute to improving the energy efficiency of existing buildings. In addition, supporting overall solutions (e.g., a combination of consulting, design, and financing concepts) instead of individual solutions ensures a holistic approach to the barriers that homeowners face. The proposed systematization has its limits in terms of completeness. Therefore, carrying out studies that identify barriers by type of building owner and building (chap. 2-3) can extend this conceptual research. It is also important to broaden the systematization in chapter 5 to find patterns and gaps in business models. Future research may also address broad changes in political, social, environmental, and economic aspects. In addition, the aspect of potential conflicts of objectives that may arise among initiators must be examined. Intellectual property is protected knowledge and is only available to society at high cost. For example, to integrate analytical and diagnostic software into building services as a standard would require government intervention. With the help of patent races (e.g., an award system), the government has the opportunity to announce project goals, winners of these competitions receive a reward, and at the same time, the innovation becomes a public good. Furthermore, the state can offer training programs for startups. The systematization and guideline developed in this paper can inspire and help prospective companies to develop new sustainable business-model ideas.

Acknowledgement

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Social housing energy retrofitting: Business Model and supporting tools for public administration

Penna P[1], Schweigkofler A[1], Brozzi R[1], Marcher C[1,2], Matt D T[1,2]

[1]Fraunhofer Italia Research, via Volta 13/A, 39100 Bolzano (BZ)
[2]Free University of Bozen-Bolzano, piazza Università 5, 39100 Bolzano (BZ)

paola.penna@fraunhofer.it

Abstract. High refurbishment costs and uncertainty of the investment payback period account as the main reasons of low rate of energy retrofit of the European building stock. Moreover, assessing energy and economic benefits of energy retrofitting may result difficult e.g. due to the unpredictability of users' behaviour which may alter the effectiveness of energy refurbishment intervention. This paper deals with the question whether approaches exist, aimed at securing the profitability of energy retrofitting and at creating the market condition to incentivize the energy refurbishment on a large scale. The paper presents the operational tools, developed to support the public administrations along the entire retrofit process, and the Business Model (BM), structured to financially support the refurbishments by the energy cost savings. This tools and the BM has been developed for the South Tyrolean context, to promote the energy retrofit of the social housing building stock of the Autonomous Province of Bolzano. The results presented in this paper are part of the ongoing research project "KlimaKit", founded by operational programme European Fund for Regional Development of the Autonomous Province of Bolzano EFRD 2014-2020 – Investments in Growth and Employment.

1. Introduction

The European Commission [1], as well as the Intergovernmental Panel on Climate Change [2], identify the construction sector as the one with the highest potential in reducing energy consumptions and environmental pollution. According to the European Commission the CO_2 emissions of the residential sector should be reduced about 90% by 2050 [3]. Considering that the annual growth rates of new constructions is around 1.0–3.0% per annum [4,5], it means that existing building stock represents the main opportunity to save energy. For reducing the CO_2 emissions, the political measures of the 28 EU countries set to 2,5% the energy retrofit rate of existing building stock by 2020 and 5%-5.5% by 2030 [6]. Despite this, the renovation rates of residential buildings still remain relatively low, about 1% per year in most of the EU countries [5, 6]. In South Tyrol the trend is similar to Europe: more than 50% of the residential buildings were built before 1970 (Table 1) and the retrofit rate is about 1% (550 buildings per year) [7]. For this reason, at regional level, the objective for 2020 is increasing the overall amount of renovated buildings to 1,500 per year, namely equal to 2.5% of the existing housing stock. Some of the main barriers in investing in energy refurbishment are the high investment costs, the lack of information [8], the uncertainty related to payback time [9], lack of collaboration of stakeholders involved in retrofit process [10] and the wide variety of possibilities offered by the market [11]. For changing the dynamics of the market, a figure of a frontrunner is essential.

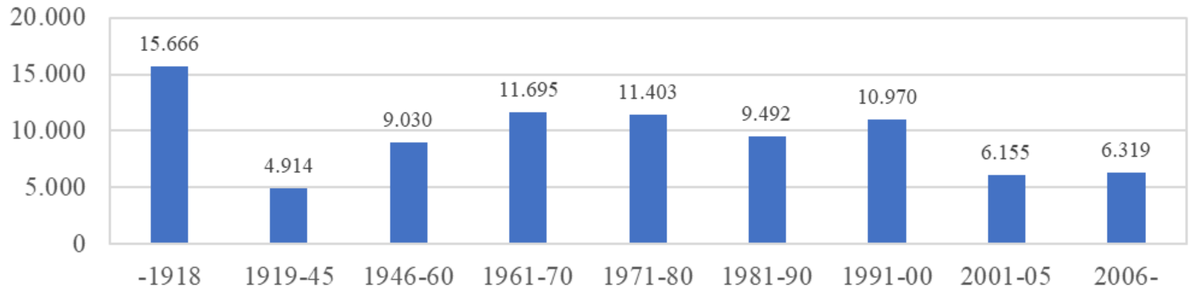

Figure 1 - Number of residential buildings by construction period (Source: ASTAT).

Social housing associations have a key role in mobilizing the refurbishment market, becoming an inspiring example for the private sectors. Once technical solutions and business models have been developed and tested on the social housing stock, it is much easier to penetrate the private housing market [12]. For this reason several studies [13, 14, 15, 16] and European projects [17, 18, 19, 20, 21, 22] deals with energy refurbishment of social housing. A promising strategy to promote the energy refurbishment seems to be the development of standardized retrofit solutions [23, 24], especially since social housing buildings are characterized by a typological and technological homogeneity [13, 14]. The definition of integrated packages of Energy Efficiency Measures (EEMs), developed based on representative building, allows take advantage of synergies between EEMs [8, 25] and improve the collaboration among stakeholders of building and energy sector. The idea of moving from one-off project towards standardized refurbishment packages with defined energy performance underpins the Dutch program Energiesprong [12, 26, 27]. By linking up home owners, skilled builders, financing institutions, housing associations, researchers and local government, it was possible to transform more than 100’000 home into net zero energy buildings. The basic concepts are the realization of the retrofitting works within 10 days and a 40-year energy performance warranty from the builder [28]. This retrofit concepts are combined with a Business Model (BM), which allows the financing of the refurbishments by the energy cost savings. The success of the BM is a key driver for shifting the model to large scale [29, 30, 31].

The paper presents the operational tools developed to support the renovation of the building stock of the social housing association of the Autonomous Province of Bolzano (IPES - Istituto Per l´Edilizia Sociale) and the BM defined to drive the changes of energy refurbishment market in South Tyrol. IPES is rather sensible to the topic of energy refurbishment and it is already involved in some important renovation processes, such as the European Sinfonia Project [17], which aims at testing urban-scale strategies for improving the energy efficiency of social housing stock [32, 33]. However, the major part of the social housing stock has not been renovated and still presents high energy consumptions. Section 2 presents the methodology used to develop the supporting tools and the BM. Section 3 reports the results of the analysis carried out to define the main critical issues of the energy retrofitting supply chain and the existing retrofit process. The supporting tools and the proposed BM are presented in Section 4. Section 5 identifies the limitations and the opportunities of the proposed solutions. Conclusions with the main recommendations and future development of the work are reported in Section 6.

2. Methods

The methodology used to develop the supporting tools and the BM for energy retrofit of social housing includes two distinct steps. The first step entail the systematic analysis of the management of energy retrofit process by the local social housing department. To this aim, the Director of the technical services Division and the Director of the west technical Office of IPES attended semi-structured interviews (approximately 60 minutes based on predefined open questions). The experts interviewed contributed to define the specific characteristics of the process, the main organizational challenges emerging along the entire energy retrofit supply chain and the different actors involved in each phase. The second step consists in a series of workshop, reported in Table 2, carried out to discuss the proposed solutions. The series of workshop was conceived as an iterative process where the experts validate progressively the results of the project, enabling the research team continuing the development and finetuning of the most promising concepts. The different stakeholders were not involved at the same time during the workshops, but they took part at the meetings where they are directly involved in the decision making process, in order to preserve high commitment into the project.

Table 1. Structure of the workshops

Workshop	Objective	Participants
Concept	Description of organisational structure First draft of the Business Model	Social housing department
Implementation	Benefit and role of actors Team requirements	Social housing department Energy service provider
Simulation	Market and legal scenarios Risk management plan	Social housing department Public procurement agency Tenants association
Validation	Supporting tools Business Model	Social housing department Energy service provider Public procurement agency Tenants association Companies

In the first workshop, a draft of the BM concept, formulated according to the information collected during the interviews, was presented to the social housing department. The BM has been compared with other national and international similar experiences. Through the second workshop, the implementation of the supporting tools has been proposed and discussed. Specific solutions and the stakeholders role were defined for each phase of the retrofit process. The third workshop provided concrete scenarios supporting the introduction of the energy retrofit model in the market. The legal aspects along the entire renovation process were also considered and discussed with the local public tender agency. During the final workshop the supporting tools and the validated BM were presented to the stakeholders involved in the energy retrofit supply chain, including different companies and suppliers. The different workshops, conducted between November 2017 and December 2018, consisted of presentation of preliminary results and open discussion moderated by research team, composed by researchers of Fraunhofer Italia and the Institute of Renewable Energy of Bolzano.

3. Findings of the Analysis

The systematic analysis of the existing energy retrofit process allows to identify the most critical aspects of the energy retrofit supply chain and the existing structure of an energy refurbishment project carried out by the social housing association. The main findings are reported in the following sessions.

3.1. Critical aspects of the energy retrofit supply chain

For each phase of the energy retrofit supply chain the most common problems have been identified.

- *Preliminary design.* During the preliminary design the requirements of the retrofit project are defined. In this phase, the most critical aspect is related to the choice among several option offered by the refurbishment market.
- *Designing.* The design project is entrusted to external professionals through a public tender. The choice of the reliable partners appears to be the most critical step because of the tendering process that it is not structured in a proper way.
- *Building Construction works.* In this phase it is noted a poor control over quality of building works. This aspect generates uncertainties in costs, timing and architectural quality.

- *Operational Phase.* In the current process, energy savings assessment and planning of maintenance of the building system are not scheduled. This lack generates uncertainty on the retrofit benefits and the malfunctions of the technical system are not prevent.

3.2. Existing retrofit process

Besides the critical aspects of the supply chain, according to the existing retrofit process a real BM for encouraging the retrofit process on a large scale is not present and all the incurred costs are faced just by the social housing association. As shown in figure 2, before the retrofitting, the tenants pay a fix rent to the IPES, calculated based on family income. The comfort conditions, as well as the condition of the building, are not taken into account for the rent calculation. An average estimation of this cost is about to 200€. In addition, the tenants has to pay for the energy supply of the utilities. This cost changes on a monthly base and it is managed and debited to the tenant by IPES, which acts as an intermediary between the tenants itself and the energy supplier. For exemplifying purpose, a cost of 150€ for the overall energy supply has been estimated. A total expense of 350€ per month for each apartment is collected by IPES from tenants. On the other hand, the social housing association takes care of the maintenance of the building and the heating system during the operational phase (estimated about 40 € per month). In this framework, since there is not a real planning of the management and maintenance of the building, the costs tend to be higher than it should be. Once the building has to be retrofitted (Figure 3), the retrofit is not structured to take advantages of synergies between different EEMs, but it often involves just some individual measures. The design phase and the realization work are entrusted respectively to external professionals and construction companies by means of a public tender. All the construction activities are supervised by the IPES technicians, which have to guarantee the achievement of specific standard of architectural quality. Based on IPES experience, a total cost for the energy retrofit of about 30.000€/flat has been estimated. This cost is entirely financed by IPES. According to this process, the only stakeholder that benefits of the energy refurbishment is the tenant, who pays less for energy supply and enhances indoor comfort conditions. The monitoring and the assessment of energy performances after retrofit are not planned and no guarantee of performance is due. This process is characterized by a fragmented supply chain, resulting in many difficulties in communication, planning and coordination.

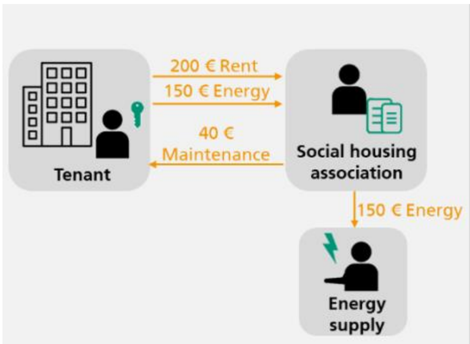

Figure 2 – Costs before the retrofit.

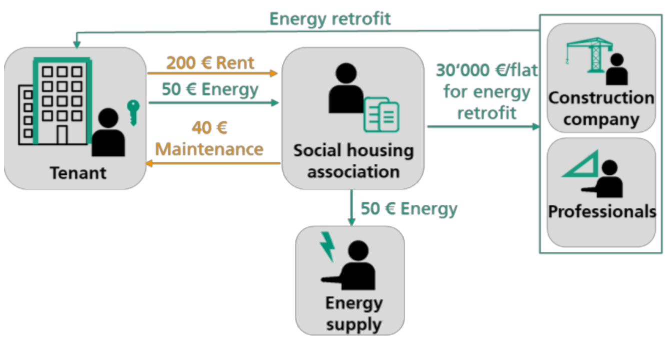

Figure *3* – Existing retrofit process of the social housing association IPES

4. Results

The series of workshop allows to define and validate the identified solutions to the critical aspects of the energy retrofit supply chain. During the workshop the BM has been developed based on the South Tyrolean context and according to the social housing association requirements and needs.

4.1. Supporting tools for public administration

To support the public administration and IPES during the refurbishment process, the following operational tools have been developed:

- *Building Analysis*: during the preliminary design a decision support tool can help in choosing among different EEMs, improving the awareness of decision makers. To develop this tool, the social housing stock of Merano has been analysed [34] and five reference buildings, representative of the building heritage, were selected. Based on the these buildings, five standardized retrofit packages with heterogeneous levels of certified energy saving performances, have been defined. By answering a set of questions, related to an existing building belonging to the South Tyrolean housing stock, the tool identifies the most similar reference building and, according to a series of drivers, recommends one of the standardised retrofit packages. Beyond the recommendations of the technological solutions, the tool provides a reliable range of information regarding the expected energy savings, the reduction of CO_2 equivalent emissions, the retrofit costs for the envelope and for the technical system and an estimation of the payback time of the intervention. The process development of the tool is presented in [35].
- *Soft Criteria:* The introduction of soft criteria into a public tender is a practical input to support the public administration in choosing reliable partners during the designing phase. Soft criteria should not be compulsory, but they should award professionals and building companies that include the following aspects into their offer. The first criterion is the warranty of building energy performances. In particular, the public tender participants should specify the method used to calculate the energy savings and the time-frame within this performance should be guaranteed. The second criterion is the application of a monitoring system for checking the indoor thermal conditions and the energy consumptions post retrofit. Especially in case energy savings are lower than the expected ones, it is important to define whether the responsibility belongs to the construction company or to the user behaviour. The planning of management and maintenance of the building and the building system is the third soft criteria. Planning these aspects is particularly important to prevent malfunctions and to avoid deteriorations of the system.
- *Building Information Modelling (BIM) Methodology*: In a retrofit project the use of BIM methodology leads to several benefits. First of all, during the realization phase, by improving the management of the building site, it increases the control on the quality of the realization. BIM allows also to create a database with all the information related to the retrofit project, for example the specification of construction materials applied to the building, the characteristics of the glazing or heating system, etc. This information can be integrated in a facility management system and can improve the management and maintenance process. Moreover, coupling BIM with the data coming from the monitoring system allows to easily visualize comfort conditions within the building and to detect malfunctions of the building energy system.
- *Contracts*: The relationship between the stakeholders involved into the BM has to be defined by contracts. It is particularly important for the application of the BM to regulate the relations between the social housing association and the energy supplier, as well as the relationship with the tenants. At this purpose, the guide line, for supporting both the realization of the building retrofit project and the following phase of monitoring and management, has been defined. By means of the consultancy of the Faculty of Law of the University of Trient, the regulatory framework, the main structure of the contract and the contractual elements, that has to be integrated into the contract, such as obligations, compensation, legal protection or duration, have been specified.

4.2. Business Model (BM)

The developed supporting tools facilitate the application of the BM. The idea behind the BM is similar to the one proposed by Energiesprong [12, 25] and used as a model by Energy Service Companies (ESCOs): integrating the energy bills of the tenants into an energy plan. This allows the social housing association to recover part of the retrofit investment cost by means of energy savings. The proposed BM is summarized in the schema below (Figure 4). The social housing association applies one of the standardized retrofit packages, able to optimize synergies among different EEMs. The investment cost related to each retrofit packages changes according to the package itself and to the level of energy performance, defined in each package. It varies from 15’000 €/flat to 40’000€/flat. Also the energy savings changes according to the package and the level of performance (from 50% until about 90%). For exemplifying purpose, an investment cost of 30’000€/flat and an energy reduction of about 80% have been considered. The soft criteria allow the selection of reliable partners for the designing and the realization phase. The entrusted professionals and construction companies apply the retrofit packages and a monitoring system, giving the warranty of energy performance and architectural quality of the realization.

After the refurbishment, the tenants continue to pay a fixed renting rate and a service fee. These costs are equal to the sum of the rent and the energy bills paid before the retrofit (350€ per month). The service fee (150€/month), paid as a fixed monthly fee, guarantees the thermal energy supply, for maintaining an indoor temperature of 20°C, domestic hot water and an electricity bundle for electric utilities. If tenants exceed that agreed amount of energy performance, they pay the additional energy consumption. In this way, since the energy costs are reduced, the energy savings allow IPES to recover some of the investment costs. The monitoring system provides information to tenants about their energy consumption and if the performances are not consistent with the estimated ones it provides the cause, whether it is behavioral or technical. On the other hand, also the social housing association pays a service fee to the energy supplier, for the management and maintenance costs for the building energy system. A regular maintenance of the system improves the system efficiency and permits costs reduction. This BM presents several benefits:

- It allows social housing association to recover part of the investment costs for retrofit that can be one more time invest in other refurbishment project, spreading the refurbishment on a large scale;
- It protects the tenants to future energy prices;
- It defines a long-term customer loyalty between energy supplier and social housing association;
- It improves the collaboration among stakeholders, that should collaborate to create integrated solutions with warranty of energy performance.

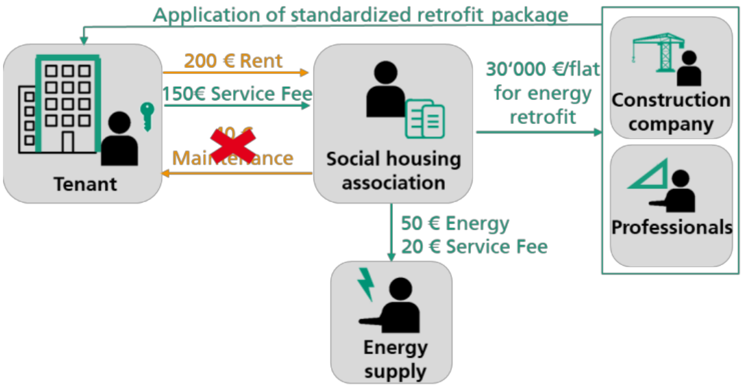

Figure *4* – The proposed Business Model

5. Discussion

The success of the BM is a key driver for shifting energy retrofitting of the existing building to large scale. In this paper some operational tools for supporting the application of the BM on the South Tyrolean context have been presented. The application of this BM has to face several difficulties, first of all, the agreement with tenants that normally benefits of the retrofit interventions without being charged of any renovation costs. In fact, IPES is not allowed by provincial legislation to increase the monthly rent after the refurbishment and this could compromise the feasibility of this BM. In this framework, the communication strategies pays a crucial role to make the tenants aware of the importance

of reducing the energy consumptions and to make them understand that even if they do not have an immediate reduction of the energy costs, they can benefit of enhanced indoor comfort conditions.
It is important to highlight that the identified supporting tools, combined with the BM, have been developed for the social housing association of the Autonomous Province of Bolzano, therefore, to extend the results on a national or European level, both tools and BM need some changes.

6. Conclusion

The paper presents some of the main outcomes of the KlimaKit project. In particular, it presents the methodology used to develop the supporting tools and the BM for supporting the social housing association of the Autonomous Province of Bolzano in promoting energy refurbishment in South Tyrol. A systematic analysis allows to identify how the process of energy refurbishment is carried out by IPES and the most critical aspects of the existing retrofit supply chain. By means of a series of workshop, the supporting tools and the BM have been discussed and validated by the main stakeholders. The idea behind the proposed BM is to integrate the energy bills of the tenants into an energy plan. This enables the social housing association to recover part of the investment costs for retrofit and to invest more in other refurbishment project. The application of an efficient BM is crucial in energy refurbishment project, because it allows to start a virtuous circle able to scale up the refurbishment on a large scale.

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Effects of the tenants electricity law on energy system layout and landlord-tenant relationship in a multi-family building in Germany

Braeuer F, Kleinebrahm M and Naber E

Karlsruhe Institute of Technology, Institute for Industrial Production

fritz.braeuer@kit.edu

Abstract. Multi-family buildings (MFB) accommodate 53% of the German apartment stock. Although PV-systems on single-family buildings are widely implemented, the PV-potential on MFBs has barely been touched. Therefore, the German government introduced the *Mieterstromgesetz*, the tenants electricity law (TEL), in 2016. This law exempts electricity directly produced and consumed in a building from certain charges and taxes. Within the TEL framework, the landlord acts as the local electricity provider and can profit from selling electricity to the tenants and tenants can save electricity costs. This paper analyses the techno-economic effects of the TEL on the energy system layout of a MFB in Germany. Furthermore, it gives implications on how the TEL affects the tenant-landlord relationship. In this analyses, a MILP model is used to maximize the net present value (NPV) and determines the optimal layout and dispatch of the energy system. The model can choose to invest in PV, CHP and a battery storage system. Additionally, one to six electric vehicles (EVs) are integrated into the model. The novelty of this paper is the model-based analysis of the German *Mieterstromgesetz* considering EVs. The results show that the combination of PV and CHP is the most profitable system layout with NPVs up to 31.9k€. An optimized charging strategy increases the self-consumption rate and the NPV substantially compared to a fast-charging-strategy. Thus, the TEL can create a symbiotic relationship between landlords and tenants.

1. Introduction

The building sector accounts for a big share of the German energy consumption, which is mainly related to space heating and cooling. Thus, it is mainly regarded as an energy sink. Nonetheless, recent development in the sector of single family buildings (SFB) has proven that as a prosumer home owners can actively contribute to the energy transition process. By installing a photo voltaic (PV) system on their roof or integrating a combined heat and power (CHP) unit, they become an additional energy source. Nevertheless, this development is mostly restricted to single-family buildings. Although 53% [1] of German household units are set in multi-family buildings (MFBs), this potential energy source remains mostly untapped. To foster this potential, in 2016, the German government amended the *Mieterstromgesetz*, the tenants electricity law (TEL), which is regulated in the renewable energy act (EEG)[2] and the combined heat and power act (KWKG)[3]. The main goal of the TEL is to create a legal framework to increase the amount of locally produced and consumed electricity from renewable energy sources. Doing so, the law regulates and incentivizes landlords of MFBs to invest in PV-systems and CHP-units in their buildings and to operate as electricity provider for the tenants in a tenant electricity model (TEM). In this TEM tenants can voluntarily participate and directly consume the self-produced electricity in their building and can reduce their spending for electricity. According to TEL, landlords operating a TEM have to offer electricity to participating tenants at least 10% cheaper than the retail prices of the local basic electricity provider (BEP). As 52.4% of the German apartment stock is rented and about 80% of these are located in MFBs [1], TEMs might have a substantial effect on the future electricity mix in Germany. This paper evaluates the energy system of a MFB within the special framework of the TEL. It computes the maximum net present value (NPV) of the energy system from the landlord's point of view considering PV, CHP, energy storage technologies, a varying number of electrical vehicles (EVs) and the current legal framework. For applying the constructed model a MFB in Karlsruhe, Germany, built in 1978 and with 10 apartments is used. The results of this paper address the following questions:

(i) How does the TEL influence the optimal sizing and operation of an energy system in a MFB?

(ii) How do EVs and different charging strategies influence the profitability of a TEM and the layout of an energy system?

(iii) How does the TEL influence the tenant-landlord relationship?

To answer these questions, a mixed-integer optimization model (MILP) is implemented. The model maximizes the NPV of a landlord's investment and determines the optimal sizing and dispatch of the electricity generation and storage units. The analysis varies the number of EVs, charging strategy and the tenants' electricity price. Rent levels and building operation costs are not considered.

In the following, section 2 gives a short overview of the TEL and its economic framework as well as a summary of recent studies on energy systems modeling in MFB and landlord's investment decision processes. In section 3, the methodological approach and the optimization model are presented. Then, section 4 presents the model results and section 5 discusses these results and gives a critical reflection on the methodology. Finally, section 6 gives concluding remarks and an outlook on topics of future research.

2. State of the art

The TEL regulates that, if landlords operate the PV-system or CHP-unit, they act as an energy provider for the tenants. Landlords must provide electricity to a fixed price either directly-produced or coming from the grid. The electricity contract has a maximum run-time of one year and has to be renewed thereafter. Additionally, participation cannot be linked to the rental agreement, thus, participation in a TEM is voluntarily. The following requirements need to be fulfilled in order for a TEM to conform to the TEL.

- Self-produced electricity must be consumed in immediate geographical proximity.
- The public grid must not be utilized for the transmission of self-produced electricity for direct consumption.
- Electricity prices for tenants must be less than 90% of the price of the BEP

Conformance to these requirements enables to profit from the following subsidies:

- Exemption from grid fees, levies and taxes on directly-consumed electricity except the EEG-surcharges.
- A tenant electricity premium (TEP) is paid to the PV-operator for directly consumed PV-electricity. A similar premium is paid for direct consumption of CHP-electricity.

In scientific literature the TEL is investigated by the following authors. [4] and [5] give a compact overview of the TEL for PV-self-consumption. [6] present possible business cases and discuss the socio-cultural hurdles of implementing a TEM with PV-generation. [7] present the legal and economic framework for a CHP-use case. [8] present a comprehensive collection of studies on the TEL. Among the different articles, [9] elaborate on the political background of the TEL and discuss future developments. [10] analyses the profitability of a TEM utilizing a PV- and CHP-generator with a fiscal focus. A variety of scientific publications focuses on a model-based approach to study PV-self-consumption and CHP integration in buildings. A comprehensive number of studies analyzes the self-consumption of PV-energy in buildings. While most studies focus on SFBs, considerably fewer optimize the energy system in MFBs. [11] simulate the energy system for four different building types considering the PV- and heating installations. They focus on the increase in self-consumption and found out that the installation of PV on a large-residential building can yield higher returns on investment than smaller buildings due to higher self-consumption rates. [12] investigate the cost-optimal energy system of a new MFB in Germany. They apply a MILP-Model to identify the cost-optimal investment and operation of the system. They conclude that the installation of a CHP-unit and a PV-system is optimal as they complement each other. The high heat demand in winter and the resulting high electricity output of the CHP-unit correlates with low energy production of the PV-system, vice-versa in summer. Similarly, [13] formulate a MILP to determine the optimal size and operation of an energy system for heat and electricity supply. They model the German market and legal framework accurately but do not consider EVs nor a TEM.

[14] is identified as the only peer-reviewed publication mentioning the TEL. [14] study the electricity self-supply of a MFB with non-subsidized PV-electricity with and without an energy storage in Austria and Germany. The authors use a multi-objective MILP approach to minimize electricity cost and maximize self-consumption. Furthermore, they investigate the tenant-landlord relationship for different values of the weighted average cost of Capital (WACC). The WACC considers increase in operational cost and rent. While [14] raise an interesting research question, they do not apply their model to the specifics of the German TEL TEL. Neither do they consider heating nor electric mobility. [15] present a comprehensive Excel-tool for a detailed description of the TEL regulations. With only minor flaws, the tool is suited to obtain a quick assessment of the profitability of individual technology combinations, while EVs are not taken into account. Nonetheless, one can observe deficiencies in scientific publications that properly asses the energy system of MFBs. Especially the influence of the TEL and EVs has rarely been studied.

Investment decisions in building service equipment such as PV, CHP, batteries with a service life of more than 15 years are considered long-term investments. These decisions are based on diverse economic objectives or management strategies and are set depending on individual preferences and building future prospects[16]. Apart of the economic expectations related to personal attitude or enterprise philosophy, other tangible and intangible criteria such as comfort, eco-friendliness and reputation can be decisive criteria[17]. However, actuarial return, payback assessment, NPV and visualization of financial implications are the methods of choice in building related investments decision-making[18]. From both perspectives of owner-occupier and landlords, an optimization of the NPV is regarded as adequate[18]. Despite the appropriateness of a NPV based approach, most of the identified studies do not maximize it.

Before encountering the decision-making situation, awareness and acquaintance with the TEL are perquisites. Then, motives and barriers trigger the decision making process. These can vary across landlords. For more details on motives and barriers in retrofit and for investments into building service equipment refer to [19, 20, 17, 21, 22, 23].

3. Methodology/Model

The model used to determine the energy system of the MFB is based on [24]. They developed an MILP model to identify optimal design and operation of the energy supply system of a residential building. The model calculates the energy flows in the system in an hourly resolution to match the households' energy demand for one representative year. For determining the optimal system layout and operation *NPV* maximization is set as objective and calculated over a time period of 20 years. The decision variables are energy flow, the size of the technological units and the binary variables for the operation of the CHP-unit as well as the differentiation between different remuneration levels. A schematic overview of the modelled energy system is given in figure 1. The model is implemented in Matlab and solved with the CPLEX solver.

For this paper, multiple EVs are implemented in the model and modelled according to [25]. The *NPV*

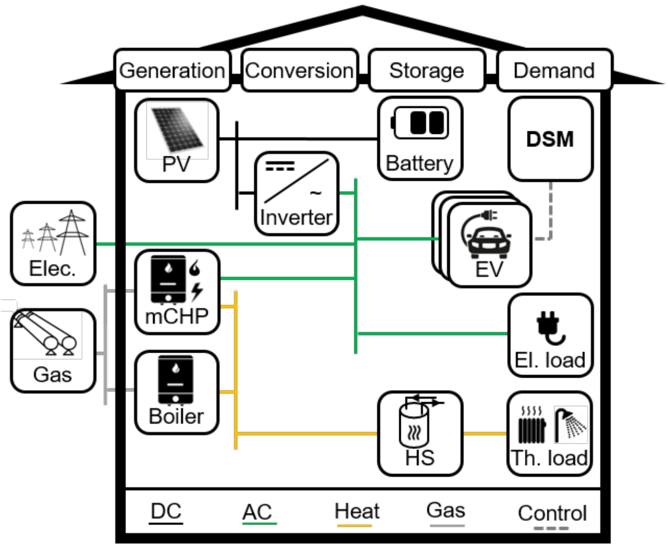

Figure 1. The modelled energy supply system (Elec:electrolysis, FC: fuel cell, el: electrical, th: thermal)

(equation 1) is the difference between the discounted investment (C^l_{inv}) and the discounted annual cash flow (acf). The investment for each technology l in equation 2 consists of an initial investment in the year $a = 0$, a discounted reinvestment after the calendar lifetime (clt) of technology l is reached and a discounted residual value after the considered investment period A. The annual cash flow is represented in equation 3. It includes a term for operation and maintenance, which is a percentage of the installed capacity (cap^l). Hourly electricity flows (P^t) are differentiated between electricity directly consumed ($P^{t,l}_{direct}$) and fed into the grid ($P^{t,l}_{feedin}$) for every technology l. The technologies considered are PV, CHP, a battery storage system and electricity from the grid. Therefore, the cost for directly consumed electricity $c^{l,a}_{direct}$ can be positive as in the case of PV or negative for the grid. Furthermore, except for c_{feedin} the electricity prices rise every year by a fixed rate r_{el}. Finally, the model considers variable costs ($c^{l,a}_{el,prod}$) due to electricity production ($P^{t,l}_{el,prod}$) as in the case of the CHP.

The specific costs and earnings for directly consumed electricity are further explained in equation 4, 5 and 6. Equation 4 shows the earnings for directly consumed PV-electricity. The landlords' earnings are compiled of the tenants' electricity price (c_{tenant}), a percentage of the price of the BEP (c_{basic}), and the tenant electricity premium(c_{TEP}). Their expenditures consist of the EEG-levy (c_{EEG}), value added taxes (VAT) and cost for metering and invoicing ($c_{M\&I}$). (The tenant electricity premium and the feed-in tariff are gradually reduced from a size of the PV-system smaller than $10kWp$, smaller than $40kWp$ and smaller than $100kWp$.) For CHP, equation 5 is composed similarly. There is a CHP-premium for directly consumed electricity (c_{CHPP}) and a premium for avoided grid charges (c_{AGC}). For electricity from the grid, landlords have to pay electricity fees of their electricity provider ($c_{landlord}$) and simultaneously sell the purchased quantity to the tenants for the TEM retail price (c_{tenant}).

$$\max NPV, NPV = -\sum_{l\in L} C^l_{inv} + \sum_{a=0}^{A} \frac{acf^a}{(1+i)^a} \tag{1}$$

$$C^l_{inv} = c^{l,a=0}_{inv} \cdot cap^l + \frac{c^{l,a=clt^l}_{inv} \cdot cap^l}{(1+i)^{clt^l}} - \frac{clt^l_{rem}}{clt^l} \cdot \frac{c^{l,a=A}_{inv} \cdot cap^l}{(1+i)^A} \tag{2}$$

$$acf^a = \sum_{l=1}^{L} -c^l_{O\&M} \cdot cap^l + \sum_{t=1}^{8760} (P^{t,l}_{direct} \cdot c^{l,a}_{direct} + P^{t,l}_{feedin} \cdot c^l_{feedin} - P^{t,CHP}_{el,prod} \cdot \frac{c^{CHP,a}_{el,prod}}{\eta^l}) \tag{3}$$

$$c^{PV,a}_{direct} = c^a_{tenant} + c_{TEP} - c^a_{EEG} - VAT - c^a_{M\&I} \tag{4}$$

$$c_{direct}^{CHP,a} = c_{tenant}^{a} + c_{AGC}^{a} + c_{CHPP} - c_{EEG}^{a} - VAT - c_{M\&I}^{a} \quad (5)$$

$$c_{direct}^{grid,a} = c_{tenant}^{a} - c_{landlord}^{a} \quad (6)$$

The assumed prices are based on the year 2018. The input parameters are shown in the appendix table 2. The building is assumed to be in Karlsruhe, Germany, TRY-region 12 (test reference weather year of the DWD). The building consists of 10 apartments with a total number of 38 occupants. The area of the roof is $176m^2$, the total electricity consumption per year without EVs is $44,666kWh$ and the total heating consumption is $92,517kWh$ for space heating and $27,208kWh$ for domestic hot water. The driving profiles of the EVs are derived from the German mobility panel[25]. For the analysis, the number of EVs is varied between 0 and 6 EVs. Additionally, the tenant electricity price is altered. The values range between 85% and 90% of the BEP price. The results are compared using the *NPV* for the landlords' and the discounted energy cost savings (ΔC_{el}) for the tenants' point of view for all households over the investment period. ΔC_{el} defines the difference between the electricity cost for a reference price ($c_{el,tenant,ref}$) and the energy cost for the TEM electricity price.

4. Results

Table 1 shows the model results for an increasing number of EVs. The upper part of the table shows results of an optimized charging strategy and the lower part results of fast charging strategy, where EVs are charged with its full power capability as soon as the EV arrives at the home charging station. The results show that the *NPV* increases with a higher number of EVs. More EVs lead to a higher total energy demand ($44.7MWh$ per year for zero EVs, *EV0*, and $51.7MWh$ for six EVs, *EV6*), which leads to a higher self consumption rate. The objective function states that directly consumed electricity generates higher profits than feeding electricity into the grid or buying it from the grid. The effect is most visible comparing the optimized and fast charging strategy. In the optimized strategy, the model has a certain amount of freedom to decide when to charge the EV. Therefore, it shifts many charging periods into high PV- and CHP-production periods, resulting in up to 13% higher self-consumption rates for the optimized case compared to fast charging. In the latter fast charging case, the model has no freedom to decide on the EV charging periods. Furthermore, only in the cases of four or more EVs and optimized charging, it is profitable to install PV-systems bigger than $10kWp$. Above this threshold, the feed-in tariff decreases from $0.122€\backslash kWh$ to $0.1187€\backslash kWh$. The higher investment for a bigger PV-system is only feasible when the self-consumption rate increases substantially. In contrast in the fast-charging-case, the self-consumption rate increases only slightly and no PV-system greater than $10kWp$ is installed. On the other hand for six EVs, the installed CHP-capacity in the fast-charging-scenario is greater than in the optimized-charging-scenario. This can be explained through the overlap of charging-periods and heat-production-periods. Noteworthy, in none of these cases does the model install a battery storage system.

Figure 2 shows the discounted cash flows for the investment period of the respective energy system component over 20 years and the resulting *NPV*. A shows the optimized charging strategy and B shows the fast charging strategy, both for six EVs and 90% of the BEP price. The figure shows that investment in a PV-system by itself is already profitable. However, a TEM with both a PV-system and a CHP-unit creates a higher NPV. The figure shows that the highest expenditures and returns are generated by the CHP-unit. The earnings from CHP are divided into a thermal and an electric component. The operational costs for heating from CHP are passed on to the tenants. The model dimensions the CHP-unit to maximize the directly consumed electricity and reduce its feed-in. This can bee seen in the difference from graph A to B. In B, the optimized charging of the EVs reduces the fed-in electricity of the CHP to zero.

In the presented scenario, electricity consumed directly from the grid generates a positive cash flow. This is explained by the positive difference between tenants electricity price and grid purchase price. Due

Optimized charging		***EV0***	***EV1***	***EV2***	***EV3***	***EV4***	***EV5***	***EV6***
NPV	$k€$	23.3	23.8	25.9	27.7	30.6	31.1	31.9
ΔC_{el}	$k€$	14.9	15.0	15.5	16.0	16.9	17.0	17.2
cap^{PV}	kW_p	10.0	10.0	10.0	10.0	13.2	13.6	14.5
cap^{CHP}	kW_{el}	4.6	4.6	4.6	4.6	4.7	4.8	4.8
$r_{self-consumption}$	%	46.3	46.8	48.9	50.7	52.7	53.0	53.5
$r_{self-coverage}$	%	77.5	77.6	78.4	78.8	81.9	82.4	83.0
Fast charging								
NPV	$k€$	23.3	23.8	24.2	25.0	26.2	26.4	26.7
ΔC_{el}	$k€$	14.9	15.2	15.4	15.9	16.7	16.8	17.0
cap^{PV}	kW_p	10.0	10.0	10.0	10.0	10.0	10.0	10.0
cap^{CHP}	kW_{el}	4.6	4.7	4.7	4.9	5.0	5.1	5.1
$r_{self-consumption}$	%	46.3	46.5	46.7	47.0	47.3	47.4	47.5
$r_{self-coverage}$	%	77.5	76.6	76.2	75.8	74.3	74.1	73.8

Table 1. Results for multiple EVs and a tenant electricity price of 90% of the BEP price. The upper results show an optimized charging strategy and the lower results a fast charging strategy.

to economies of scale the landlord is able to obtain a lower grid purchase price than the respective tenant would be able to negotiate for his sole purchase quantity. At prices below 87% of the BEP, landlords have to spend money. Nevertheless, the financial burden for the landlord is minor.

Figure 3 shows the results of varying tenants' electricity prices in percentage of the BEP price for the 10 participating households with 6 EVs. The solid and dashed line indicate the landlords' NPV of the optimized charging strategy and the fast charging strategy respectively. The dotted line indicates the discounted electricity cost saving(ΔC_{el}) of the tenants, optimized and fast charging. In case of fast-charging, at around 88% the NPV is almost as high as ΔC_{el}. Increasing c_{tenant}, the investment is more beneficial for the landlord than for the tenants and vice versa. If tenants would agree to charge their EVs in an for the landlord optimized manner the NPV of the landlords would rise while ΔC_{el}would remain the same. In the optimized scenario, to reach a state where the NPV and $\Delta C_{el}$are equal, c_{tenant} would need to be reduced to 87%. In this state, the NPV is still higher than following a fast-charging strategy at c_{tenant} of 89%. The findings emphasizes the symbiotic relationship between landlords and tenants.

5. Discussion and critical reflection

The results show that for MFBs PV-systems and CHP-units are complementary technologies. This is in line with findings of [12]. Under current prices, the installation of a battery storage system is not profitable. Simultaneously, integrating EVs in the system leads to a higher energy demand, which increases the profitability of the TEM. When the demand increase coincides with a higher degree of demand flexibility, as for the optimized charging process of EVs, even greater NPVs can be reached. For this case, it is more profitable to install more PV-capacity than a greater CHP-unit. The heat demand constrains the capacity expansion of the CHP-unit. Furthermore, the results show that the profitability depends strongly on the self-consumption rate. This rate depends on the electrical load of the households and eventually on the EV-charging pattern. Therefore, assuming perfect foresight and a representative load profile offers a high degree of uncertainty. Moreover, the financial risk of landlords for buying electricity from the grid is low. As a result, the highest risk is in over-sizing the technology dimensions resulting in low self-consumption rates. Additionally, the findings emphasizes the symbiotic relationship between landlords and tenants. Usually, these parties are trapped in an principal-agent dilemma (landlord-tenant dilemma), which is based on opposing interests. The results show that a reduction of the tenant electricity prices would increase the electricity cost savings for tenants. This could be an incentive for tenants to follow an optimized charging strategy. Ultimately, this could lead

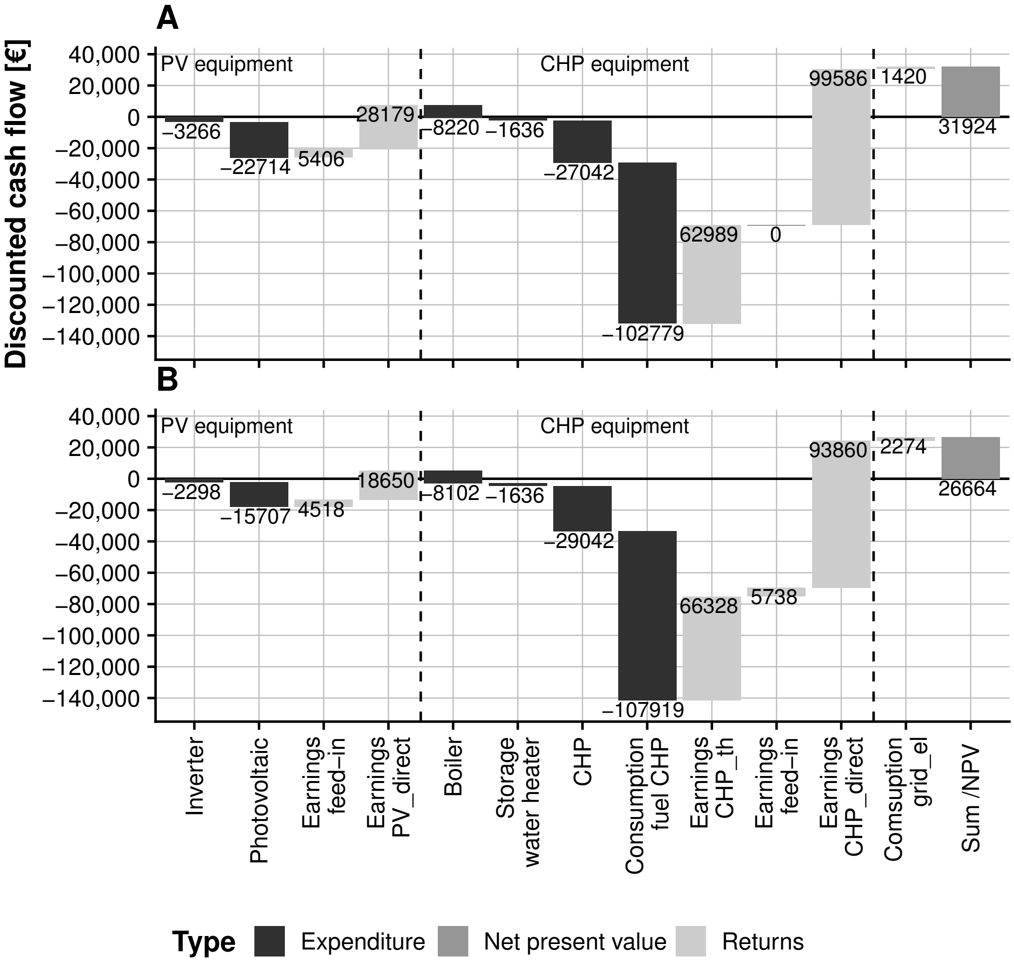

Figure 2. Discounted cash flow and *NPV* sorted by system components and operation (six EVs, $c_{tenant} = 90\%$). A shows optimized charging strategy, B shows the fast charging strategy.

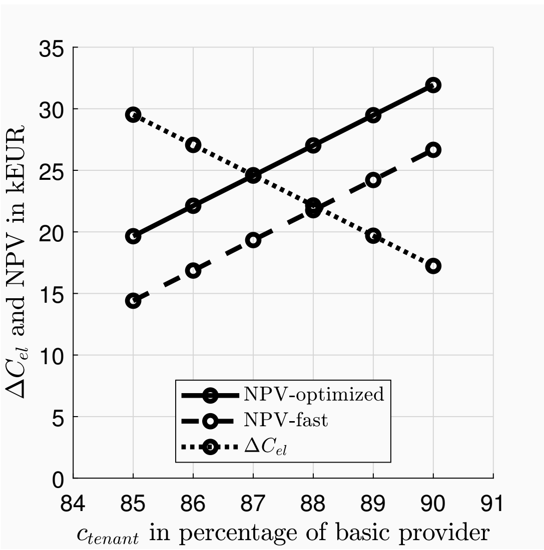

Figure 3. NPV and ΔC_{el} for 6 EVs for varying c_{tenant} in percentage of electricity price of the basic provider. Shown is the case of optimized charging and fast charging for six EVs. (The lines are for graphical understanding and do not resemble model results.)

to an increase in the NPV, electricity cost savings and CO_2-mitigation. The current installation rate of PV-systems that participate in a TEM in Germany since 2017 is constant. The total installed capacity is $9.74MW$[26]. It seems that awareness and acquaintance with the TEL is the most prominent hurdle for its successful implementation. While this contribution considers solely the NPV, a more detailed insight into other economic performance indicators could reveal different effects. Finally, some of disputable assumption and constraints of this study are mentioned in the following. For the analysis all tenants participate in the TEM continuously over the investment period of 20 years. Then, landlords profit from scaling effects and acquire electricity to better conditions than tenants. An electrical and heating load of one year is used, as well as driving and charging behavior of EV-owners. The EV-charging infrastructure is given and integrated into the MFB's electricity grid. No additional grid charges are considered.

6. Conclusion and outlook

With their high energy demand, MFB are well suited to make a substantial contribution to the German energy transition. The newly introduced TEL incentivises landlords and tenants to increase the self-consumption rate for directly produced electricity from PV-systems and CHP. This paper investigates the optimal energy system for a MFB that applies a TEM. The objective is to maximize the NPV for landlords considering a varying number of EVs. The EVs are charged with an optimized or a fast charging strategy. Additionally, the tenant electricity price is varied between 85% and 90% of the BEP price. For future studies, one should apply a holistic approach that includes heating and building refurbishment. The results indicate that he profitability depends strongly on the heat driven dispatch of the CHP-unit. Additionally for general applicability of the results, future studies need to consider different building types, construction ages and renovation states. They should focus on different locations, varying PV-potential, different electric load and heating load resulting in a alternate CHP-potential. Furthermore, investigations should be conducted that consider the variety of decision making techniques for investors in the building sector. Finally in order to properly assess the tenant-landlord relationship, other factors as rent and operational costs need to be included.

7. Appendix

Parameter	Unit	Value
$c_{el,basic}$	€$\backslash kWh$	0.2946
$c_{el,landlord}$	€$\backslash kWh$	0.2551
$c_{el,tenant,ref}$	€$\backslash kWh$	0.2858
c_{EEG}	€$\backslash kWh$	0.1134
c_{gas}	€$\backslash kWh_{el}$	0.066
$c_{inv}^{PV,a=0}$	€$\backslash kW_p$	1350
$c_{inv}^{inverter}$	€$\backslash kW$	250
c_{inv}^{CHP}	€$\backslash kW_{el}$	5000
$c_{inv}^{battery,a=0}$	€$\backslash kW_{el}$	600
c_{inv}^{boiler}	€$\backslash kW_{th}$	175
A	*years*	20

Parameter	Unit	Value	
i	%	4	
r_{el}	%	2	
c_{TEP}	€$\backslash kWh$	0.037	$cap < 10kW$
c_{TEP}	€$\backslash kWh$	0.0337	$cap < 40kW$
c_{TEP}	€$\backslash kWh$	0.0211	$cap < 100kW$
c_{feedin}^{PV}	€$\backslash kWh$	0.122	$cap < 10kW$
c_{feedin}^{PV}	€$\backslash kWh$	0.1187	$cap < 40kW$
c_{feedin}^{PV}	€$\backslash kWh$	0.1061	$cap < 100kW$
c_{CHPP}	€$\backslash kWh$	0.04	$cap < 50kW_{el}$
c_{AGC}	€$\backslash kWh$	0.001	$cap < 50kW_{el}$
c_{feedin}^{CHP}	€$\backslash kWh$	0.11826	$cap < 50kW_{el}$

Table 2. Input parameters

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Implementing sustainable sourcing in construction: Results of a current analysis of the Austrian market

Wall J[1,2], Hofstadler C[2]

[1]Ed. Züblin AG, Europa-Allee 50, 60327 Frankfurt am Main, Germany
[2]Institute of Construction Management and Economics, Graz University of Technology, Lessingstr. 25/II, 8010 Graz, Austria

johannes.wall@zueblin.de

Abstract. Achieving the UN sustainable development goals, construction industry shows a great potential. Since 50% of the total resource consumption and 40% of the entire energy demand in the European Union are caused by the construction sector, procurement processes indicate a crucial starting point improving sustainable construction. Currently, organizations struggle with implementing sustainable procurement processes. Missing information on sustainability issues can be stated as an important problem in the sourcing procedure. Consequently, interactions of planning processes and sustainable procurement represent a fundamental topic. To investigate the current situation on procurement especially in Austria, an expert survey has been carried out. Therefore, a set of three central research questions has been elaborated that could be evaluated by a detailed survey. Based on the detection of relevant stakeholders, by means of a standardized online-questionnaire the implementation of life cycle-oriented sustainability issues has been surveyed. The contribution is going to illustrate the current situation of lifecycle-oriented planning, awarding and tendering of construction works in Austria. Furthermore, deductions were made based on the results of the survey, indicating action areas and presenting future potential of the application of building information modelling.

1. Introduction

Fighting climate change is one of our main contemporary tasks. The United Nations stated 17 sustainable development goals to adopt 'The 2030 Agenda for Sustainable Development' [1]. Several of these goals emphasize the importance of construction and building industry in this context. For instance, goal number 7 'affordable and clean energy', number 9 'industry innovation and infrastructure' along with goal number 11 'sustainable cities and communities' and the overall target of goal number 13 on 'climate action' are further linked to construction activities. Approximately 40% of the global energy use is related to buildings as well as 50% of the resource consumption can be linked to construction activities [2].

1.1. Sustainable procurement and sourcing

After determining the requirements for a future building and stating the demands based on its usage, the procurement stage begins on how the conceptional design should be developed further in what specific contractual arrangement. Procurement sets up legal boundaries, based on the specific conditions within a project is going to be developed. Thus, the procurement process represents an important starting point for implementing sustainability issues. Therefore, over the last few years several initiatives on European and national level targeting public responsibility have been published; cf. COM 96 (583) final and COM 98 (143) final. Focussing on the integrations of environmental aspects in public procurement the European directive 2004/18/EC supports the awarding of contracts based on the most economically advantageous tender. Following this approach, specific criteria have to be provided, supporting the decision-making process during the awarding stage, to reach the goals of a sustainable development focusing on a life-cycle performance. Supporting sustainable sourcing, the European directive 2014/24/EU enables such a procedure by empowering a more life-cycle orientated perspective in terms of highlighting specific awarding criteria.

1.2. Role of public authorities

Public procurement especially indicates a main driver for implementing sustainability aspects into the sourcing processes of construction services. Due to market size and the potential related to public contractors, the public sector should lead the market and influence the private sector towards a more sustainable building supply chain. But focusing the practical implementation a different view arises. The current procurement process within harsh and competitive market conditions is characterized by a strong focus on emphasizing financial issues.

2. Methodology

Investigating the current situation and getting a better understanding of the challenges on public procurement, sustainable sourcing in construction and building industry an expert survey has been carried out, focusing the current situation in Austria. Therefore, a set of three main research questions has been elaborated:

- What's the situation of sustainable procurement and sourcing of construction works in Austria?
- What are the main requirements, to facilitate sustainable sourcing in the construction and building sector?
- How can data-information management tools like building information modelling support sustainable sourcing in construction industry?

To investigate and evaluated these main research questions an online-questionnaire has been developed. The aim of the expert survey was to use an empirical primary data collection, for generating valid data to understand the relationships of planning, tendering and awarding processes regarding the consideration of sustainability aspects.

2.1. Research design and questionnaire development

The questionnaire was developed based on previous explorative studies [3] [4] serving as an extensive question pool for the current survey. Additionally, a comprehensive literature review on sustainable public procurement has been conducted [5]. These measures have been part of a major research project at Graz University of Technology on sustainable design processes and integrated facades [6].

The questionnaire comprised five parts as shown in Fig. 1. General questions are covered in part 1. Part 2 focused on notions and concepts of sustainable and life-cycle orientated buildings. Part 3 targeted the design process. Part 4 concentrated on tendering and awarding aspects. Finally, part 5 considered the implementation of building information modelling in the context of sustainable building.

According to the classification of experts, the questionnaire was structured into three different paths (clients and planners, researchers and legal experts), allowing the participants to answer only questions related to their field of expertise and professional activity.

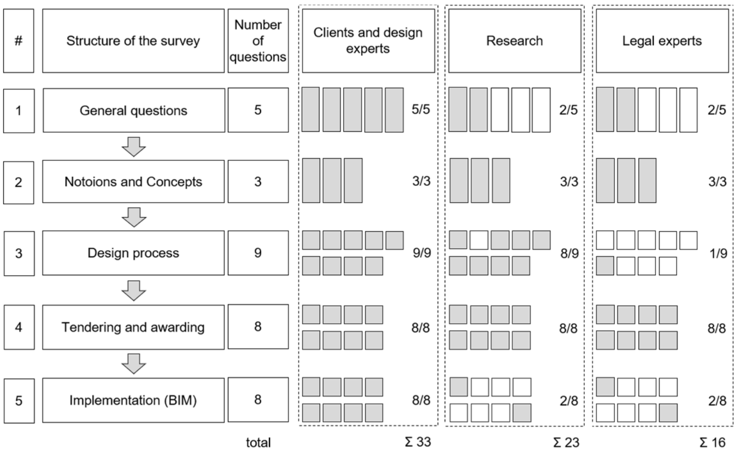


Figure 1. Structure of the questionnaire.

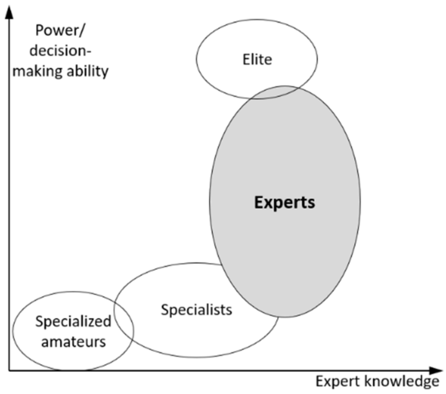


Figure 2. Definition of experts.

2.2. Selection of participants

Conducting an expert survey, it is crucial to identify appropriate participants by answering the following questions: Who is an expert for the specific subject area? Who got relevant information? Who is able and ready to provide and share this information? Experts can be characterized with many years of experience in a responsible and senior position related to subject-specific knowledge of the implementation of sustainable construction. Furthermore, experts are people with special knowledge, insights and information as well as contributing significantly to the decision-making process; illustrated in Fig.2 [7]. The chosen experts have been associated to the sphere of the client, representing the view of the contracting authorities and their agents.

The survey was conducted in April and May 2017. Overall 320 experts have been invited and 96 participated (in terms of complete replies to the questionnaire). The demographic information revealed that respondents could be classified into the following groups: public clients (30%), project controlling and management by clients (17%), designers (21%), researchers (10%), consultants and experts (12%), legal experts (5%), and the remaining 5% could not be assigned further. The respondents possessed 21 years of work experience in average. They majority of them is in an executive position (managing director, head of department, project manager) and all of them are involved in implementing sustainable construction.

3. Results

In the following section selected results from the survey are shown. Starting with general statements about the situation of sustainable procurement in Austria, followed by a closer examination of planning processes. Also, the level of implementation and the role of building information modelling is presented.

3.1. General statements on sustainable procurement in Austria

Despite the fact, that public authorities are addressing sustainability through a wide range of strategies and initiatives, the survey illustrated that implementing sustainable sourcing seems to be limited to individual aspects (e.g. energy efficiency) - an integrated holistic concept is often missing. That's because of insufficient consideration and implementation of sustainability aspects in early design stages. Referring to this, the survey showed, a prevalent application of sequential planning processes. Which means, each planner only focuses on his area of expertise, without taking contributions from others into account and not valuing possible interactions to improve a common project goal. As a result, only limited quantifiable issues and methods being used for sustainable sourcing. Establishing a sustainable sourcing process, awarding and selection criteria are key elements for sustainable procurement justifying the tendering decision, therefore the planning stages are crucial to identify such issues.

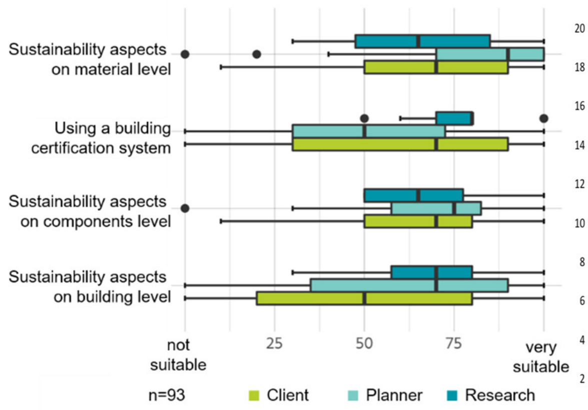
The current practical situation on sustainable sourcing can be characterized by considering sustainability issues mainly as individual ones without a common implementation and reference to the whole building performance.

3.2. Importance of the design process

Furthermore, the results of the survey showed, that the design process is very crucial for setting up the procurement process and providing evaluation and awarding criteria for sustainable sourcing. Based on various groups of experts, there is a different level of awareness, at which project stage sustainability issues should be considered. Planners need requirements and certain target values to consider these aspects during their design process. Clients have another perception, they seem less focused on sustainability aspects in early project stages, but when it comes down to the point of construction completion and commissioning, they are getting more aware of the future operational performance of the building including the life-cycle perspective [8]. However, the client is usually in charge of providing adequate information to define the specific qualities and quantities especially targeting the life-cycle performance of a building. Because without this input it is hardly possible for the design team to reach a certain quality level, when relevant information is missing.

3.3. Level of implementation of sustainability aspects

Trying to answer the question on what level sustainability aspects should be implemented, different views arise from the surveyed experts. As shown in Fig. 3, especially the planners would recommend implementing these aspects on material level. Using a building certification system is seen as a suitable approach by the group of clients and researchers. Building certification schemes as a comprehensive assessment method with a straightforward illustration on performance achievement (levels of certification depending on the respective organization range from bronze, to silver, gold and platinum) can support the communication of sustainable qualities easier compared to sustainability aspects on building level. This seems comprehensibly, especially according to the perspective of decision makers with limited knowledge on life-cycle orientated buildings.



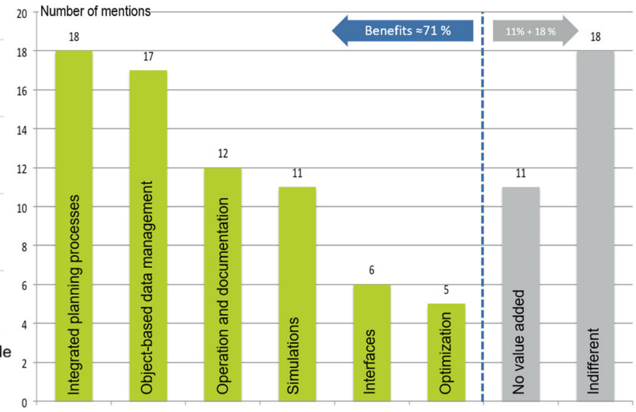


Figure 3. Implementing sustainability aspects. **Figure 4.** Benefits of using BIM.

3.4. Benefits of using building information modelling

Focusing on possible benefits of using building information modelling as a project management tool, the participants reported their expectations on improved integrated planning processes and a better object-based data management. Also, simulations and detailed coordination of interfaces are expected as benefits of using BIM as illustrated in Fig. 4. However, there are still a lot of responses reporting no real additional value or have indifferent opinions on using building information modelling.

4. Fields of action

Based on the results of the survey, specific fields of actions have been identified. In the following section three action areas have been selected and described in more detail:

- Information flow (interactions of planning and sourcing)
- Process-thinking and design
- Process support using data information management tools

4.1. Information flow

Missing sustainability aspects in sourcing of construction services are often caused by incomplete information flows between the planning and procurement stage. Improving consistency and enabling such interactions, it is crucial for the sourcing unit to understand not only the single requirements in terms of a specific label or evidence, but also the intended overall performance of the building with its elements.

The results of the study explored aspects on how procurement processes should be structured and suggested starting with the definition of requirement as a basis for the call for tender in earlier project stages to include the knowledge of different experts from the integral planning team. Applying systems thinking in such a context with consistent information flows, not only single improvements are possible but also a holistic approach can be targeted. Therefore, conventional sequential planning processes need to be considered in detail how to improve and structure interfaces for better information workflows [9]. This would enable a progressive value creating achievement as well as reducing additional expenses. Having a comprehensive knowledge on the targeted performance, improvements are possible when examining design alternatives. Collaboration in general is associated with a higher intensity of innovation.

Therefore, transparent information flows are required, which make it feasible to recognize the overall value and single contribution of each task. This helps to overcome insufficient information sharing between designers, contractors and suppliers. Doing so, process thinking becomes more significant.

4.2. Process thinking and design

Due to increasing complexity and interdisciplinarity of construction projects, especially if targeting and improving the life-cycle performance of buildings, the need arises to focus more on processes. Taking the building life-cycle performance into account, it is crucial, implementing user and operational requirements into early design stages, to allow the planners to consider these issues for a better building design.

Facilitating a holistic approach, various interfaces between the contributing disciplines and experts need to be arranged in a certain way, to maintain a value creating workflow. Therefore, several initiatives and research activities are performed to implement and improve process thinking, c.f. [10]. Additionally, over the last few years lean management principles from the production sector influenced the construction workflows. Starting at the construction site form operations planning and scheduling but focussing more and more on the detailed design and execution planning processes [11].

Lean philosophy concentrates on the elimination of all waste form a process, while targeting the maximum user value. From this point of view lean philosophy could be used as a control system to be implemented in sustainable building projects, improving the life-cycle performance of buildings. Both approaches (lean construction and sustainable building) are targeting the reduction of environmental impacts. Doing so, process thinking is necessary to focus on the value and further contribution to the overall performance. Especially if specific criteria are needed for the sourcing procedure awarding the contract.

Other helpful tools are building certification systems (e.g. BREEAM, LEED or DGNB/ÖGNI). They can provide guidance through the project workflow supporting the stakeholders to keep the overall performance in mind. Overall a collaborative workflow is determinant of the successful adoption of sustainable building.

4.3. Process modelling and visualisation (BIM)

Over the past few years digitalisation gained importance in the construction and building industry in terms of implementing building information modelling. Using BIM is expected to solve or at least reduce various problems like e.g. insufficient or missing information and poor collaboration. Still there are technical boundaries like missing connectivity and interchangeability of data and information. Based on the results of the survey, integrated planning processes and an object-based data management are expected benefits of using BIM. But to unlock these potentials, a common baseline of understanding the requirements and workflow is necessary.

Standardisation is necessary to communicate attributes and properties of building elements. There is the need of interchanging data and information on sustainable buildings, without any losses between the various stakeholders. Additionally, the properties should be interchangeable with possible suppliers fitting future requirements on e-procurement in the context of building information modelling.

Focusing on public clients, BIM should be encouraged by the government and industry to act as an information data management tool. Furthermore, transparency would be increased, supporting the information flows e.g. on building material properties, starting from the early drafts to contractors and suppliers. This would help to provide the right information to each project partner at the respective project stage.

5. Conclusion and outlook

Based on their market share and responsibility, public clients can act as a role model for several action areas on implementing strategies fighting climate change focusing the building sector. Thus, several strategies on procurement solutions are available, but their practical implementation seems to lag. Therefore, sustainable sourcing can be identified as a major issue to deal with the complex situation of supplying and purchasing in the building and construction industry, due to the various suppliers and trades involved.

Focusing on the current situation in Austria, an empirical study has been conducted. Experts in the field of sustainable construction have been queried with a standardized online-questionnaire comprised of five thematic categories: general data, notions and concepts of sustainable and life-cycle orientated buildings, design process, tendering and awarding procedures and the implementation of building information modelling.

The findings illustrate, that sustainable sourcing is currently based on single criteria or the use of building certification systems. Inconsistent information flows during the planning stages can be seen as a major reason for missing a holistic approach. A lack of incentives to adopt sustainable procurement in construction has been reported by previous studies [12].

Another result from the conducted study highlighted the importance of green procurement policies. Additionally, the need to open up the ‘golden triangle‘ of cost, time and quality to more comprehensive aspects and also targeting the life cycle perspective, taking into account the usage stages - not only focusing on the construction phase of the building.

This paper emphasized the relevance of interactions on sourcing and life-cycle orientated planning processes. Therefore, not only product/object-related aspects of construction works are important to focus, also process-orientated aspects need to be considered in more detail. Consequently, the design process needs to be targeted and arranged towards a better information flow. The main requirements are stated by the client in early design stages and the implementation of sustainability into the sourcing process is still limited to the willingness and capability of the client and how comprehensive his requirements are described in early planning stages [13].

Additionally, the responsibility of the involved stakeholder needs to be improved for stronger collaboration on the sustainability performance of a building. Facilitating such a performance-based approach, focusing the practical implementation of data-information management tools can be helpful. Therefore, BIM is just a tool, not bettering projects itself. In this context the clarification of a crucial baseline (definition of sustainable properties) and common project standards are necessary. Performance requirements can be communicated using standardized information with potential suppliers allowing them to adapt their solutions to the project specific requirements.

Further research is required on how e-procurement in context with building information modelling can support a more sustainable sourcing process [14]. But without a clear and structured workflow and a specific definition of the expected building performance at the beginning, their application doesn't seem effective. [15] Implementing sustainability starts with the know-how of all project members and a high level of collaboration.

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Business-models of gravel, cement and concrete producers in Switzerland and their relevance for resource management and economic development on regional a scale

Meglin R[1], Kliem D[2], Scheidegger A[2], Kytzia S[1]

[1] University of Applied sciences Rapperswil, Switzerland
[2] University of Applied sciences St. Gallen, Switzerland

rmeglin@hsr.ch

Abstract. Traditionally, gravel, cement and concrete producers focus on their role as material or resource suppliers. The higher the material turnover, the higher the economic success. Hence, the business-model conflicts with the societal goal of increased resource efficiency. Driven by stricter regulations, companies started to extend their business models with additional services in waste management and logistics.
In the research project "Co-Evolution of Business Strategies in material and construction industries and public policies" the most relevant business-models of gravel, cement and concrete producers in Switzerland are identified based on case studies of ten different companies. The analysis reveals how these business-models differ with regards to value added, resource consumption and CO2-emissions. To analyse the relevance of the different business-models on regional scale, an assessment model is developed based on Material Flow Analysis. It is used to analyse the value chain of construction minerals in an alpine region and its effect on value added, resource consumption, waste generation and CO2-emissions. A comparison between the results of both analyses – companies scale versus regional scale – reveals how alternative business-models could affect resource management and economic development on a regional scale and which types of business-models accelerate or hinder the transition towards a sustainable built environment. The study will show, that it is essential to identify alternative business models in the building materials industry and understand their impacts on the use of primary and secondary resources.
In this paper, we identify two business models, which, at first glance, seems identical as they produce and sell concrete and gravel, but show that the success of a business model highly depends on the source for raw-materials (gravel pit, river extraction or processing excavated materials with high gravel content), the possibility to landfill excavated material and the resulting effects on resource consumption.

1. Introduction

Traditional business models in the construction industry link economic success to material turnover. This promotes an inefficient use of natural resources and contradicts macroeconomic objectives, such as circular material flows and reduced material consumption. Decreasing construction activity and increasing competition among construction material companies provide a complex and challenging environment to these business models. Business model adjustments have been observed along the entire value chain, challenging a rather static industry. For example, building contractors become service agents in materials management of construction sites, and their turnover and profit will become more independent of the consumption of natural raw materials (decoupling of economic growth and resource consumption). This transition to a circular economy can be seen already on entrepreneurial level and regional scale in Switzerland, as an increasing number of companies focus on the preparation and use of secondary building materials. A dominant driver of this transition is the geographical and social limitation of access to natural resources, leading to fierce land competition among companies.

Yet, it is difficult to clearly differentiate between alternative business models in the Swiss building material industry. Today, a diversity of companies varying in size and degree of vertical integration can be found. Few large players with vertical integration dominate the market for concrete, ranging from the production of cement as well as concrete and aggregates. A number of innovative niche players are very strong on regional markets in urban areas with growing market shares. In recent years, some construction companies started providing material management as service on large construction sites including construction waste management, on-site recycling as well as concrete production.

- Can the success of alternative business models be explained by boundary conditions in the specific markets, in the regional supply of natural resources or incentives from public administration?

- If a business model is considered favorable in the transition towards a circular economy, can it be transferred from one region to another without losing its economic benefits?

- How does such a transition towards alternative business models affect regional resource consumption, emissions and value added on regional scale?

In the research project "Co-Evolution of Business Strategies in material and construction industries and public policies" we try to answer these questions by identifying the most relevant business-models of gravel, cement and concrete producers in Switzerland based on case studies of ten different companies. We analyze how these business-models differ with regards to value added, resource consumption and CO_2-emissions. In a second part of the research project we analyze how business model innovations can be encouraged by public policies to stimulate a transition towards a circular economy.

In this paper we present first results of our research focusing on two business models that we could identify and describe so far. The relevance these business-models on regional scale is assessed for a case study region.

2. State of research

2.1. Business-Models and transition management

In our research, we focus on the concept of co-evolutionary transition dynamics, which can be described as the developments within subsystems, influencing the development of a larger system. For example, co-evolution between science and technology, between culture and technology and between technology and society [1], or between institutions and technology [2], or between organisations and institutions [3] haven been researched. A number of studies presented empirical evidence for interdependencies between different societal subsystems, e.g. environmental regulation and the firms' competitive performance ([4],[5]), environmental taxation and resource management [6] or alternative business models (e.g. niche players) and mass market players [7]. For the case of construction materials, [8] and [9] showed the importance of planners and engineers as mediators between builders and construction industries for a transition towards resource efficiency. The importance of competing business-models in a changing regulatory environment, however, has not yet been analysed for construction material industries. We try to fill this gap in our research. In our analysis, we consider a business model as the articulation of a company's strategy [10]. Literature suggests that value proposition (product/service, customer segments and relationships); value creation & delivery system (key activities, resources, technologies, etc.); and value capture (cost structure and revenue streams)" form key components of business models [11]. Research on sustainable business models expand this traditional framework by including social and ecological value creation for an extended range of stakeholders [7].

2.2. Assessment of resource consumption, environmental impacts and value added

For the assessment of transition management in the built environment, defined as business environments for construction industries, material flow models are frequently used (an overview is given in [12]). These studies mainly focus on stock-flow-models of defined regions (e.g. Switzerland) [13]–[17], but also comparisons between nations or regions (e.g. EU 25) are available ([18], [19]). Yet, these models describe the underlying cause-effect only with coefficients related to the technical efficiency of processes involved (e.g. recovery rates). The main drivers of development are exogenous parameters such as rates of construction, demolition, or assumed correlations with socioeconomic parameters such as population number or GDP (e.g. [17]).

As a component of the analysis of material flows, Input-Output-Analyzes (IOA), in form of Input-Output-Tables (IOT) can be used in combination with environmental and economic performance indicators to form economic and environmental extended Input-Output-Tables (an overview is given in [20]). IOT, as a tool for analyzing interindustrial interdependence, have become the standard since the 1930's. At this time Wassily Leontief developed the first detailed IOT for the United States [21]. In the following decades the IO-Analyses have constantly developed. An overview of the developments of IO-Analyses gives [22]–[24]. Today IOT are used by most governments to carry out analyses of the respective national economy [25], [26].

This paper will introduce an assessment model for environmental and economic impacts in form of environmentally and monetary extended input-output-tables based on Material-Flow-Analysis (MFA). This method was first presented in [27] and is applied on scale of companies as well as regions.

3. Methods and Data

In our study, we identify and describe alternative business models combining methods from business administration as well as environmental and process engineering. In addition, we analyse a regional resource management system for construction minerals. In this section we present the methods used to collect relevant data.

3.1. Definition of criteria for classification and indicators

The analysis of business models is based on the definition of business models presented in [11] and complemented with aspects of research on sustainable business models [7]. For each company the following aspects are analysed:

Value proposition: It describes how the organization attempts to create the willingness-to-pay of its target group to pay for the offered product or services [11]. Furthermore, it describes the intended target audience, enabling evaluation whether the proposed value, relative to the company's competitors, is creating competitive advantage.

Value creation: Describing the operationalization of the company's strategy and internal value chain clarifies how the companies uses their resources and capabilities to create value for its stakeholders.

Building on aspects from research on sustainable business models, the attempt to satisfy a wider range of stakeholders, influencing consumption itself becomes a crucial aspect of corporate responsibility.

Value capture: Value capture completes the picture by examining how the company captures economic value from the consumer and the modes of transaction. Richardson (2008) highlights that economic value is especially dominant in traditional entrepreneurial literature, distinguishing between the economic and revenue model. In essence, the captured value from incorporating sustainability describes the "business case for sustainability", combining profits with positive impacts.

In addition, we analyse how each business model effects regional resource management systems, economies and the natural environment. To this aim, we define a number of indicators (see table 1). To compare different business models, we use each companies output (in tons) per year as functional unit, differentiating between two major product categories: concrete and aggregates.

table 1: indicators for the assessment

Indicator	Unit	Description
Amount of virgin gravel/sand extracted	ton per year	Most companies extract virgin gravel/sand from surface water or mine in gravel quarries. The rate of substituting virgin material with secondary resources can vary from company to company.
Amount of excavated material deposited		Excavated material is mostly used to refill empty gravel pits. In certain areas in Switzerland, however, the gravel content in excavated material is high enough to use this material as substitute for virgin gravel. In this case, natural resources can be preserved.
Amount of recycling materials used for producing construction materials		Crushed concrete and mixed construction waste can be used to substitute virgin gravel in the production of aggregates and concrete. A high content of these secondary resources the overall material input can indicate a transition towards a circular economy.
Value added	CHF per year	This value is used to indicate effects on the regional economy. It represents factor income generated by labour and capital on regional scale. For each company, this factor income is analysed for each process in the production chain (including internal transports) by subtracting material costs from material turnover, both estimated by multiplying material flows with material prices. Costs of electricity are only considered in cement production.
Global Warming Potential (GWP)	Kg CO_2 eq. per year	This value is used as indicator for environmental impacts. It is estimated for all processes in the production chain of each company including greenhouse emissions generated in the supply chain (e.g. for electricity production)

3.2. Collection of data

A case study with ten companies is used to determine the relevant business models. Each company covers a specific step in the value chain of construction minerals, ranging from extraction of primary materials, over processing virgin/recycling aggregates, producing concrete, producing cement, constructing building and infrastructures and providing services in logistics, demolition, to sorting of construction wastes and waste management. Most companies' activities in this study focus on concrete production with a variation in the degree of vertical integration as well as major resource input (primary versus secondary).

table 2: collection of data

Workshop no.	Aim of the workshop	Data collected	Methods	Reference
1	Understand fundamental business model logic	Socially and environmentally extended business models perspective	Flourishing business models canvas	[28]
2	Identify physical flows economic indicators associated with key resources, value proposition and value capture.	Material flows and respective prices and costs	Material flow analysis	[20], [29]

With each company, two workshops are carried out (see table 2). In the first workshop, the companies' business model is analysed using the business canvas introduced in [30]. Thereby, the data collection exceeds purely economic aspects and includes social and environmental dimensions. In the second workshop, material flows and production costs are analyzed using MFA on company level. The results of each workshop are discussed with the companies' representatives and validated with company internal data on material flows and costs. CO_2-emissions are assessed with data from the ecoinvent database using the indicator GWP (global warming potential) to cover all emissions relevant for climate change.

The analysis on regional scale is intended to provide a reference system for evaluating the effect of alternative business models. Yet, identifying a region for that purpose posed a major challenge. [13] showed that consumption of construction minerals varies significantly from canton to canton due to imports and exports across the Swiss border as well as between cantons. To eliminate such effects, we chose an alpine region which is self-supplied with gravel and sand as well as landfill capacity. It is densely populated with around 82'000 inhabitants and its settlement growth rate is near the Swiss average. In this region, we can identify companies with different business models. In order to ensure confidentiality of all company data, we decided not give any additional information on the region itself but to use it as a representative "model region" named ALPVAL (for "alpine valley").

The material flows in this region were assessed by interviews with representatives of all mayor companies located in the area. In addition, data was gathered from reports of the cantonal waste management authorities as well as statistics of gravel extraction from ground as well as rivers. Data on communal data was collected to additionally assess fees on gravel extraction.

3.3.Assessment of business models

The assessment of each company is based on a Material-Flow-Analysis (MFA) with data collected in workshops as described in section 3.2. Each company MFA was transferred to an Input-Output-Table (IOT) describing input, output and internal flows. IOTs were used to combine MFA data with additional information on prices of products, services and production factors and estimate factor income (value added) for each process in the production chain as represented in figure 1. For each process CO_2 eq. were estimated to assess GWP according IPCC 2013 based on data from the database ecoinvent (version 3.4) using standard datasets of gravel, concrete and construction waste in Switzerland.

4. Results

Following workshops with different companies, distinguishable features of each business model emerged. Building on features that are present in both business models, the unique attributes are summarized in table 3. To differentiate between these two idealized companies, the value proposition, value creation and value capture are further discussed. As mentioned earlier, competition for land has increased the value of accessible land for extraction and disposal purposes. The relevance of these boundary condition will further be highlighted in the remainder of the discussion.

table 3: insights and differences between the two business models

	Similar features	Distinction company A "Extraction"	Distinction company B "Recycling"
Value proposition	• Provision of gravel & concrete according to norms to construction companies. • Intake of disposable and excavation material	• Desired equilibrium between intake of disposable material and output of gravel	• Material management on construction site as service. • Vertical integration →Construction services • Development of Niche products for (1) specific application and (2) reduced primary raw material input
Value creation	• Disposal volume is profitable and scarce • Machinery and infrastructure	• Gravel extraction creates volume for disposal of material.	• Gravel extraction does not create volume for disposal. • Increase available volume for intake of disposal material with treatments • Cooperation's with engineers aim at adjusting norms in favour of recycled products
Value capture	• Sales of loose gravel/ concrete (CHF/m3) • Accept disposal and excavation material (CH/m3) • Tie incoming and outgoing deliveries	• Community management is crucial for access to key resources (land/gravel quarries)	• High quality products to increase uptake of recycling products.

4.1. Identification of idealized business models

To showcase preliminary results from this ongoing research project, two representative business models are identified and discussed: company A "extraction" and company B "recycling". Extraction, as well as recycling companies, provide raw materials for the built environment and handle the material flows that leave the building stock. Along this value chain, extraction and disposal processes are different, whereas the technical processing of raw materials is rather similar (see figure 1). The access to gravel quarries, being a key resource, appeared to be central to the extraction business model. Both business models strongly depend on the access to land, either for the storage of material before processing, or for mining purposes. The negative externalities for the local communities appear to be significant in both business model, yet the financial compensation for mining purposes has gained more traction in recent years. Thereby, a tendency of extraction companies to focus on community management to ensure long term access has been observed. Recycling companies appear to be focussed on actively influencing market demand, by promoting the uptake of recycled products among engineers and planners. Increased material turnover frees capacity to accept more valuable volume for storage and processing of excavation material.

We find that both business model builds on similar value propositions and value capture, yet fundamentally differ in terms of value creation. As both business model build on similar processes and differ mainly in the access to gravel quarries (see section 4.2), we elevate these process to a regional level to understand the systemic implication (section 4.3).

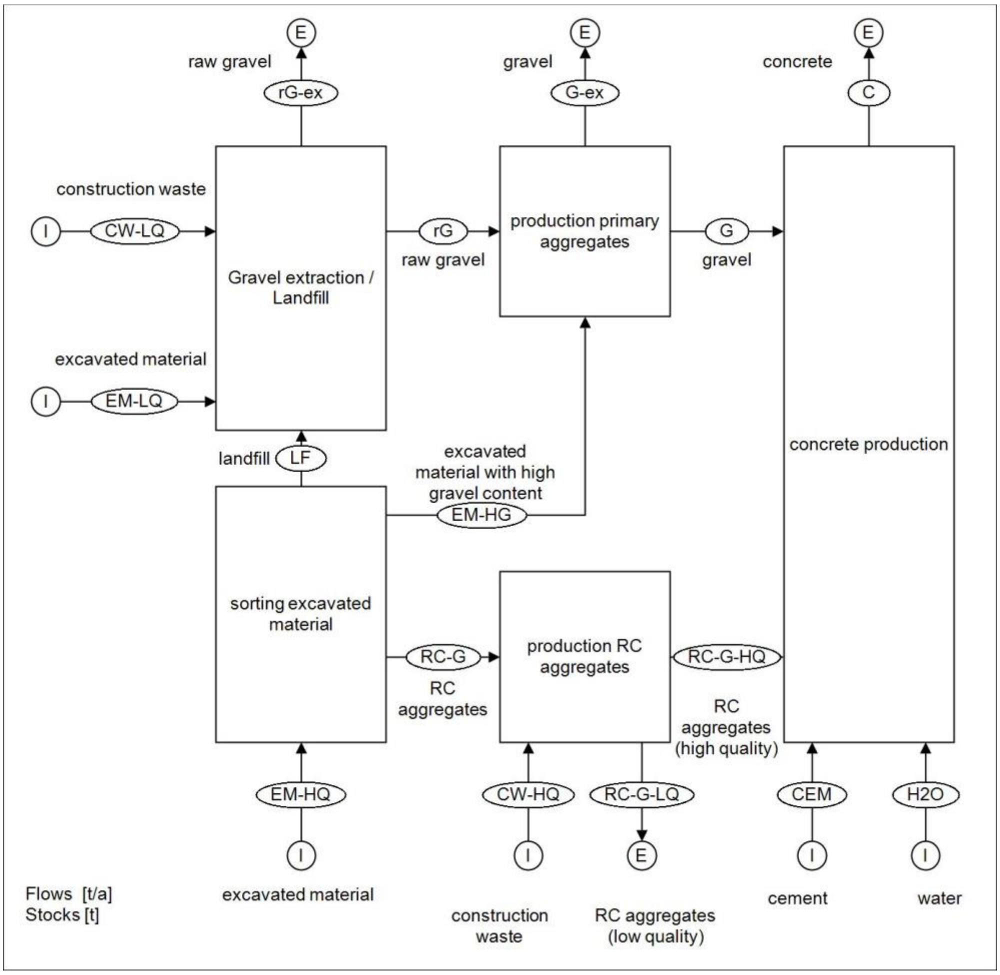

figure 1: Generalized system definition of gravel and concrete producers

4.2. Assessment of business models

Two companies were identified as representatives of the two idealized business models described in section 4.1. The company representing “Extraction” (Company A) owns several gravel pits and sells waste management services for depositing excavated materials (in empty gravel pits) and sorting and processing mineral construction waste. It sells mostly concrete and a comparatively small amount of gravel. The company representing “Recycling” (Company B) produces gravel and aggregates using virgin gravel extracted from rivers, excavated materials with a high gravel content and processing mineral construction waste. It sells concrete as well as gravel. We calculated all values for the indicators listed in table 1, but a comparison of the total numbers is not meaningful as both companies differ in product mix differs as well as total amount of material turnover.

For a meaningful comparison, value added is used as reference value. For both GWP and primary resource consumption, the performance of Company B “Recycling” exceeds the performance of Company A “Extraction” with 2.21 GWP per CHF (Company B) to 2.66 GWP per CHF (Company A) and 0.01 tons of virgin gravel per CHF (Company B) to 0.02 tons of virgin gravel CHF (Company A). To better understand these differences, we also compared the indicator values per tons of concrete and gravel produces by each company. For one ton of concrete, company A “Extraction” uses 0.49 tons of virgin gravel whereas company B “Recycling” only needs 0.32 tons. This difference is even more distinct for gravel production with 0.77 tons of virgin gravel for one ton of gravel sold (company A “Extraction”) compared to 0.44 tons of virgin gravel for one ton of gravel sold (company B “Recycling”).

To compare value added of processes in both companies, it is interesting to look at the contribution of the different processes as well as the different products. As shown in table 4, the sums of value added generated by the different products vary only slightly between the two companies. Company B "Recycling" has a higher value added for concrete and recycling aggregates than company A “Extraction” whereas company A performs better in the production of primary aggregates. In the results of the value added of the production of one ton of primary aggregate, it can be seen that the value added shifts from the gravel pits and landfill in the case of company A “Extraction” to production of primary aggregates (gravel) in the case of company B “Recycling”. This is due to the fact, that company B processes excavated material with high gravel content to produce primary aggregate and increases the value added significantly.

table 4: value added of the two companies

	Change in Value added per ton of concrete		***Change in Value added per ton of primary aggregate***		***Change in Value added per ton of recycling aggregate***	
[CHF]	**company A**	**company B**	**company A**	**company B**	**company A**	**company B**
landfill	*3.38*	-	*5.67*	-	*-1.30*	-
gravel pits	*7.34*	*4.83*	*11.50*	*6.54*	-	-
production primary aggregates	*1.58*	*7.10*	*2.47*	*12.19*	-	-
production recycling aggregates	*2.81*	*2.60*	-	-	*15.49*	*14.63*
concrete production	*19.50*	*21.60*	-	-	-	-
	34.61	***36.13***	***19.64***	***18.73***	***14.18***	***14.63***

The global warming potential according IPCC 2013 can be seen in table 5. By assuming, that both companies produce concrete with the same mix design (355 kg cement CEM II A-LL, 1855 kg aggregates and a water-cement-value of 0.53) and normalizing the material flows, company B "Recycling" has a slightly lower GWP than company A. This can be explained by the lower GWP of the production of recycled aggregates in contrast to the production to primary aggregates. It has to be noted, that the transport outside of the company, e.g. transport from construction site to the company, is not considered. It can also be seen, that the GWP is mainly influenced by concrete production due to the input of cement. Furthermore, it is interesting to see, that concrete production has a much higher impact per ton on GWP than on value added.

table 5: GWP of the two companies

	Change in GWP per ton of concrete	
[kg CO_2-Eq]	**company A**	**company B**
landfill	-	-
gravel pits	-	-
production primary aggregates	*3.13*	*2.82*
production recycling aggregates	*0.69*	*0.66*
concrete production	*99.22*	*99.22*
	103.04	***102.71***

4.3. Influence of alternative business models of regional scale

The results of regional MFA for construction minerals is shown in figure 2. It includes the following processes:

Gravel pits/landfills: In ALPVAL gravel is extracted from rivers as well as traditional gravel pits, that are also used as landfills to deposit excavated material from construction sites. In 2018, the amount of gravel extracted exceeds the amount of excavated material deposited.

Production primary aggregates: Primary aggregates are produced with either virgin gravel/sand from gravel pits and rivers or excavated material with a high content of gravel. This is a typical situation for an alpine valley where glaciers deposited virgin gravel on the entire valley bottom during ice age. The majority of aggregates is used to produce concrete.

Production RC aggregates: RC aggregates are produced with mineral construction waste. High quality aggregates (mostly from crushed concrete) are used to produce concrete; low quality aggregates are used for road construction and similar purposes.

Concrete production: Only 14% of all concrete in the region is produced with RC aggregates. All concrete is used in regional construction.

Building stock: The building stock is still growing as the amount of construction minerals used exceeds the amount of construction waste. Yet, there is a significant amount of excavated material generated in construction. Only a minor share of construction waste is landfilled.

Sorting excavated material: This process is defined to simplify material balancing. In reality, sorting takes place on the construction sites and is determined by the capacity of companies to use excavated materials with high gravel content to produce primary aggregates.

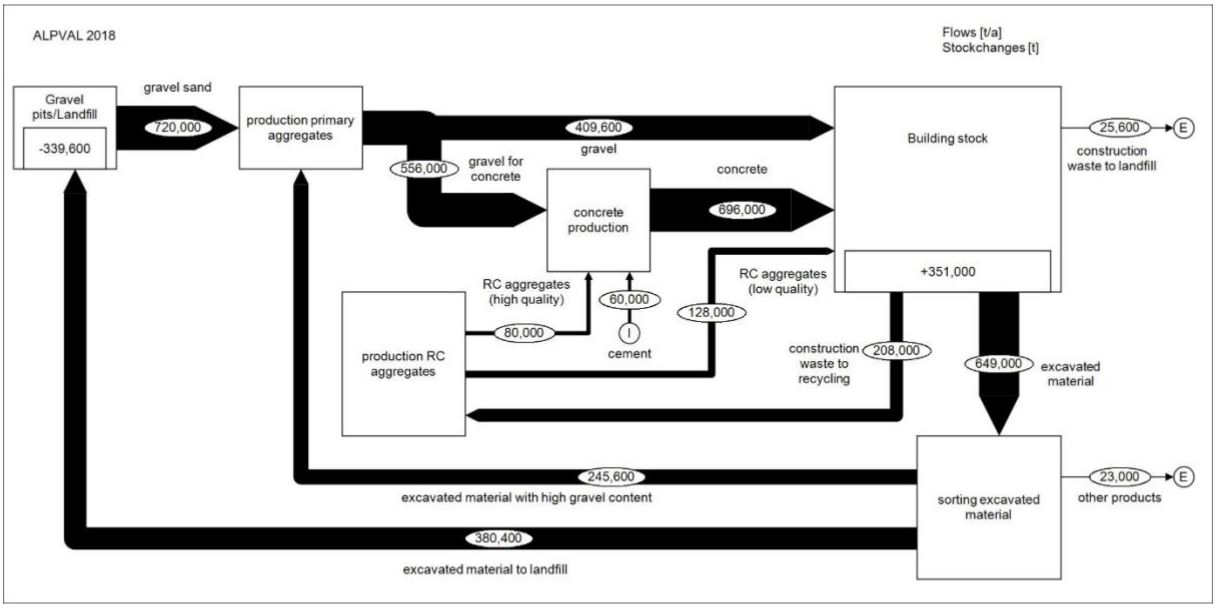

figure 2: material flows of the region ALPVAL

To assess the impact of alternative business models on regional scale, we analyse two alternative scenarios and compare it to the status quo presented in figure 2:

Scenario A: All concrete and gravel produced in ALPVAL is produced by company A "Extraction"
Scenario B: All concrete and gravel produced in ALPVAL is produced by company B "Recycling"

Table 6 presents the results of the scenario calculation. It shows that the amount of virgin gravel/sand extracted per year decreases in both scenarios: by 44% in Scenario B "Recycling" and in Scenario A "Extraction". This implies that the company we chose as representative for the business model "Extraction" uses more secondary resources than the average company in ALPVAL. Yet, it also deposits more excavated materials per year than an average company in ALPVAL because a smaller share of virgin gravel is gained by processing excavated materials. In scenario B "Recycling" no excavated material is deposited because the entire amount is used in gravel production. The amount of recycling materials used in production increases in both scenarios.

table 6: comparison of the companies on a regional level

	status quo	Scenario A	Scenario B
Amount of virgin gravel/sand extracted (tons per year)	720'000.00	656'432.00	402'944.00
Amount of excavated material deposited (tons per year)	380'400.00	485'264.00	0
Amount of recycling materials used for producing construction materials (tons per year)	208'000.00	253'280.00	253'280.00
Value added (CHF per year)		33'948'144.00	34'690'928.00
Global Warming potential (kg CO2 eq per year)		71'715'840.00	71'486'160.00

Value added and GWP are calculated for both scenarios but no comparison to the status quo is possible due to lacking data. But if we calculate GWP and Value added per capita for ALPVAL we see the industries relevance on regional scale. The production of gravel and concrete is of minor importance for the regional economy with a share of 1% in the regional GDP per capita. For climate gas emissions, however, concrete production accounts for 19% of the direct emissions (per capita) and 6% of the global emissions (per capita) – both closely related to CO_2 emissions in cement production.

5. Conclusions

For a transition towards a circular economy in the building materials industry it is essential to identify alternative business models and understand their impacts on the use of primary and secondary resources. In this paper, we identified two business models which, at first glance, seems identical as they produce and sell concrete and gravel. By investigating these businesses in detail, we wanted to answer the following questions:

Can the success of alternative business models be explained by boundary conditions in the specific markets, in the regional supply of natural resources or incentives from public administration?
It could be shown, that the success of a business model highly depends on the source for raw-materials (gravel pit, river extraction or processing excavated materials with high gravel content) and the possibility to landfill excavated material. Both have a relevant impact on value added and lead to different strategies to create and capture value. Demand for primary and recycled materials can vary from region to region, as different public policies influence the market (e.g. share of recycled concrete, availability of land/gravel quarries). For the business models described in this paper, the availability of raw material is crucial and both companies developed strategies to cope with this challenge. It is interesting to see, that both strategies are economically beneficial with a comparable amount of value added per unit of output. Compared to the case study region, both business models use more secondary resources that an average gravel and concrete producer. In the further course of the research, we will

have to find a better representative for the business model A "Extraction" to get a clearer distinction between both business strategies.

If a business model is considered favorable in the transition towards a circular economy, can it be transferred from one region to another without losing its economic benefits?
In this study, it is assumed that both companies produce with same costs and sell at comparable prices. In reality costs for gravel pits (e.g. concessions) and landfills differ significantly due to geological, political and economic boundary conditions. Also prices highly depend on demand of building materials and waste management services induced by building activities and economic development on regional scale. Based on our current results, no well-founded answer can be given to question above. In the further course of the research, we will analyze more case study regions that differ in the level of building activity, geological boundary conditions and vicinity of the national border. We expect to find significant difference in costs and prices that will have an impact on the development of business models.

How does such a transition towards alternative business models affect regional resource consumption, emissions and value added on regional scale?
As seen in section 4.3 the effects on resource consumption can be significant. In the cases shown here, resource consumption on a regional scale differs widely. Above all, the amount of excavated material deposited has to be mentioned. But also the amount of virgin gravel used in production strongly depends on the dominant business models in construction industries on regional scale. The effect on the regional economy is negligible. Concrete production has a significant impact on GWP on regional scale if the cement is produced in the region itself (direct emissions). But even if imported from other regions, the impact is not negligible. For our further research, we will analyze how different business models affect the use of cement in concrete production.

In this paper we compared a traditional, linear business model "Extraction" with a circular business model "Recycling". Building on quantitative data, we demonstrated their impact on a regional scale. It appeared that in terms of value generation, the differences were marginal. These indifferences results from the coupling of value capture and material turnover. A higher material turnover leads to a higher revenue, a logic that is inherently contracting concepts of sustainable business models. Nevertheless, business model so far do not fully decouple this logic, but expand their value proposition with additional services such as waste management. While these have not been fully captured in this paper here, further research will detail how circular economy ideas change business models towards more sustainability, and their impact on regional resource consumption, emissions and value added.

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Possible strategies and obstacles in the pathway towards energy transition of residential building stocks in Switzerland

Flourentzou F

Estia, EPFL Innovation Park, Lausanne, Switzerland

flourentzou@estia.ch

Abstract. The Swiss strategy for energy transition towards a sober energy world targets a 2000 W per capita society in 2050. This objective for an owner of a building stock is translated to a refurbishment of all existing residential buildings to near zero energy buildings, consuming less than 55 kWh/m² of primary energy for heating with a rhythm reducing the overall energy consumption by an average of 2.6 kWh/m² until 2050.
The article analyses energy consumption of 10'000 residential buildings in Geneva Canton since 1994 and shows that the target of energy reduction at this rate has been achieved in the period 1994-2016, decreasing from 187 kWh/m² in 1996 to 134 kWh/m² in 2016. However, projections for the next 3 decades with the current refurbishment rhythm (0.8-1.5%) and the current real energy performance after deep refurbishment and energy upgrading, show that at this rate and with the performance gap not resolved, the final target will not be achieved.
Based on the analysis of real energy consumption after refurbishment actions on statistically significant building samples and analysing the potential energy refurbishment actions of a 161 buildings stock, we have simulated possible and realistic ways to achieve the 2000 W society target.

1. Introduction. The 2000W society and strategic energy and CO2 targets.

The Swiss strategy for energy transition took the name of "2000W society". This idea started in the years 2000 in the academic circles. It was accepted as a political target in the majority of the cantonal energy Laws and communal Energy Regulations. The Swiss Engineers and Architects Association (SIA) edited a documentation describing the targets of this strategy focusing on buildings: exploitation energy consumption, gray energy for construction or refurbishment and mobility [1].

The 2000 W society targets to reduce the 6000 W nonrenewable energy intensity per capita during the year 2000 to 2000 W of non-renewable energy consumption in 2050 and 2000W total energy consumption of which 500 W nonrenewable in 2100. It also targets 2 tons of CO2 emissions per capita by the year 2050 (1 ton in 2100). This energy intensity was experienced in Switzerland in the fifties and it is argued by the promoters of this idea that it is possible to achieve these targets preserving the current comfort and welfare. The world mean energy intensity was 2000 W in the nighties while at present it is around 2500 W. The application of the 2000 W society idea worldwide, considers equal access to energy resources for all citizens of the world.

The SIA documentation 2040 analyzed the Swiss national statistics in terms of surface area per capita for living, working, learning, etc. and translated the global per capita nonrenewable primary energy and CO2 targets to building targets per square meter, distinguishing new and refurbished buildings.

	Surface /person	Embodied Energy	Energy for Operation	Energy for Mobility	Global Target
	[m²]	[kWh/m²]	[kWh/m²]	[kWh/m²]	[kWh/m²]
New Construction	45	30	90	40	160
Refurbishment	45	20	**100**	40	160

Table 1 Surface and primary energy targets for new construction and refurbishment

The CO2 emission target for operation is 6 kg/m² for new construction and 8 kg/m² for refurbished residential buildings. These CO2 emission targets are very ambitious and cannot be reached with the use of fossil fuels. For existing residential buildings (multi-family houses), it is illusionary to imagine complete abandon of fossil fuels by 2050, except if there are massive investments in urban infrastructure to provide urban district heating with low CO2 and low nonrenewable primary energy content. Buildings complying to primary energy targets but not to CO2 targets may be considered as "in transition" towards 2000W society. A building may be considered compliant "in transition", if it may reach the 2000W society targets with future modifications of the technical installations. As in this article we focus on apartment building stocks for housing and the strategic actions of their owners, we focus only on primary energy targets for heating and hot water production. A building complying to primary energy targets, heated provisionally with gas, may be classified "in transition", because it does not comply to CO2 targets. These targets may be attained with future actions on heat production installations changing the energy source.

As we see on Table 1, refurbished and new buildings have the same total target for construction/refurbishment, operation and mobility. However, as refurbishment impacts less than construction of a new building, it is allowed 10 kWh/m² more primary energy and 2 kg/m² CO2 emissions for operation of refurbished buildings.

Energy for building operation counts heating, hot water, ventilation, cooling, lighting and electricity for housing appliances. SIA 2040 desegregates theses energies providing typical values for each type of use. Using these typical values, and the values of table 1, we may find the targets for heating and hot water consumption: 55-60 kWh_P/m^2 of nonrenewable primary energy. This indicator is important because it can be read directly on fuel energy bills for heating and hot water.

This target is coherent with the targets of low energy building labels. Class B buildings corresponds to <63 kWh/m² of final energy and Minergie – Refurbishment to 60 kWh_{CH}/m^2 of weighted[1] energy for heating, hot water and ventilation. We keep as refurbishment target value of 2000 W for residential buildings heating and hot water consumption 55 kWh_{CH}/m^2 of weighted energy. This value is coherent with Minergie-Renovation targets that takes into account electricity for ventilation and auxiliaries.

In the year 2000 the mean energy performance of residential buildings in Geneva was 181 kWh/m² of weighted energy. To get the target of 55 kWh/m² in 2050 it is necessary to reduce energy consumption by 126 kWh/m² in 5 decades. This means a rate of reduction of 26 kWh/m² per decade or 1.4% per year with basis the 2000 energy consumption.

2. Geneva Canton residential building stock energy consumption since 1994

In Geneva Canton, every residential building owner with more than 5 energy consumers, has the obligation to communicate to the Cantonal Energy Office the heat consumption of the building. These data are collected since 1992, and since 2010 all buildings of a certain importance have to communicate

[1] Weighted energy is a Swiss speciality replacing the primary energy factors with « state energy policy weighting factors », having 2 for electricity, 1 for fossil fuels and 0.6 for biomass instead of 2.69 NRE for electricity, 1.22 for oil, 1.05 for gas and 0.1-0.33 for biomass with unit symbol kWh_{CH}.

their energy consumption. All these data are public and accessible on the Canton Information Service on the web.

We filtered and analyzed the data of all residential apartment buildings present in the database. The statistical set is composed by 6874 buildings of 12 million m² in 1994 and up to 10’000 buildings, 16.2 million m² in 2016. Every year more buildings are added in the database. This statistical set is constituted of practically the whole stock of residential apartment buildings of the Canton. If we consider 45 m² per inhabitant, this building stock concerns potentially housing of 266’000 people out of 495’000 population of the canton.

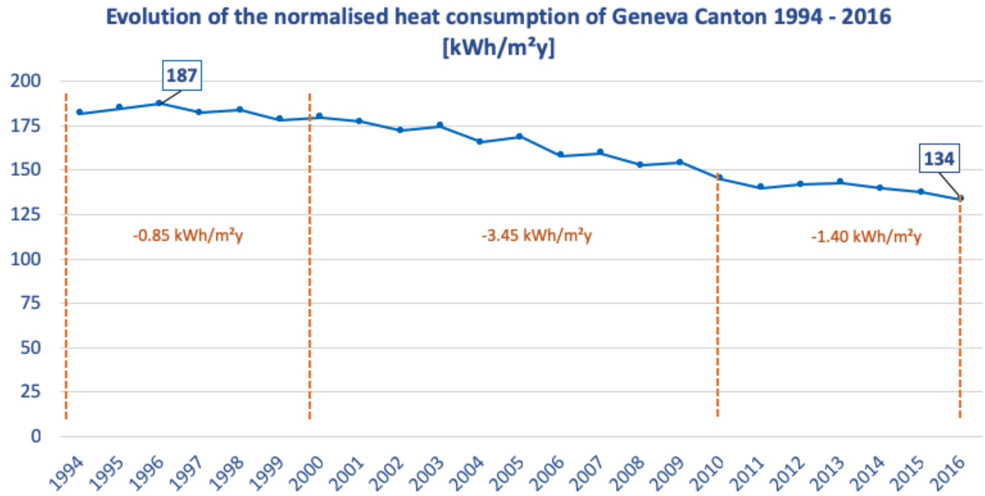

Figure 1. Evolution of the final energy consumption of 10’000 residential buildings, 12 million m², in Geneva.

As we see on Figure 1, in the period 1994-2000 the energy reduction was tiny, -0.85 kWh/m². In the period 2000-2010 the significant boost of energy savings gives an energy reduction of 3.45 kWh/m² per year. After 2010 we observe a deceleration of the evolution with 1.40 kWh/m². During these first two decades of energy transition, 1996-2016, we observe a significant reduction of energy consumption of an overall of 53 kWh/m². This represents a reduction of 28% with a mean rate of 26 kWh/m² per decade. The transition targets towards 2000 W society for the first two decades are achieved successfully, although the reduction rate was not constant during the whole period.

We observe a downturn after 2010 with weaker rate of reduction although the national energy requirements become more ambitious. The lower energy prices of this period and other macroeconomic reasons might play a role for this. Another factor of the downturn of energy consumption reduction is the low refurbishment rate. According to the report of the Cantonal Energy Directors [2], in Geneva Canton, more than 60% of the buildings built before 1990 have not been refurbished the last 30 years. This means a refurbishment rate lower than 1.5%. According to the same source, refurbishment rate of facades is between 1 and 1.1%, roofs 2-2.4% and windows 3.5%. As the energy reduction is due to optimisations and partial interventions rather than global energy upgrading, energy-saving potential is reducing year by year, because the most efficient actions have already been implemented.

2.1. Evolution of the energy classes during the first 2 decades of the energy transition

We classified the buildings according to their specific heat consumption. We calculated the partial class thresholds according to the Swiss national classification regulation. According to this standard, normal heat consumption determining the threshold of class B is 63 kWh/m² (heating and hot water). This determines the module of the x axis of the following graphs.

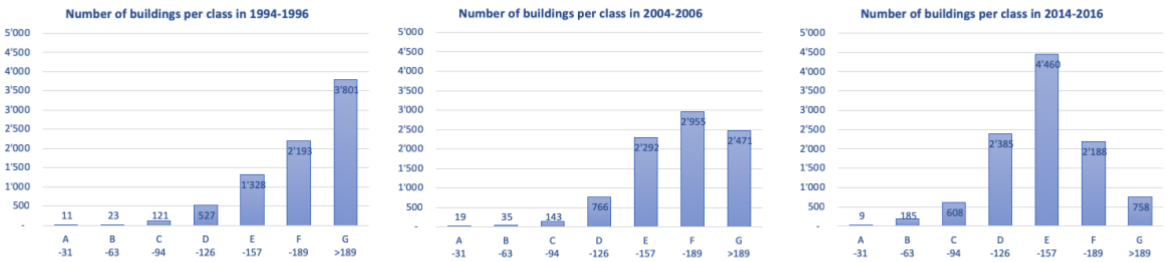

Figure 2. Evolution of the class distribution of residential buildings in Geneva, 1994-96, 2004-06 and 2014-16.

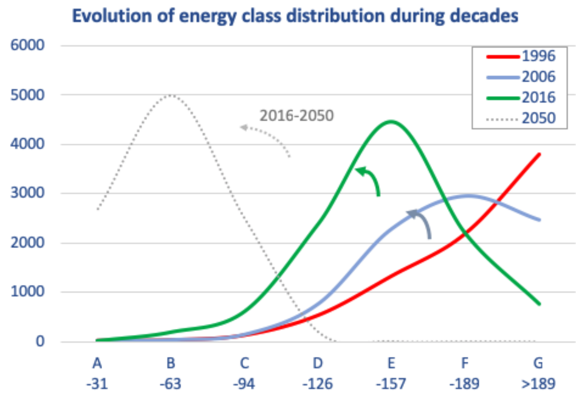

Figure 3. Evolution of energy class distribution during decades.

As we may see on Figure 2 and Figure 3, the residential building stock classification evolves towards lower energy classes. In 1996 there were 3801 buildings out of ~8000 in class G, in 2006 this number was reduced to 2471 and in 2016 they remain only 758 buildings out of ~10'000. The median class was reduced by more than one class during 2 decades. If the energy transition towards 2000 W society continued with the same rhythm until 2050, the energy target would be achieved. The distribution curve of that time might seem like the dotted line, centered on class B with the majority of the buildings, more than 25% of buildings in class A with buildings easy to refurbish with accessible cheap renewables and 25% of class C and some exceptions in class D. These class C and D buildings could be the protected heritage buildings or buildings not yet refurbished.

2.2. Major risks of low refurbishment rate and insufficient real energy performance.

Analysing these graphs, we may identify and quantify 2 major risks:

The first one is the current rate of refurbishment. If during the last 3 decades, only 3500 buildings were refurbished according to [2], what is the driving force that will modify the motivations of the building owners to retrofit 6500 buildings in the next 3 decades? As we see in Figure 1, the rate of energy consumption reduction decelerated, and it is less than the average value since 2010. With the current rate of energy consumption reduction, the targets of 2000 W society cannot be achieved.

The second risk that we may observe on Figure 2, is the few buildings of real energy class A and B. If in 2016 we have only 9 buildings of class A and 185 buildings of class B, someone may question why there are so few low-energy buildings, although there were subsidies since 2010 for deep refurbishment and hundreds of new buildings have been built with high energy standards? What will change so that the building sector may manage to perform for 7'500 buildings in the next 30 years what it has not managed in the past decade?

3. Refurbishment strategies

If we analyse the energy performance distribution of the building stock, we may see that 2/3 of the buildings are of energy class E, F and G. We also know from [2] that more than ~2/3 of the buildings built before 1994 have not been refurbished over the last 30 years. This means that many of the buildings of class D achieve their energy performance without deep refurbishment and therefore, we may bring the buildings consuming more than the median consumption to the median with partial refurbishment and energy optimisation actions.

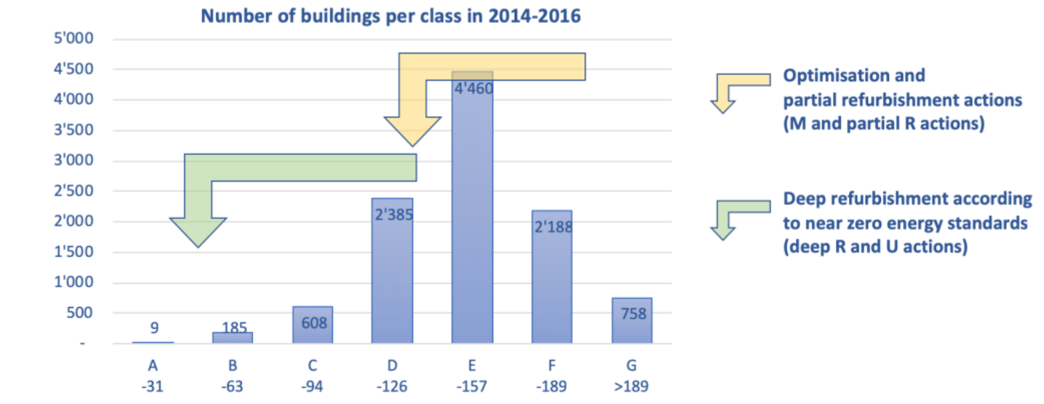

Figure 4 Energy consumption distribution of residential buildings in Geneva and actions to change their energy class.

According to the Swiss Norm SIA 469 [3], we may classify building conservation measures to 3 categories:

- Maintenance with ordinary and extraordinary limited actions.
- Refurbishment, bringing the building components to habitability normal conditions.
- Upgrading, with actions offering better performance.

Optimisation actions do not imply any investment, other than the monitoring cost. Simple settings, like a more adapted heating curve, night setback of the heating and water system, more adapted ventilation rates, correction of dysfunctionalities of production and distribution systems, optimisation of the operation of existing installations.

A list of building elements may be replaced independently from a deep global refurbishment without compromising future coherence of the energy systems. Windows, ventilation system, roof or ground slab insulation, an installation of solar collectors for hot water preheating, a new smart control of the heating system, or boiler replacement, are such actions. They may generate significant energy savings waiting deep refurbishment in the near of far future.

Concerning deep global refurbishment, some cantonal regulations define it for buildings investing more than 40% of the reconstruction value and apply special complying procedure to the norms. Upgrading actions target higher energy performance than the minimum legal target. Minergie®-Renovation label, Minergie-P® are such labels, but in Geneva and other Swiss cantons there are also regional labels, like HPE and THPE (Haute Performance Energétique and Très Haute Performance Energétique).

We have simulated the most usual refurbishment actions for a typical building of 1965 (Table 2). The building presents the dimensional and energy consumption characteristics of the median non-refurbished building of our cantonal database (3 entrances of 1800 m² each, 20 apartments each, measured energy class E). We calculated the theoretical energy savings of each action or combination of actions. As we are interested in the real impact of the different options on energy savings, we identified sets of buildings of significant statistical sample and tested the real energy saving effect of different actions. We compare the evolution of energy consumption of the test set of refurbished or optimised buildings with evolution of the reference set (generally the whole building stock). This shows the real impact on energy performance due to the action on the test set.

3.1. Monitoring and optimisation actions

We compare the evolution of specific heat consumption of a group of 123 buildings under energy performance contract with the whole building stock. As we may see on Figure 5, the selected buildings for optimisation consume a bit more energy than the whole building stock before 2014 when optimisation actions started. Before the beginning of the optimisation actions in 2013, the set of optimised buildings consume 149 kWh/m² instead of 143 kWh/m² of the whole building stock. 3 years later, this group consumes 127 kWh/m² instead of 134 kWh/m² of the whole building stock. The whole building stock reduced its energy consumption for heat by 9 kWh/m², 6.3%. As the reference building stock is huge and the deep refurbishment actions insignificant (less than 1% per year) we may suppose that the reference building stock without optimisation is the whole building stock with 10 000 buildings. The optimised group of buildings reduce its energy consumption by 22 kWh/m², 14.8% compared to 9 kWh/m² of the reference set. The pure reduction of the optimisation actions counts for 13 kWh/m², 9.1%. As the results are normalised with a reference meteorological year according to the year heating degree days, we see only the action influence independently from weather variation. Here we simply compare the mean energy consumption of each group. More detailed statistical methods may be used to compare the two groups of buildings.

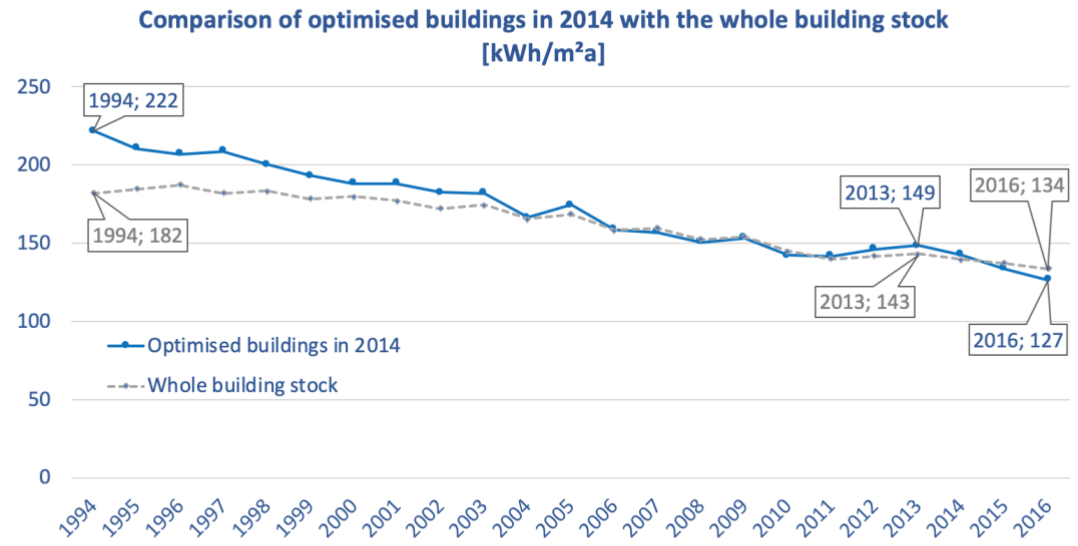

Figure 5. Comparison of the evolution of specific energy consumption for heat of a group of 123 optimised buildings with the whole building stock

3.2. upgrading actions with deep refurbishment.

Comparison of a significant set of 59 refurbished buildings according to the high and very high energy standards shows the real potential of these actions. The target was 30 kWh_{CH}/m^2 for the very high energy standard and 60 kWh_{CH}/m^2 for the high energy standard, including weighted electric energy for ventilation (6-7 kWh_{CH}/m^2 for buildings with heat recovery and 1 kWh_{CH}/m^2 for buildings with simple systems). Electricity for ventilation is not included in the measurements of heat consumption in the database. The majority of these high-performance buildings are designed with heat recovery systems. Excluding ventilation, we keep the indicative target of 55 kWh/m² for heat. An official compliance verification certified the design objectives of these buildings.

As we can see on Figure 6Figure 6, refurbished buildings according to high and very high energy standards, reduce drastically their energy consumption for heat. However, the real energy performance does not achieve the theoretical performance according to the declared objectives and does not meet the 2000W society goals. Although there is a reduction of 85 kWh/m² in heat consumption since 2005 (46%), there are 45 kWh/m² missing to meet the goals.

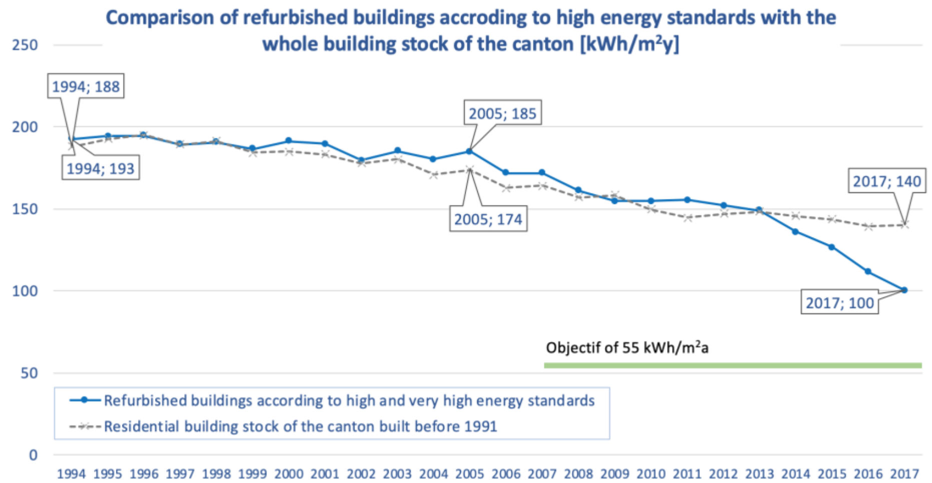

Figure 6: Comparison of 59 buildings upgraded to high and very high energy standards with with the whole building stock of residential buildings built in Geneva before 1991.

The real heat consumption of this set of refurbished buildings is 100 kWh/m² instead of <55 kWh/m² that it should be. The majority of these buildings are still heated with oil or gaz. The following graph shows the energy consumption distribution of these buildings.

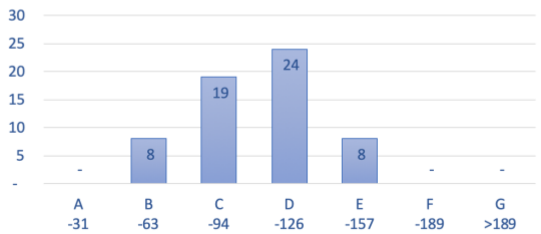

Figure 7 Number of "High Energy performance" buildings per energy class (normally class A and B)

The phenomenon of the performance gap of refurbished buildings in Geneva has been studied by several research projects [4][5][6]. According to Khoury [6], in a sample of 26 buildings, targeting 153 kWh/m² energy savings, they realised 101 kWh/m², 65% of the ambitions. These results on a smaller sample, but analysed deeply in detail, are of the same order of magnitude as those of Figure 6. According to [5], the reason for this kind of performance gap is 30% due to bad settings and 30% due to lack of monitoring, resulting overheating of the apartments to >23°C and window openings >15% and poor heat production efficiency. In the following table, we compare the expected energy savings simulated on our typical building according to standard conditions and the energy savings observed on relevant statistical sets.

	Calculated savings		Performance gap
	kWh/m²	%	
Smart heating control	**28**	16%	+
Replacement of windows	**33**	22%	+++
Roof Insulation	**16**	11%	+
Boiler replacement	**7**	5%	+
Wall insulation	**42**	28%	++
Demand control ventilation	**9**	6%	-
Solar DHW preheating	**6**	4%	+++

Table 2. Theoretical energy-saving potential of most usual refurbishment and optimisation actions and potential performance gap.

4. Simulation of energy transition pathway of a building stock towards 2000W society.

From Table 2 action list we may combine two types of refurbishment strategies for the buildings:

- Optimization and partial refurbishment actions, concerning the buildings of classes E, F, G that are not going to be refurbished in the next 15 years. The theoretical potential target is 100 kWh/m² but the real observed energy performance is ~125 kWh/m².
- Deep refurbishment following a given strategic refurbishment rate. The theoretical potential target is 55 kWh/m² but the mean real observed performance 100 kWh/m². The best refurbished buildings after optimization consume 70-75 kWh/m².

We analyzed a building stock of 161 buildings of the total surface area of 324'032 m². Its energy consumption for heating and hot water in 2016 is 133 kWh/m², very similar to the whole Geneva building stock average. The evolution of the energy consumption since 1994 is following very closely the cantonal building stock evolution. 95 buildings, 59%, are of classes E, F, G with mean energy consumption 150 kWh/m². The current rate of deep refurbishment is less than 1%. However, the investment rate is ~1.5% of the building reconstruction value. This means that almost half of the current investment budget is for partial refurbishment.

We tested 2 refurbishment strategies.

Scenario 1: realistic rate of refurbishment according to the current practice, the current budget and available personnel. This is translated to 1.5 buildings per year with deep refurbishment (1%). To this we add 8 buildings per year partially refurbished or optimized for the next 10 years. We use the energy targets observed in reality.

Scenario 2: an ambitious scenario, with 8 buildings per year partially refurbished or optimized and 1.5 buildings deeply refurbished until 2029, and 3 buildings per year refurbished from 2030 until 2050 (2% deep refurbishment after 2029). Until 2029 we use the energy targets according to those observed in reality and after, we use the potential theoretical ones.

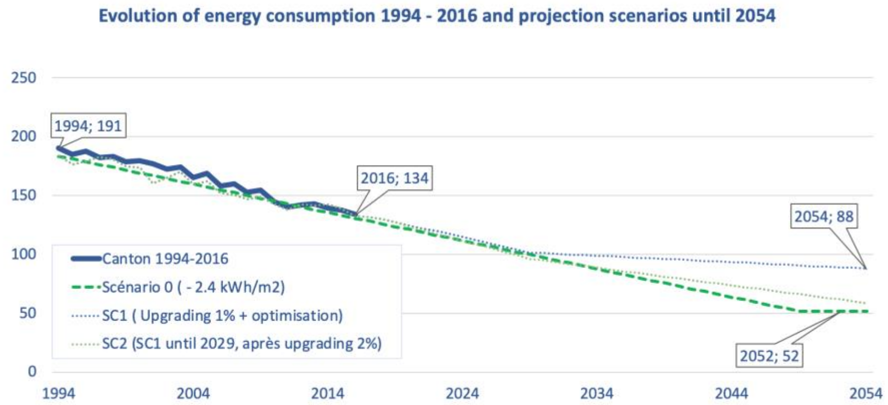

Figure 8. Evolution of energy consumption and projections until 2054

As we see on Figure 8, the evolution according to the current parameters of refurbishment rate and real energy savings does not lead to a 2000W but to "a 3200W" society (scenario SC1). However, combination of the low current rate for deep refurbishment with partial refurbishment and optimizations may be acceptable to stay on the course for the next decade. In order to approach the resulting energy to the 2000W society targets, it is necessary to double gradually the rate of refurbishment to reach 2% and make the performance gap negligible for the decades after 2029.

5. Conclusions.

In the first 2 decades of the energy transition, 1996-2016, the mean rate of energy consumption reduction was following the objectives, although the rate of reduction was weakened since 2010. For the next decades there are 2 considerable obstacles to meet the goals: the low rate of deep refurbishment and the performance gap. In order to catch the objectives, it is necessary to rise gradually the rate of energy refurbishment to 2% per year and reduce the performance gap to obtain a mean of <55 kWh/m² after refurbishment, instead of 100 today.

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Fleet-based LCA applied to the building sector – Environmental and economic analysis of retrofit strategies

Göswein V[1], Dinis Silvestre J[1], Freire F[2], Habert G[3]

[1] CERIS, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001, Lisbon, Portugal
[2] ADAI/LAETA, Department of Mechanical Engineering, Universidade de Coimbra, Polo II Campus, R. Luís Reis Santos, 3030-788 Coimbra, Portugal
[3] Chair of Sustainable Construction, IBI, ETH Zurich, Stefano-Franscini-Platz 5, 8093 Zurich, Switzerland

verena.goswein@tecnico.ulisboa.pt

Abstract. CO_2 emissions need to be reduced by 40% in 2030 in Portugal as an intermediate target of the Paris Agreement. This challenging goal is expected to be achieved through incentive-based regulations and voluntary actions. This study improves the understanding of renovation strategies to reduce emissions caused by the built environment. A fleet-based Life Cycle Assessment (fb-LCA) is adapted and applied to the building sector. Fb-LCA integrates LCA and a fleet model to describe stocks and flows associated with a class of products over time. The method is tested for a neighbourhood in Lisbon, Portugal. The analysis compares 3 scenarios of dynamic renovation rates for the next 30 years: business as usual, a public economic incentive to renovate, and mandatory renovation. Different technology scenarios including bio-based ones, are compared. Among the latter, alternative material solutions, e.g. insulation cork boards, are emerging, providing carbon sequestration. Results highlight the environmental benefits of bio-based materials considering the temporal profile of renovation activity. Furthermore, the cost and sensitivity analysis help stakeholders to justify retrofit actions from an environmental and economic point of view. The adaptation of a fb-LCA approach proves to be an easy-to-use method to assess technology options and policy scenarios at a neighbourhood scale.

1. Introduction

1.1. The built environment as a cause of pollution and as an opportunity to tackle climate change

The Paris Agreement aims to tackle climate change by limiting global temperature rise this century well below 2° Celsius above pre-industrial levels, or even limit it to 1.5° Celsius. The ambitious goal is an 80% reduction of CO_2 emissions by 2050 compared to the year 1990. By ratifying the agreement in October 2016, Portugal and many other countries have committed themselves to comply with the intermediate targets of reducing the national CO_2 emissions at least by 40% in 2030 [1]. This challenging goal is expected to be achieved by means of incentive-based regulations and voluntary actions.

The built environment consumes 62% of final energy and is a major source of greenhouse gas emissions (55%) [2]. In Portugal, almost 70% of the buildings were built before 1990, when the first Portuguese regulation regarding thermal comfort in buildings was published. In 2010, 35% of the buildings in Portugal needed major retrofit works and about 3% presented a high level of degradation

[3]. According to 2014/15 European work program, the renovation of buildings represents more than 17% of the primary energy savings potential of the EU for 2050 [4].Therefore, the renovation of buildings has a high capacity to influence the environmental impacts and global objectives of climate change mitigation.

1.2. Bridging the gap between embodied and operational energy

In the existing literature, direct emissions during the use phase of buildings and indirect emissions in the production, construction and waste management phases, are usually disconnected. To achieve climate sustainability goals, we need to find a way to understand the dynamics of the built environment by bridging these two levels. Low-impact solutions, on both levels, for example through thermal refurbishment of the façade, are needed. In this regard, traditional insulation materials for retrofit might not always be the best solution in terms of impacts, but alternative material solutions, e.g. insulation cork boards, are emerging [5]. Bio-based products offer the opportunity to account for carbon sequestration, which offers an environmental benefit that might compensate for the impacts caused during production and construction [6].

The objective of this study is to explore potentials of greenhouse gases (GHG) and other emissions reductions associated with the renovation of buildings. It wants to improve the understanding of renovation dynamics in relation to achieving climate targets. For this purpose, a method called fleet-based Life Cycle Assessment (LCA) will be adapted and, in a simplified way, applied to the building sector.

1.3. Technology diffusion

The question if "a product-centred approach to LCA is always the best" was answered by Field *et al.* [7] by introducing the "fleet-based" LCA (fb-LCA). This approach deals with effects distributed over time, and integrates LCA and a fleet model that describes the stocks and flows associated with a class of products over time. Instead of making use of a single element for the declared unit, it looks at a set of units in service. Fb-LCA is able to model temporal changes and effects of technology diffusion because it considers the dynamics of replacing products that reached their end-of-life with new ones. And because it considers how resource consumption and environmental impacts change over time, it is a useful method to analyse technological transitions.

Even though until now the application of purely fb-LCAs is relatively restricted to fields that underlie high technology innovations, e.g. cars, the method shows advantages that seem beneficial also for assessing building stocks and scenarios for retrofitting. This method can be used to assess the dynamics of introducing or increasing the share of a specific type of insulation material, considering different retrofitting rates depending on the location. In a study on the development of residential building stocks [8] used an approach that reminds of fb-LCA. The authors estimated country-wide future renovation activities on the residential building stock that needs retrofitting by defining building cohorts. However, a Europe-wide analysis would require generalized parameters to model the composition of the building stock.

1.4. Building stock modelling

A model is always a simplification of reality. A complex system like a building stock needs an appropriate model to be analysed. There are two general approaches in building stock modelling: top-down and bottom-up models. Top-down models work with aggregated data. Bottom-up stock accounting uses material intensity coefficients to estimate the material quantity in a single unit of the examined end-use objects at a specific moment in time. With simple typologies, it is already possible to obtain interesting results regarding future policy and technology scenarios for a building stock at the urban scale [9].

This study will make use of a bottom-up approach and will focus on a defined set of buildings and materials to explore the opportunities of a fb-LCA applied to the diffusion of retrofit strategies.

2. Data and Methods

The framework for the model, presented in figure 1, reminds of a typical LCA, but it uses an up-scaled declared unit that is the whole opaque façade area of all buildings under study. The product stages A1 "Raw material supply", A2 "Transport", A3 "Manufacturing", and construction process stages A4 "Transport" and A5 "Construction installation process", as well as the use stage B6 "Operational Energy Use", are taken into account to estimate environmental impacts. The analysis focuses on the impact categories Global Warming Potential (GWP) and Primary Energy Non-Renewable (PE-NRe), but Abiotic Depletion Potential (ADP), Acidification Potential (AP), Eutrophication Potential (EP), Ozone Depletion Potential (ODP) and Photochemical Ozone Creation Potential (POCP) are also considered to be in line with the European recommendation for the application of LCA to construction products and services [10]. Moreover, the study also estimates the economic costs associated to Life Cycle (LC) stages A1 to A5, cradle to gate, and the energy cost of heating and cooling during the study period related to LC stage B6.

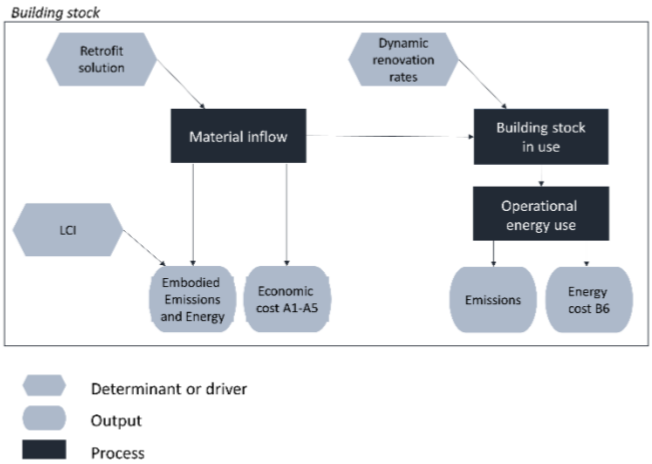

Figure 1. Framework of the model

The developed method is tested for one type of construction typology in the Lisbon neighborhood Alvalade. This neighborhood is of particular interest since it was built within a short period, between the 1940s and the 1960s, promoted by an urban expansion plan of the Lisbon municipality in 1944. Here, a specific type of construction called "Placa", mixed masonry-reinforced concrete, is particularly prominent. In total, 230 buildings were identified to be similar to that type and considered in the present study. The declared unit is the total opaque façade area of all buildings: 124,577 m^2.

The analysis incorporates the fleet-based approach by analysing dynamic renovation rates (see figure 2). It describes the next 30 years in accordance with the EU energy directive [11], which is also a commonly chosen time frame in Economic and Energy LCA. The Business as Usual (BAU) is compared to two scenarios: one assumes that a public economic incentive is introduced to promote the renovation of exterior walls. For the public economic incentive scenario, a Weibull probability density function is applied. The other scenario is that of a legislation that makes renovation of exterior walls within the next 30 years mandatory. For the mandatory renovation scenario, a Normal distribution is assumed, which is often used in building stock modelling.

Furthermore, different technology scenarios are analyzed: the building stock as it is without any retrofit action is compared to two different scenarios with an external thermal insulation composite system (ETICS) applied to a single leaf wall: one with the commonly used insulation material extruded polystyrene (EPS); and the other one with the bio-based insulation cork board (ICB). The technology scenarios are paired with the dynamic renovation rate scenarios described before. Also, a sensitivity analysis on heating and cooling use is carried out. The default value for the consumption of energy during the B6 sub-stage is assumed to be only 10% of the heating and cooling needs, in accordance with the national use pattern. This value is compared to fulfilling 20%, 30%, 40% and 50% of heating and cooling needs.

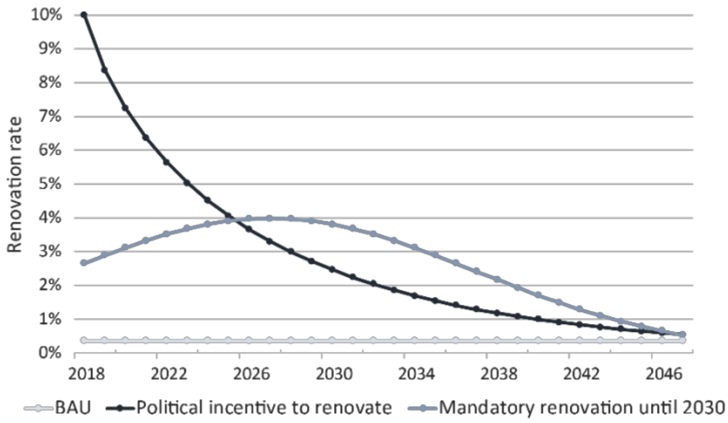

Figure 2. Renovation rates under study.

The costs of LC stages A1 – A5, that include the installation of the ETICS system in the building, in units of m^2 of wall, were taken from various sources [12–14]. The calculation of the energy cost in each year, per m^2 of external wall, relates to the energy use for heating and cooling, based on the method given in the national regulations [15].

3. Results

3.1. Environmental impacts - Renovation all at once

As a first step, the cradle to gate impacts for the declared unit were calculated for the hypothetical case that everything is renovated at this moment in time. The alternative of not renovating has 0 impacts for LC stages A1 to A5. The impacts for the two technology alternatives, an ETICS with ICB and an ETICS with EPS, in both cases 0.08 m thick, are compared in figure 3. GWP is negative for the ICB solution since biogenic carbon capture is considered based on a recent Environmental Product Declaration [16].

Furthermore, the embodied energy related to heating and cooling needs, for the default value of 10%, was estimated for the reference case and the two retrofit scenarios. The U-values are 2.41W/m^2K for no retrofit, 0.42 W/ m^2K for the ICB solution and 0.38 W/ m^2K for the EPS solution. The results for PE-NRe and GWP can be seen in figure 4. In both impact categories, the reference case "no retrofit" performs the worst. The differences between the two ETICS scenarios are small with 2,202 kg CO_2 eq. for the ICB solution vs. 2,176 kg CO_2 eq. for the EPS solution, and 34,040 MJ vs. 33,639 MJ respectively.

During LC stages A1-A5 and B6 for 30 years the ETICS with ICB causes less 53% GWP and less 28% PE-NRe compared to no retrofit. ETICS with EPS has a smaller reduction potential than the one with ICB with 19% less for GWP and 17% less for PE-NRe compared to no retrofit.

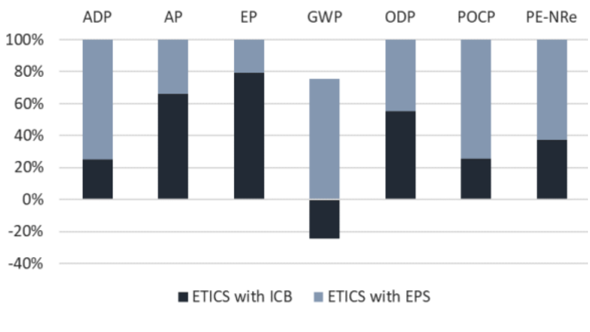

Figure 3. Comparison of environmental impacts for LC stages A1 – A5.

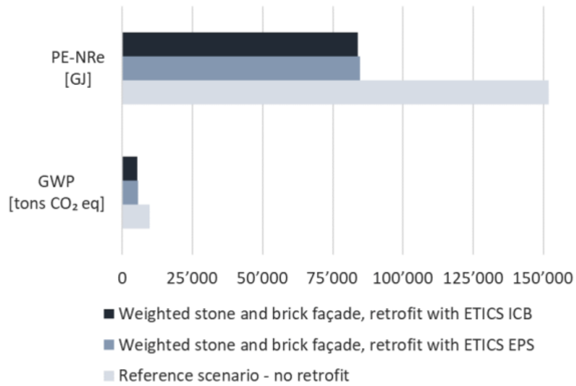

Figure 4. Heating and cooling impacts during 30 years (LC stage B6) for the declared unit.

3.2. Economic and energy costs

The economic cost for LC stages A1-A5, and the energy cost in LC stage B6 with the default value of 10% consumption of energy needed to fulfil the heating and cooling needs during the next 30 years, were estimated for all scenarios. The assumed discount rate was 3%. The economic performance considers market prices, e.g. the acquisition cost including manufacturing, transport to site and installation in the building, as well as the economic savings potential that the thermal retrofit solutions offer. This includes the potential improvements of energy performance of the building envelope after the installation of the ETICS system and the related energy saving potential. The economic costs and energy costs for the three different options are shown in figure 5. It highlights than none of the suggested retrofit solutions offers economic savings compared to the reference case “no retrofit”.

The energy costs are € 22.63 for the energy use for heating and cooling after 30 years study period for 1 m^2 of non-retrofitted wall, compared to €12.64 for 1 m^2 of wall with ETICS with ICB and €12.50 for 1 m^2 of wall with ETCS with EPS. Moreover, EPS has a lower market price than ICB. These values scale linearly with the opaque façade area. However, the energy cost was calculated based on the assumption that only 10% of heating and cooling needs in LC stage B6 are fulfilled. Since in many cases more than 10% needs need to be fulfilled, a sensitivity analysis on this parameter was conducted. Figure 6 shows the results of the sensitivity analysis. Illustrated are the relative differences of the sum of economic and energy cost, compared to the reference case “no retrofit”. One can see that, with an increased value of 40-50% heating and cooling needs fulfilled, the two ETICS solution became equally cheap or even slightly cheaper than the reference case.

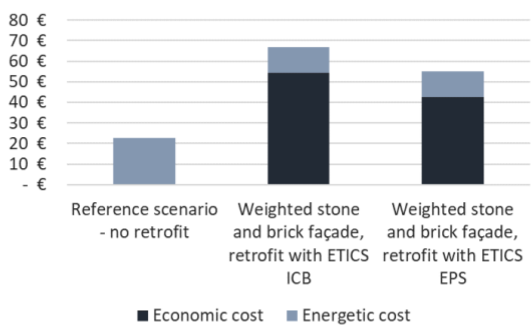

Figure 5. Comparison of the economic cost for LC stages A1-A5, and energy cost for the LC stage B6, after 30 years for 1 m^2 of exterior wall.

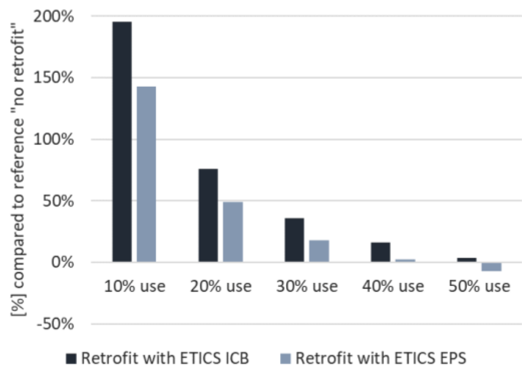

Figure 6. Sensitivity analysis of heating and cooling needs. Based on the total economic cost for LC stages A1-A5 and energy cost for B6.

3.3. Environmental impacts – dynamic renovation rates

Renovation rate as a driver of the model has direct impact on the emissions released over time. The translated GWP for the three different renovation rates under study, as described before, are shown in figure 7. The values in the figure were obtained by holding the renovation technology fix, which is ETICS with ICB, and comparing the different policy scenarios. The chart shows renovation with ICB compared to doing nothing. Only LC stages A1-A5 are considered. If compared to a renovation scenario with EPS the CO_2 saving potential of ICB would be even bigger. In fact, only with bio-based construction materials such as ICB, carbon can be stored in the building. This needs to be considered when analysing the policy scenarios: not only renovation activity as such needs to be promoted but also bio-based materials. The CO_2 savings related to LC stage B6 follow the shape of figure 7.

The BAU has a linear trend line that does not offer a significant potential regarding negative CO_2 emissions. In contrast to that are the two hypothetical policy scenarios, where renovation is either mandatory or promoted with an economic incentive. The first critical step regarding the intermediate goals of the Paris agreement is the year 2030. In that year, the estimated cumulative negative CO_2

emissions will be only -40 tons CO_2 eqv. for the BAU scenario compared to -383 tons CO_2 eqv. for the mandatory renovation scenario and -546 tons CO_2 eqv. for the public economic incentive to renovate.

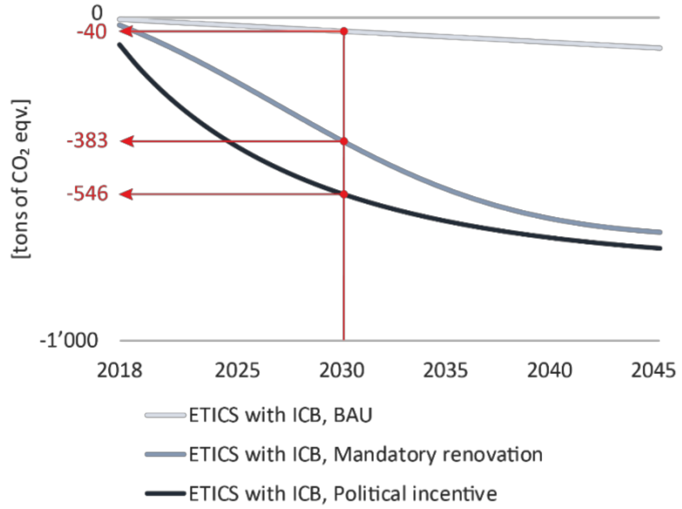

Figure 7. Dynamic cumulative GWP in kg CO_2 eqv. for the declared unit for cradle to gate impacts.

4. Discussion

The purpose of the present study is to improve the understanding of possibilities to reduce emissions caused by the built environment given the fact that binding global climate deals set targets that need to be fulfilled by every participating member. Based on the literature, we propose to use a fb-LCA with a bottom-up building stock modelling that helps to assess the combined potential of technology and policy scenarios. The technology aspect stands for different exterior wall insulation systems and the policy aspect for different renovation rates.

4.1. Technological retrofit options

The present study analysed different retrofit scenarios from an environmental and economic point of view. It was found that, regarding the cradle to gate impacts arising during A1-A5 and the operational energy use in B6, an ETICS system with EPS required slightly less PE-NRe than the one with ICB, 33.9 MJ vs. 34.2 MJ. However, cork as a bio-based insulation material offers the advantage of capturing carbon during its growth which can be accounted for as a negative GWP during construction stage. Both solutions caused significantly less GWP and PE-NRe than the reference scenario "no retrofit". Other researchers have tried to translate that environmental advantage into monetary units by applying weighting factors to make the different dimensions of sustainability easier comparable in a decision making process [17]. Yet, the monetization of impacts is a controversial topic [18] and many scholars argue that is very subjective to trade between economic, social and environmental dimensions sustainability. An option here would be to weigh costs and emissions from different point of views, for example a "green" approach vs. a cost-saving vs. a focus on the service life vs. architectural aspects etc. [19,20]

Regarding the cost analysis, the overall cheapest option was not to renovate. In that case there is no economic cost related to life cycle stages A1 to A5, and the overall cost, economic cost plus energy cost during the 30 years under study (B6), was lower than for the two technological retrofit scenarios with ETICS. The cheapest energy cost was obtained with an ETICS with EPS. The difference to the ETICS with ICB however is small, not even 1%. Moreover, the default value for consumption of energy for all these values was only 10% of the heating and cooling needs and therefore very low. The sensitivity analysis revealed that, with an increased amount of consumption of energy, the energy cost gains importance compared to the economic cost. By assuming that the consumption of energy is around 40-50% of the heating and cooling needs, the two ETICS systems under study had an equally low total cost, economic plus energy for 30 years, as the reference case "no retrofit". An energy consumption in that range is becoming more realistic, considering that people stay at or work from home more often, that some of the apartments are used as, for example, medical practices, or that the cost of electricity might increase in the future [21].

4.2. Dynamic renovation rates

A fb-LCA approach, which has not yet been applied to the building sector, was used to assess technology transitions over time. The model was simplified such that neither changes in background processes nor technological improvements over time were considered. Both are characteristics that are important in the fb-LCA in sectors with fast technological innovation, such as the electric car industry, but not so much in the construction industry, which is traditionally a rigid sector and little prone to technology innovation. In that way the method is well suited to answer the given question. The renovation rates were modelled dynamically because buildings have a long lifespan and should be understood as service providers with different future scenarios. Therefore, it is important to consider the temporal profiles of emissions so that the LCA result for each emission is a function of time rather than a single number. The results of the present study showed that, firstly, the emission profile is directly related to the assumed dynamic renovation rate, as was shown with the linear BAU projection compared with the policy scenarios (vs. the normally distributed renovation rate of legally mandatory renovation and vs. a public economic renovation incentive based on a Weibull distribution). Secondly, the difference between a linear rate and a dynamic one is big regarding the cumulative emissions and the emissions at each moment in time, which was shown in figure 7 regarding the critical year 2030. In that year, given the assumptions made for the public economic scenarios, a public economic incentive to renovate proves to be more effective than a law that makes renovation mandatory. Even though after 30 years these two scenarios reach basically the same cumulative negative GWP value, the incentive proves to be more effective at the time step 2030, which is an interesting finding regarding how to translate climate goals into action-making.

The model helps understanding the temporal profile of emissions. However, it is needed to understand how much GHG emissions CO_2 eqv. Are the actual target by 2030 and, further down the road, this needs to be known by sector and geographic boundary, e.g. for Portuguese building stock.

4.3. Limitations of the study and future research

There is a high uncertainty of the renovation rates and dynamics. The here presented rates should be understood as such. However, they can provide policy-makers with the relevant figures to make informed choices on how to achieve climate targets. There is also uncertainty in the heating and cooling needs. For this reason, a sensitivity analysis was performed. Yet, these interesting dynamics of operational energy needs should be included in future studies, such as the one done by Peuportier *et al.* [22] who already modelled the energy demand of buildings and districts with a dynamic LCA approach that accounts for the temporal variation of electricity production, and of its consumption in buildings.

5. Conclusion

The present study used a specific type of building in a well-defined geographical area to test the effects of retrofit actions of exterior walls of residential buildings considering LC stages A1 to A5 and B6. The results highlight the environmental savings potential of bio-based material to support reaching national and global GHG emission targets. The cost and sensitivity analysis provides information for stakeholders to justify retrofit actions from an environmental and economic point of view. The adaptation of a fb-LCA approach and its application to the building sector has not been done before and proves to be an easy-to-use method to assess different technology options and policy scenarios at a neighbourhood scale.

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Potential for energy savings in Czech residential building stock by application of a prefabricated mass retrofitting system

Lupíšek A, Sojková K, Volf M, Hejtmánek P

University Centre for Energy Efficient Buildings, Czech Technical University in Prague, Třinecká 1024, 273 43 Buštěhrad, Czechia

antonin.lupisek@cvut.cz

Abstract. Buildings are responsible for a significant share of EU energy consumption. To improve energy efficiency of the building stock, it is needed to significantly increase renovation rates. To overcome actual barriers related to this problem, such as partial and non-systematic renovations, lasting unrest during renovation or time-consuming wet processes, an industrialized construction system using prefabricated modular elements seems to be a possible way. Such system for mass energy retrofitting of residential buildings in Central Europe was developed in H2020 project MORE-CONNECT. The work presented in this article aimed to roughly estimate potential yearly energy savings by applying this new modular retrofitting system on one typology segment of the Czech residential building stock: non-renovated multifamily residential buildings built between 1946 and 1960 with total gross floor area covering over 7 million square meters. The main objective of the research presented in this paper was to make a hypothetic rough estimation of potential yearly energy savings by applying the new modular retrofitting system on a target typology of the Czech residential building stock. According to the calculations, application of proposed retrofitting system on the chosen building type would reduce the total energy consumption in Czech residential buildings by 2.9 % and by 1.8 % compared to energy consumption in all Czech buildings.

1. Introduction

1.1. Need for improved renovation rates in EU building stock

As the European Commission states, *"Buildings are responsible for approximately 40 % of energy consumption and 36 % of CO_2 emissions in the EU. Currently, about 35 % of the EU's buildings are over 50 years old and almost 75 % of the building stock is energy inefficient, while only 0.4–1.2 % (depending on the country) of the building stock is renovated each year. Therefore, more renovation of existing buildings has the potential to lead to significant energy savings – potentially reducing the EU's total energy consumption by 5–6 % and lowering CO_2 emissions by about 5 %."* [1] Thus, finding new ways for unleashing the potential of deep energy retrofitting of the existing building stock is a major concern.

1.2. Barriers

Directorate-General for Internal Policies of the European Parliament in its study on boosting building renovation [2] identified five categories of barriers to renovation: awareness; process; regulatory; financial; and technical.

Since in Czechia there are ongoing public subsidies for renovation and energy savings campaigns, the last barrier – technical – was determined as the crucial one to boost the building renovation in short time period. A technical solution that would overcome disadvantages of present practice was needed.

The technical barriers are in the report further split into three sub-categories: lack of technical solutions; cost of technical solutions; lack of knowledge of the construction professionals. A potential response to these barriers was identified in creating a new retrofitting system that would engage industrialized production of elements at improved level of automation for a specific sub-group of the existing building stock due for retrofitting in the coming years.

1.3. European and Czech residential buildings stock

According to Buildings Performance Institute Europe BPIE [3] in 2011, residential buildings represented 75 % of the EU building stock. At least 80 % of residential buildings were older than 20 years and it seems that residential sector represents a major proportion of the energy-saving potential.

For Czechia, there is available an analysis of the national residential building stock [4] published by the Czech NGO Chance for Buildings. The report indicates that the group of single-family houses built before 1990 (built in poor energy standard) approximately accounts for a total gross floor area of at least 179.3 M m^2. For the multifamily residential buildings, the study presents 104.5 M m^2 in buildings built before 1980. Building stock built between 1946 and 1960 covers approx. 15.7 M m^2 according to the study, which represents 10.0 % of the total gross floor area in Czech multifamily residential buildings (as of 2011).

In another report on building stock renovation strategies [5], Chance for Buildings presents outcomes of a complex modelling of the Czech building stock that the total national energy consumption in buildings in 2016 was 349 PJ, of which residential buildings accounted for 224 PJ and non-residential buildings 125 PJ. The modelled energy consumption included the same consumption categories as energy performance certificates (heating, cooling, ventilation, air conditioning, hot water preparation, lighting, and auxiliary energy).

1.4. Modular retrofitting system for residential buildings as potential tool for significant energy savings in the Czech residential building stock

The EU project MORE-CONNECT [6–8] developed a new modular system for deep energy retrofitting of residential buildings in Central Europe to various energy levels including net zero energy level. The system is based on timber frame panels with thermal insulation for external insulation of façades and roofs and it integrates HVAC, monitoring and renewable energy systems in one package [9].

1.5. Objectives

The main objective of the research presented in this paper was to make a hypothetic rough estimation of potential yearly energy savings by applying the new modular retrofitting system on one typology segment of the Czech residential building stock. The question of interest was, whether it the energy saving potential is significant (i.e. at least 5 % of the final energy consumption of the Czech national building stock), or rather negligible (i.e. bellow 1 % of the final energy consumption of the Czech national building stock). When it turns to be significant, then it would be worthy to seek for policy support to make it happen. On the other hand, when it turns out to be negligible, it would not be worth further investigation.

2. Methods

To estimate the potential yearly energy savings, description of the building typology of concern had to be made at first. Second, a brief summary of the developed retrofitting system with key parameters was composed. Third, a case study of a typical multifamily residential building suitable for application of the new retrofitting system was made. Fourth, the results were roughly extrapolated to the suitable building stock using estimated savings in specific yearly energy consumption and the estimated floor area available for retrofitting.

2.1. Building typology of concern

The system developed in the MORE-CONNECT project was intended primarily for multifamily residential buildings typical for the post-war era. After 1945, there was a huge demand for new flats. At the same moment, left-oriented and since 1948 communist governments ruled the country having socially oriented agenda with the aim to secure jobs and flats for the people. A typical building of that era, that dominated the category of new multifamily residential building until 1960's, was a simple building of up to four floors, with flats of minimum floor area, massive structural external walls made of bricks of typical thickness of 45 cm, pitched roof with ceramic tiles on timber rafters with free loft area, typically with cellars partially underground (see CZ.N.AB.03 in Figure 1). After 1960, a new type of massive prefabrication stepped in and replaced the brick-and-mortar buildings by concrete slab housing, typical in Eastern part of Europe (CZ.N.AB.04 and CZ.N.AB.05 in Figure 1).

Both these typologies together present a major group in Czech building stock. The newer concrete slab houses were examined by Estonian partners of the MORE-CONNECT project, this paper deals with the multifamily residential buildings built before 1960 (CZ.N.AB.03). Their building typology has a high potential for application of precast modular retrofitting solution because of its energy inefficiency; simple design with low architectural quality; or high number of similar building with unified design. It also carries further challenges concerning low quality of after-war materials and thus its structures.

Figure 1. Overview of Czech residential building typologies with a highlighted typology of concern. Figure taken from TABULA report [10].

2.2. New system for modular retrofitting of post-war residential buildings

To provide desired rapid refurbishment to the building owners and users, the new system was designed to integrate as much functions as possible. Complete building refurbishment thus uses number of structural prefabricated modules (wall, roof, basement module, balcony) and technological modules (ventilation module, engine room etc.). These modules get combined and connected to the existing building using tailor-made steel anchors. The main load-bearing core of the structural modules was created by timber frame and strengthened with fibre boards. Interior side of the modules is designed to fit tightly to the uneven original façade surfaces. The system is variable; the total *U*-values of the refurbished envelope can vary within wide range of values. The core is fitted with main layer of thermal insulation and the module is finished with external thermal insulation of variable thickness with final façade layer. Where needed, the thermal bridges are minimized using aerogel. Windows equipped with electric window blinds are part of the module. The system also enables extension of the unit's floor area by attaching an additional balcony.
Structural elements are fitted with all necessary technologies: HVAC providing air ventilation with heat recovery, hydraulic heating pipes, electric window blinds to control overheating. In the Czech case, the engine room would be installed in one of the empty rooms in the building basement. There were developed inter-modular connectors that enable connection of the integrated sensors for monitoring indoor air humidity, temperature, or moisture content with control system and equipping each apartment with new Wi-Fi routers. The indoor environment in apartment can be controlled by app on smart phone or tablet. Further technical information is available in [9].

Complete solution is protected by national utility model.

2.3. Case study of a typical representative of the typology

2.3.1. Description of the building. As a reference building, a post-war residential block in Milevsko, Czechia, built in 1958 was chosen. The building by its typology and material basis represents a significant part of the residential housing stock of Czechia suitable for retrofitting. This particular building, used as social housing, has 24 studios (living/sleeping room, kitchen, bathroom), 31 m^2 each, in three stories (see Figure 2).

Figure 2. The building type from the case study in Milevsko, Czechia.

Each flat has two windows oriented either to the east or to the west. Technical and housing facilities and cellars are put in the basement, which is partially underground. Entrance to the building is from the north, leading to the wide central hall with north-south orientation. At the southern façade, central hall is ended with a loggia. The building has a gable roof (33°), attic space is currently unused. Building has longitudinal wall structural system made of bricks (450 mm), ceilings are made of reinforced concrete. Façades are plastered, original windows and exterior doors have been replaced with insulating double-glazed ones with plastic frame.

2.3.2. Retrofitting strategy. The general strategy came out from the analysis of typical representatives of the select typology, their technical shape and needs, and from the SWOT analysis of typical common retrofitting interventions offered on the market nowadays. The limitations given by the building typology are given by the fact that the major part of the building envelope is at the same moment the load bearing structure – typically the masonry walls of 450–600 mm form the supporting structure for the concrete floor structures. Therefore, there is no option for their replacement, the only way is to make an addition upon the existing walls. There is also planned an additional layer of thermal insulation to be placed in the attic and the floor above the cellar will be insulated as well. A mechanical ventilation system with heat recovery supplies fresh air into each of living rooms and can also provide space heating. The air ducts are integrated in the wall panels together with sensors for controlling the indoor environment in each apartment.

2.3.3. Simulation outcomes. For the case study building, a set of computational simulations has been performed both for the state before renovation and for the renovated building. Results of these simulations have been used for estimation of energy savings presented in this section.

Before renovation, calculated total energy consumption accounted to 308–318 kWh/(m^2·a), energy consumption for heating was 230–237 kWh/(m^2·a) (depending on a heat source – district heating system and natural gas boiler were considered as initial state). The report [10] indicates for the given typology typical specific energy consumption for heating 222 kWh/(m^2.a), which is in line with our case study.

Common retrofitting practice is wall insulation with ETICS supplemented with insulation of attic and the floor above the cellar, and windows replacement. However, as can be seen from the report [11], the renovation employing the MORE-CONNECT system provides a solution of a higher standard with comparable costs. Therefore, a potential of energy savings presented further in the text is based on the MORE-CONNECT solution.

Depending on a renovation level and a possible heat source replacement (see [11] for details, results presented there expressed in primary energy and GWP), total energy consumption can decrease up to 33–90 kWh/(m^2·a) (89–71% savings), which corresponds to specific energy consumption for heating between 25–41 kWh/(m^2·a) (89–82% savings). Thanks to mechanical ventilation, *U*-values at a passive standard level (mean *U*-value is 0.25 W/(m^2·K)), and generally deep energy retrofitting, this surpasses the predictions reported in [10] where typical energy need for heating after application of progressive measures reaches 63 kWh/(m^2·a). Expressed as specific energy saving potential, retrofitting using MORE-CONNECT solution can save 251 kWh/(m^2·a) from total energy consumption in average (up to 285 kWh/(m^2·a) at maximum).

2.4. Extrapolation to the building stock

For further calculations, the total gross floor area of the Czech multi-family residential building stock built between 1946 and 1960 of approx. 15,657,000 m^2 [4] was used as a basis. The developed solution has limitation given by the national fire safety regulations, which forbid combustible products to be used in the envelopes of buildings with fire height above 12.0 m (i.e. distance between first and the upmost flooring). This regulation reduces the applicable gross floor area to 10,926,000 m^2 of buildings up to four floors. As mentioned in the introduction, 35 % of the Czech residential buildings have already been retrofitted, so the remaining gross floor area available for retrofitting has to be reduced to 7,101,900 m^2.

3. Results

The result of the rough estimation comes from a simplistic multiplication of the gross floor area available for retrofitting by the specific energy saving potential coming from the case study. The resulting hypothetical energy consumption saving potential (when the proposed system gets applied to all suitable multifamily residential buildings in Czechia) is 1,783 GWh/a. The figure represents 1.8 % saving on the total national energy consumption in buildings and 2.9 % of total national energy consumption in residential buildings (compared to 2016 baseline).

4. Discussion

4.1. Limitations of the study

There are many sources of uncertainties in the study. Firstly, it is based just on one case study, which cannot be taken as representation of the whole residential building stock. At the same moment, the statistics behind the figures on the Czech building stock are potentially inaccurate.

On the other hand, the purpose of the study was only to tell globally whether the potential energy savings from the proposed mass retrofitting would be significant or negligible.

4.2. Conclusion

The result of the calculation showed, that the potential for savings in the energy consumption of the residential buildings is 1,783 GWh/a, which represents 1.8% saving on the total national energy consumption in buildings and 2.9 %, of total national energy consumption in residential buildings (compared to 2016 baseline). The result is not significant, but not negligible. A bold policy action on the national scale would not be justified, on the other hand, it is worth trying to discuss with the policy makers inclusion of the support of this type of energy renovation into the national subsidy schemes for energy savings in buildings and to look for suitable industrial partners for market uptake.

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ENERFUND - Identifying and rating deep renovation opportunities

Geissler S[1], Androutsopoulos A[2], Charalambides A G[3], Jareño Escudero C[4], Jensen O M[5], Kyriacou O[3], Petran H[6]

[1] SERA energy & resources, Westbahnstraße 26/15, 1070 Vienna, Austria
[2] Center for Renewable Energy Sources and Saving (CRES), Buildings Department, 19th km Marathonos Av., 19009 Athens, Greece
[3] Cyprus University of Technology, Sustainable Energy Laboratory, Lemesos, Cyprus
[4] Valencia Institute of Building (IVE), Tres Forques, 98, 46018-Valencia, Spain
[5] Aalborg University, Campuys Copenhagen, A.C. Meyers Vænge 15, DK 2450 Copenhagen, Denmark
[6] NIRD URBAN-INCERC, 266 Sos. Pantelimon, 021652 Bucharest, Romania

s.geissler@sera.global

Abstract. European Directive (EU) 2018/844 amending Directives 2010/31/EU (EPBD) and 2012/27/EU (EED) aims at decarbonizing the European building stock. Energy efficiency measures and renewable energy use play an important role, especially regarding retrofit of existing buildings. Identification of retrofit opportunities and aggregation of projects to benefit from economy of scale are a precondition for the implementation of large-scale renovation projects. The ENERFUND project, funded by the HORIZON 2020 programme, provides data from Energy Performance Certificates according to EPBD publicly available in the form of a map and combines them with other geo-referenced data and general information to allow for the rating of deep renovation and carbon reduction opportunities. In this way, the tool assists in identifying retrofit opportunities and aggregation of projects for financing. It also assists in supply-side energy spatial planning, because it shows where energy consumption is likely to decrease due to economic renovation potentials. This contribution shows an overview of data available for thirteen European Member States. Data sources and differences regarding the type of data are explained, and challenges such as data quality issues and data protection concerns are discussed. It is demonstrated that the ENERFUND tool certainly assists in decarbonizing the European building stock, although some improvements are still necessary.

1. Introduction

The Energy Roadmap 2050 is the European Union's long-term strategy to achieve the goal of securing sustainable energy supplies. This effort builds on the first package of climate and energy policies adopted in 2008 and on the framework for climate and energy policy until 2030 agreed upon in 2014, representing the so called Energy Union. Among other important aspects such as research, innovation and competitiveness needed for the transformation of the energy system, climate protection and the conversion to a low-carbon economy, the priority for energy efficiency is explicitly stated.

On 30 November 2016, the European Commission presented several documents intended to achieve the transition to a sustainable energy system. Among others, there were proposals for the revision of Directive 2012/27/EU (Energy Efficiency Directive EED), Directive 2009/28/EC

(Renewable Energy Directive) and Directive 2010/31/EU (Energy Performance of Buildings Directive EPBD), as well as the proposal for a regulation on governance, in order to ensure Member States' coordinated reporting on compliance, particularly with the EU Energy and Climate Targets by 2030.

In this article, the focus is on the building sector and especially on improving the energy efficiency of existing buildings. The amending Directive (EU) 2018/844 resulting from the proposals for revisions of the EPBD and the EED, transfers the long-term renovation strategy from the EED to the EPBD and introduces the obligation to specify detailed targets and milestones. Furthermore, the progress achieved shall be reported thoroughly. The new EPBD article 2a "Long-term Renovation Strategy" stipulates that each Member State must ensure a highly energy-efficient and decarbonized national building stock, with a roadmap of indicative milestones for 2030, 2040 and 2050. In order to support the mobilization of investments in renovation, Member States shall, inter alia, facilitate access to appropriate mechanisms. For example, the bundling of projects provides a possibility for small and medium-sized enterprises to gain easier access to financing (article 2a number 3 (EU) 2018/844). The goal is to develop large-scale renovation projects that can be implemented more cost-effectively than many small individual renovation projects. The new article 2a is a reaction to the fact that the 3% renovation rate has not been achieved despite years of effort (see also rec. 10 (EU) 2018/844).

With regard to energy performance certificate (EPC) databases, Directive (EU) 2018/844 introduces two new paragraphs 6a and 6b into Article 10 (6) of Directive 2010/31/EU, stating that EPC databases allow the collection of measured or calculated energy consumption of the buildings covered. At the minimum, the anonymized data collected in accordance with the data protection requirements of the Union and its Member States, shall then be made available for statistical and research purposes. These data will also be at the building owner's disposal.

The ENERFUND project explicitly aims at making use of EPC databases having been established in many EU Member States in the process of implementing the independent control system according to article 18 EPBD. A tool was developed to display energy related building data in a geo-referenced way by means of a Geographical Information System (GIS), in order to allow for identifying areas of interest for large scale and deep building renovations.

This article explains the development process of this instrument, describes encountered challenges, and shows an overview of selected country results. It concludes with a presentation of lessons learnt and future outlook.

2. Developing the ENERFUND Tool

2.1 Objectives and technical solution

The aim of the ENERFUND tool is to be a quick evaluation instrument, assisting financial institutions, owners and ESCOs interested in examining the feasibility or usefulness of deep energy renovation of commercial and other buildings in a thorough way. Therefore, identified open source databases with significant information about building energy performance were integrated in the tool in a user-friendly manner. The interface of the tool is a European map which displays buildings and building units with coloured dots, in accordance to their energy label and with several filtering options in order to assist the user to narrow the range of screening buildings according to his or her preferences. At the home page of the ENERFUND tool, a drop-down list with all countries involved is available, in order to minimise the processing duration due to the large amount of integrated data. Additionally, after selecting the country of interest, the user can compare buildings and view detailed information regarding their energy performance along with other information for the building. Furthermore, the tool provides the ENERFUND score per building or building unit on a per cent scale. This score can be used to compare buildings of any country, since the score formula used is common for all countries. Finally, the user can produce a report based on the selection criteria. As a future development of the tool, in order to increase the tool's functionality and accuracy, user inputs regarding the selected buildings will be enabled.

2.2 Available data source

In order to identify the most important data and parameters for the development of the ENERFUND tool, several key elements and criteria were initially examined according to previous studies, expert's opinions and surveys conducted in the framework of the ENERFUND project. EPC databases were identified as the major databases for the ENERFUND tool since they include a variety of important information for the energy performance of the buildings [1]. Nevertheless, additional available databases, including significant data for the energy renovation decision making process, such as Noise Databases and Building Price Databases were embedded. The level of publicly available information in EPC databases varies between Member States. In some cases, open access to EPC data is provided directly from the database of the competent authorities (such as Denmark, Bulgaria, the Netherlands, the United Kingdom); whereas in others, only aggregated results are made publicly available (such as Greece, France and Romania). However, in most of the countries studied (i.e. Cyprus, Austria), there is no publicly available access to the EPC database. Complete access to the core of the database, meaning access to all raw data, is not provided by most Member States [2]. Furthermore, in none of the studied cases data were geocoded in a way that would allow automatic mapping on the ENERFUND map.

2.3 ENERFUND score

The ENERFUND score assists the decision-making process for the energy renovation of buildings and is based on a Multi Criteria Analysis methodology. It is a result of an equation that uses eight main parameters, with different weight factors, which have been selected as key parameters for building energy retrofitting: Total Area and Energy Saving Potential (Mandatory Parameters), Construction Year, Average Building Sale Price, Occupancy Level, Own Contribution (to financing renovation), Noise Levels and Building Ownership Status. ENERFUND score uses data only from open databases available in the EU, in order to maintain up to date data. In case that any of the above parameters are not available, default values have been used. The highest score that can be granted is hundred.

3. Member States data embedded in the tool

3.1 Overview of country data

In February 2019, approximately eight million EPCs were mapped across thirteen Member States. In total more than seventy million unique data entries (such us wall energy efficiency, construction year, etc.) are available in the context of this tool, but still availability differs from country to country. For example in Slovakia, only the EPC rating and the building type are available in the tool, while for the UK, ten parameters per EPC are available. In the following sections, three countries, representing different situations, are described in detail by answering the next questions:

- How were the data made available for ENERFUND? What had to be discussed, agreed upon, or clarified?
- Is the full EPC data set included or only part of it?
- What are the reasons for a country-specific partial availability?
- What difficulties were encountered to get the data for ENERFUND and what were the solutions provided?
- What is the opinion regarding data quality and data protection?
- Which specific features are especially interesting for which target groups?
- What are the lessons learnt?

3.2 Denmark

Ever since the first EPC scheme was launched in 1997, all Danish EPCs issued were uploaded to one central database hosted by the Danish Energy Agency. Following EU legislation, the legal framework of the Danish EPC scheme has undergone several revisions. The last major revisions were in 2006 and 2011.

The first time the Danish EPC database was made available to the ENERFUND tool, all EPCs issued since 2006 were part of the data transfer. This first transfer was based on a 2015 copy of all Danish EPCs including domestic and non-domestic buildings. A quality filter ensured that only EPCs with reasonable data would be accepted. Therefore, by definition the full Danish EPC data based on the 2015 copy have been made available for the ENERFUND tool. Due to lack of permission to use data from the live database, all EPCs issued at a later date could not be included. This difficulty has now been overcome thanks to a direct University access to the EPC database. Put otherwise, now a new updated EPC data copy can be extracted at any time and transferred into the ENERFUND tool.

The quality of Danish EPCs has been increasing steadily. Since the revision of 2006, all EPCs are presumed high quality records. Concerning data protection, only buildings owned by the Ministry of Defence must be observed.

Since COP 21 and the Paris agreement, Danish target groups, especially Danish municipalities, have put special interest on the ENERFUND decarbonizing rating feature, i.e. the possibility to compare buildings concerning their carbon reduction potential. This not only applies to municipal owned buildings but also to private domestic and non-domestic buildings located on the territory of the municipality. The reason is that politicians and local authorities of a number of municipalities hold themselves responsible to meet the Paris agreement, and buildings stand for a large share of greenhouse gas emissions.

3.3 Spain

Spain follows a regional approach for the certification procedure, therefore there are no central registers, but smaller, regional ones instead. Considerable effort was necessary to transfer EPC data into the ENERFUND tool. First, it was analysed which data were available online. It was found that only ten out of nineteen registers were accessible through the internet; furthermore they use different search parameters depending on the region. The EPC rating is the only parameter all of them have in common. Secondly, the availability of geocoded data was investigated. Only two out of these ten regions displayed geocoded data, but only one presented it in such a way that it was downloadable as open data. In Royal Decree 235/2013 it was stated that the registers would allow citizens to access the information on energy performance certificates. Implementation is being realized little by little.

Finally, data for four regions are available on the tool: Comunidad Valenciana, Cataluña, Castilla La Mancha and País Vasco. Since EPC data were stored in different ways depending on regional registers, approaches to make these data available for ENERFUND vary accordingly. One region showed special interest to provide data in a quality that allows automatic updating and availability in the tool. This represents one of the ENERFUND success cases.

In Spain the full EPC dataset is not publicly available, that is the reason why only data on the EPC label is accessible within the ENERFUND tool. As a consequence, stakeholders do not consider data protection as a problem: the tool only shows data that is already public anyway. For instance, public buildings must show EPC label data.

Summarizing, the ENERFUND tool is considered to be very interesting and useful by the Spanish majority. Nevertheless, there is a need to standardize the storage and the online public availability of data among the different regions. These data should also be downloadable in a homogeneous format.

3.4 Romania

In the case of Romania, the process of implementing available EPC data in a structured format to meet the program’s requirements, started also with the national EPC database.

The national EPC database was first introduced in the legal framework in 2007 and started to receive EPCs from energy auditors for buildings in 2008. Although a full structure of the database was defined in 2010 (with an xml format for making the system automatic) and another application was developed by the responsible authority in 2016 to facilitate the on-line submission of EPCs, the system is running manually, with EPCs sent by e-mail and stored by the energy auditor.

Since there is a great diversity of received (electronic) formats (pdf, doc, docx, xls, xlsm, xlsx, jpg, tiff, gif, html, etc.), either as the final draft document or scanned copy of the signed and stamped EPC, it is almost impossible to transform the gathered information into structured data that can be further processed to supply meaningful performance information about the existing building stock.

In this context, the data to be introduced into the ENERFUND app were based on about 46,000 EPCs that were entered manually into the structured database (11,300 buildings and 34,700 individual apartments in collective buildings), representing three to four percent of all issued EPCs. The data were geo-located, filtered and introduced on the map, both as individual data and in aggregated form. The first step of aggregating data at county level did not lead to useful information (area too big), so the aggregation was performed later at smaller areas (small city or district in large cities).

The difficulties encountered in entering data into ENERFUND were first in finding relevant data (except EPCs) and secondly geocoding available data. Most of the data needed to calculate the ENERFUND score were not available and thus considered from default values (same for all areas).

The public status of the EPC data is not specifically defined, however no explicit prohibition to publish the EPC information exists in the legal framework. On the other hand, the EPC does not contain any personal data related to the building owner.

The ENERFUND features are widely appreciated by all stakeholders, but without the introduction of relevant data, the tool is not of appropriate advantage for any interested party. Thus, the population of the tool with detailed EPC data together with other type of information (like social and income information aggregated at district area, availability of experts and specialised construction companies, energy and utilities map, renovated buildings etc.) could lead to an important raise in the usefulness of the tool. Moreover, all data should be geocoded in order to facilitate the integration in the tool; the new EPC template (methodology under revision) must include geo-coordinates that should be reported in the database.

4. Challenges encountered and lessons learnt

4.1 Challenges encountered

Regarding the data necessary for a successful transfer into the ENERFUND tool, the following problems have arisen:

- EPC data is not publicly available, or in electric format that can be easily used by the public or even by the relevant authorities.
- EPC data was not geocoded and therefore it took longer than expected to display the data on the map. Geocoded addresses do exist (see for example INSPIRE directive [3]), but are not yet linked with EPC data addresses.
- In some countries, EPCs issued in the course of renting or selling a building or a building unit, are not fully trusted. The reason is that energy performance calculation is done based on default values, and often the building is not even visited.
- EPC data is not harmonised across all Member States. In some cases, all data to calculate the EPC rating is available (i.e. door surface area), while in others, only the EPC rating is available, thus making the database unusable for the needs of the ENERFUND tool. Furthermore, the classification of each data category is not standardized, therefore cross-country comparison is not always feasible.

4.2 Open Government Data (OGD) versus General Data Protection Regulation (GDPR)

Energy-related building data displayed by the EPC and describing the technical characteristics of a building can be classified as non-personal data because energy efficiency indicators are calculated using standardized usage profiles without reference to the actual users of a building. Non-personal data do not fall under the GDPR [4] but can be classified OGD if specific requirements are met, such as reliability of information, relevance for the public, and rights to publish the data. OGD are data of the administration, which are accessible to the general public for free use, distribution, and further disposition. Legal bases are several EU directives, for example Directive 2013/37/EU (re-use of public sector information) and Directive 2003/4/EG (public access to environmental information).

Reference is made here to Directive 2007/2/EC as the basis for creating a common spatial information infrastructure in the European Union (INSPIRE). The visualization of the building address is the prerequisite for the publicly accessible, geo-referenced presentation of EPC data and the utilization of information for project developments and innovations. However, in some cases, the building address could be combined with the registry showing the principal residences and thus represent a case of identifiability of individuals according to GDPR. Under this perspective, the address of a residential building can be viewed as personal data. If the GDPR applies, rules for lawful data processing will be mandatory. Usually, lawful processing takes place according to article 6 (1) e GDPR (if there is public interest) or article 6 (1) f GDPR (if there is legitimate interest).

However, there is a range of interpretation regarding the definition of "identifiability" and also "public interest". While in some countries accessibility of EPC data is clearly regulated, there is no clear view on how to deal with it in other countries, for example in Austria: there is no agreed approach on how to define identifiability and there is no established mechanism how to balance public interest against personal rights. It must be noted that the GDPR is not about data protection as such, but about the protection of personal rights. These rights must be balanced against the public interest in accessible information needed for awareness creation and better decision-making. Public access to EPC data can be seen in the context of the INSPIRE Directive, as illustrated by a JRC report on the harmonization of EPC data for use in a common spatial information infrastructure [5]. However, this report is not strong enough to invalidate GDPR-related concerns. A guidance note issued by the European Commission on the public access to geocoded building related EPC data would be useful.

4.3 Quality of EPC data: reliability, comparability, electronic format

The main data source for the ENERFUND tool is represented by the available set of EPCs for a specific country or region. Since its definition and enforcement, the EPC was acknowledged with the potential to become an effective tool to support the implementation of building policies and incentives to upgrade the energy performance of buildings. Achieving the desired impact in the market strongly depends on the actual quality of EPCs, which can be achieved through the implementation of a clear calculation methodology with explicit procedures, the creation of effective tools for calculating or selecting inputs, and the approval of a robust compliance check frame.

The issue of quality of EPC data is twofold: on the one hand the quality of the energy performance certification process, and on the other hand the quality of EPC data to fit into the ENERFUND tool requirements in order to facilitate the decision for building renovation. Another European project, the QUALICHeCK project, confirmed that problems do exist with EPC quality and input data, as well as with compliance frameworks which are still in the development process in all countries [6]. As an example, a new field study on the assessment of quality and compliance in the EPC system in Romania [7] showed that recalculation of 25 EPCs based on field-proven input data lead to a change in energy class in almost 40% of the sample for the total energy use. Although progress can be seen in most Member States, the status on the ground needs continuous monitoring. More efforts should be put into systematic data collection and the application of validation procedures in order to assure the credibility of energy performance requirements and EPC system.

A solution for these problems could be the implementation of an on-line submission of EPC data, based on a defined electronic format as it is already used by many Member States. Developing the structure and defining the requirements for an electronic format of issued EPCs to feed the central EPC register can facilitate access in real time to building stock data together with tools for the plausibility and quality checks of relevant data. Furthermore, the application of the EPC control system will be facilitated, thus improving the quality of EPC elaboration by providing feedback to energy auditors of buildings.

However, even if country specific information is publicly available in a format easy to display by means of GIS, the problem of lacking comparability remains when data from different countries should be assessed. Energy performance category B of a building in Denmark does not imply the same primary energy demand compared with energy performance category B of a building in Greece. Energy performance requirements of building components such as U-values of windows are different in Austria and Spain, for example. Nevertheless, the purpose of the ENERFUND tool is to present the building data in the most possible coherent way to help the user identifying opportunities for businesses related with deep renovation of buildings. Some information is necessarily specific to a country or even region, due to climatic reasons. Therefore the method of introducing a qualitative scale ranging from “very good” to “very poor” was introduced. However, it will be useful to specify a minimum number of data fields for geo-referenced presentation in a uniform way, such as year of construction, type of building use, m^2 useful area, type of fuel used, year of EPC issuance, overall energy performance rating, rating of energy efficiency of the walls, windows, roofs, and heating system. This format should be made mandatory for all EU Member States, as well as the obligation to make this information publicly accessible.

5. Conclusions and Outlook

5.1 Future tool development

An update of the ENERFUND tool will include a carbon-reduction benchmark. Thereby, the decarbonizing potential of any building or whatever selection of buildings can be benchmarked against any other building or selection of buildings. The carbon emission feature will be based on the actual and potential energy consumption, and in case this information is missing, the actual and potential EPC rating values. Combined with knowledge about the national energy mix or preferentially the energy supply labelling of each building, the buildings can be furnished with a carbon emission reduction benchmark. Moreover, this information can be used for a decarbonizing score.

The first countries are in preparation for GIS visualization of their carbon emission benchmarks. Among these is Denmark with an EPC data set containing the buildings’ actual and potential energy demand, and - in addition - the sort of energy supply for each building like electricity, natural gas, district heating and fuel oil. A list of carbon emission factors of each fuel and regarding electricity and district heating, the actual kg of carbon emission per kWh delivered, completes the data set.

In other words, with these features in place, the ENERFUND tool definitely will be able to contribute to the decarbonizing of the European building stock.

5.2 Recommendations

The EPBD does not require an electronic EPC database to be used as the basis for the establishment and operation of the independent EPC control system. However, many Member States or regions have chosen this approach because effective control is otherwise difficult in a cost-effective way. It also implies the possibility of using the data for energy-related purposes other than the control of energy performance certificates. The EPC is thus not only used for information on the energetic state of the building, but the underlying calculations and technical documentations are also valuable to build up databases for different purposes: for strategic investigations, project developments, and statistical analyses.

Public access to geo-referenced EPC data plays an important role in raising awareness and participation as part of the Long Term Renovation Strategy, and also in strengthening innovation in the development of products and services for greater energy efficiency and reduction of CO_2 emissions. The analysis presented here shows that harmonization across Europe is urgently needed in two ways: first, regarding energy data as such, and second, regarding geo-coding and public accessibility.

Therefore, the ENERFUND project will conclude with a recommendation to the European Commission and DG Energy in particular, that harmonisation of all energy data, not only EPC data, - and their geocoding - should become mandatory across all Member States.

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Defining a framework to apply retrofitting optimisation models for long-term and step-by-step renovation approaches

Maia I, Kranzl L

Technische Universität Wien

maia@eeg.tuwien.ac.at

Abstract. The recast of Energy Performance of Buildings Directive (EPBD) 2018/844/EU introduced in the article 19a the possibility of building renovation passports which provide a long-term and step-by-step deep renovation roadmap for a specific building. Preliminary results showed that optimisation models for deep renovation of existing building almost exclusively optimise single stage retrofitting. Different from the single stage approach, in the step-by-step approach the retrofitting measures are not performed at the same time. In the present study, we aim to understand how the methodological approach of optimisation models for single stage retrofitting can be adapted to a step-by-step renovation concept. For this, first, the existing optimisation models were compared in terms of integration with external tools for energy demand calculation, definition of the renovation measures, objective function, and the question to which extent they consider long-term dynamic aspects of step-wise retrofitting optimisation over several years or even decades. Second, after identifying possible obstacles for adapting existing optimisation approaches towards step-by-step renovation, a framework for a step by step renovation optimisation model was outlined. The framework defines how the single stage retrofitting measures could be broken down in different renovation steps over a period of several years or even decades and which criteria should determine the time-wise prioritisation of the retrofitting measures. With this approach, we prepare the ground for the development of innovative tools, supporting the provision of individual renovation roadmaps. Next steps of the present study are testing and improving the outlined optimisation approach, as well as, extending the results to a building stock scale. By that, we aim to develop a method for analysing possible impacts of step-by-step renovation measures on achieving building stock's decarbonisation targets.

1. Introduction

The building sector has been identified as one of the key sectors for achieving the energy and climate policy targets of the EU, as buildings are responsible for 40% of energy consumption and 36% of CO_2 emissions in the EU [1]. Although huge efforts have been made to reduce the energy demand of buildings, recent statistical data about final energy consumption in households [2] and share of final energy consumption per fuel [3] have shown that there is still a long pathway to achieve the EU-targets. Therefore, is it necessary to find alternative deep renovation concepts for the building stock decarbonisation.

The EPBD recast 2018/844/EU introduced in the article 19a the possibility of building renovation passports, which provide a long-term and step-by-step deep renovation roadmap for a specific building. The step-by-step deep renovation roadmap is at its core a home-improvement long-term plan, which considers the occupants' needs and specific situations and avoids the risk of lock-in effects, if future renovation measures are not considered in current activities. This document guide and help building owners through the renovation process, therefore dealing as an instrument to overcome barriers, as lack of acceptance. The building renovation passport is definitely an important instrument at EU level, to support deep renovation of existing buildings and bridge the gap between real renovation processes and the EU-targets for building stock decarbonisation.

In the literature, there is no consensus that deep renovation can also be achieved by a sequence of step-by-step renovation measures, which indicates that in fact, "deep renovation" is not necessarily restricted to single stage renovation. Nevertheless, creating more comprehensive modelling for this alternative retrofitting concept could help on accelerating the decarbonisation of the building stock due to suitable and right timing measures. In Europe, there are already some demonstration projects, which focus on the key concept of building passports, as the iBRoad EU-funded project, which works on eliminating the barriers between house owners and building energy performance, by developing building passport and step-by-step long-term deep renovation planning tool for single-family houses. Also, taking into consideration that in real life, the most retrofits activities are performed step-by-step [4], the main goal of the present paper is to outline a framework for the step-by-step renovation by adapting optimisation models for single stage retrofitting, and preparing the ground for the development of innovative tools, supporting the provision of individual renovation roadmaps.

2. Outlining a framework for step-by-step optimisation

Literature review

A retrofitting optimisation model aims at calculating the optimum solution of retrofitting measures' combination. The optimal retrofit strategy may include ecological (i.e. energy savings, CO_2 emissions, environmental impacts) and economic (i.e. net present value, investment cost, payback time, life cycle costs) objectives and/or restrictions. Many studies have presented different methods for selecting this most suitable solution, differing according to the targeted benefits, which are represented by the objective function. Therefore, the main objective of the literature review is to compare several models and to prepare the ground for outlining a framework for step-by-step optimization modelling.

The models are compared in terms of integration with external tools and database, definition of the renovation measures and, methodological approach and aspects of time wise dynamic retrofitting over several years or even decades. It was observed that most papers studied do not cover the dynamic time wise aspect by considering that retrofitting measures are applied at the same time, so called single stage retrofitting. Further conclusions to that are presented in the end of this chapter.

Most recently, Jafari et al. [5] reviewed at least sixteen literatures about energy efficiency decision-making, including not only multi-objective optimisation, but also other methods like multi-criteria, techno-economic evaluation method and others. The same authors present an optimisation framework to minimize the future cost (life cycle cost minus initial investment costs) of a building. In this approach, the energy savings are indirectly represented by the energy costs, which are part of the life cycle costs. The set of retrofitting measures goes beyond building envelope (ceilings, walls, attic insulation), including load reduction measures (heating and cooling), controlling measures (ie. programmable thermostat) and renewables option (i.e. solar thermal and solar electricity).

Pombo et al. [6] compare different retrofitting solutions, using a multi-criteria methodology. This study combines Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) by expressing environmental impacts in monetary values. Here, the minimum investment cost and minimum life cycle savings are determined through a Pareto curve. The set of renovation measures chosen aimed at reducing space heating and cooling demand by insulating roof and façade, changing the windows and installing a heat recovery system. Asadi et al.[7] developed a model to assist stakeholders in the definition of measures aiming at minimizing the energy needs for heating, cooling and domestic hot water, and maximizing the investment costs. As set of retrofit actions, the authors considered window replacement, external wall and roof insulation and solar collector type. Wang et al.[8] proposed a life cycle cost approach, which

aimed at maximizing energy savings and net present value while minimizing the initial costs. The chosen measures were lighting facilities, heat pumps, chiller, control systems and other devices, with focus on reducing the electricity energy demand. Murray et al. [9] coupled a degree-days simulation with a generic optimisation procedure algorithms and compared both implemented and calculated retrofit solutions. This study aimed at minimizing the energy cost and carbon emissions post-retrofit, under the consideration of a payback period of maximum 5 years and capital investment. The adjustable parameter set were U-value from Attic, external walls and windows, boiler type and infiltration rate.
Table 1–summarises the studies presented above, its methods, main objective functions and chosen measures.

Table 1: Summary State of the Art

Refe-rence	Title	Objective Functions Optimised	Benefits							Time step of the measures	Energy performance method
			Energy consumption	Retroffing measures	Energy cost	Retrofittig cost	Building material charactheristic	Maintenance cost	Thermal comfort		
[9]	Optimization for Building energy retrofits decision making	Minimizes the total life cost Maximizes home owners economic benefits (optimum retrofit benefit) Budget restriction	x	x	x (natural gas, and electricity)	x		x		Single-stage	eQUEST
[11]	Multi objective optimatisation for building retrofit	Minimizes retrofit costs Maximizes energy savings	x	x		x				Single-stage	Simple thermal model – building code based (RCCTE - Portuguese), based on thee ISO 13790
[18]	Sustainable retrofits under uncertainities	No				x	x			Single-stage vrs multi-stage	No
[12]	Multi-objective optimization model for the life-cycle cost analysisand retrofitting planning of buildings	Maximizes energy saving Maximizes the discount pay back period Minimizes initial costs	x	x	x (electricity)	x	x	x		Single-stage	Unknown
[19]	A new methodology for investigating the cost-optimality of energy retrofitting a building category	Bottow up approach	x	x	x	x			x	Single stage	Energy Plus
[10]	Sustainability assessment of energy saving measures: A multi-riteria approach for residential buildings retrofitting—A case study of the Spanish housing stock	Minimum investment cost Maximum life cycle savings	x	x		x	x			Single stage	Energy Plus and DesignBuilder
[13]	Multi-variable optimization of thermal energy efficiency retrofitting ofbuildings using static modelling and genetic algorithms - A case study	Minimum energy cost Minimum carbon emission Maximum simple pay back time	x	x	x	x				Single stage	CIBSE Guide TM41, Degree Days

In the literature review some differences between the studies were observed, as for example the energy performance calculation method. While some authors used simplified calculation procedures, others used more complex dynamic simulation programs. On the other hand, all methods have in common not presenting any indication about the timing, when the retrofit measures are performed. In terms of the dynamic time wise, any of those papers explicitly mention this aspect, this leads to the conclusion that it is considered that the retrofitting measures are applied at the same time, so called single stage retrofitting.

Different from the single stage approach, in the step-by-step approach retrofitting measures are not performed at the same time. Previous studies [10] on historical energy performance and deep renovation trends in the German's residential building stock proved that in many buildings single renovation measures (only windows replacement, or only roof insulation) have been performed. Beyond that, Steiger [4] affirmed that in real life, most retrofit activities are performed step-by-step sequences, and Menassa [11] presented financial advantages of multi stage retrofitting. Thus, step-by-step renovation modelling deals with following questions: how to define a renovation step? Which retrofitting measures are performed in a step? When are they performed? In which sequence are they performed?

Outlining the step-by-step optimisation approach

In the step-by-step concept, a step consists of combination of one or more retrofitting measures. The literature review showed that common retrofitting measures are: insulating building elements external walls, roof (or top floor ceiling) and floor, replacing windows, and active system (heating, cooling, ventilation, lighting and domestic hot water). In real-life, other aspects like construction site preparation and scaffold costs, are also relevant to define, if the measures will be performed together, or not.

During a building's life cycle, maintenance and operation activities constantly happen to avoid first stages of degradation and failure of building elements [12]. At the same time, usual maintenance activities and/or material replacement provide an opportunity for increasing building element's energy efficiency, and consequently improving building's energy performance. Refurbishment activities can be induced by unpredictable damages, as breaks, leakages and cracks, familiar circumstances i.e. children birth and family members move out, etc. Or predictable parameters, as material's durability, which defines the material's lifetime. In a study about factors influencing German house owner's preferences on energy retrofits, the authors [13] concluded that most homeowners have a rational behavior to wait until building components end of their useful life before approaching renovation or replacement. Therefore, predicting the building materials' aging process helps to determine the timing aspect of the step-by-step approach.

Together with technical aspects, in single family houses retrofitting, the homeowners are a key decision maker. On a study about drivers of thermal retrofit decisions, the authors pointed that the up-front costs are a key barrier to the pursuit of building retrofit [14]. Thereupon, the second important parameter refers to economic aspects. Some authors [5] [8] included the budget restriction in their models, however as a fixed value without a method justification. A plausible assumption is to address existing assets for retrofitting (based on family's income and available budget).

3. Method

This chapter outlines a method for step-by-step optimisation modelling from building owners' perspective. The main target is to maximize the net present value of (cumulated) income available for energy related expenditures minus energy related expenditures over a certain optimisation period. It is assumed, that the building owner allocates a regular part of her/his income and spends part of it for energy related expenses (investment costs for retrofitting measures, running energy and maintenance costs).

Objective Function

The optimisation model should find solutions for maximising the net present value according following objective function:

$$\max NPV = \sum_{t}^{T} \frac{CF_t}{(1+r)^t} + \frac{L_T}{(1+r)^T} \qquad \textit{Equation 1}$$

NPV, energy related net present value [EUR]; *CF*, cash-flow of energy related balance; *L,* residual value of the retrofitting measures in year T; *r*, interest rate [%]; t, time [a]; *T*, optimisation period [a].

3.1. Cash flow of energy related balance

The energy related economic balance (cash flow CF) of the building owner (assuming an owner-occupied building) in every year t is the shared of household's income (CF) (see also 0) minus the energy related expenditures (IC, EC and OMC) (see also 0 to 0):

$$CF_t = INC_t * s - IC_{er,t} - EC_t - OMC_t$$ *Equation 2*

CF, cash flow of energy related balance [EUR]*;* *INC,* household income [EUR]; *s,* allocation factor of total annual income on energy related expenses [%]; IC_{er}, energy related investment cost of retrofitting measures [EUR]; *EC, annual running* energy costs [EUR/a]; *OMC*, *annual running* operation and maintenance costs [EUR/a].

3.1.1. Cumulated and allocated energy related assets and budget restriction. The cumulated allocated asset (A_t) destined to energy related issues in the year (t) is related to the -household's income (INC), its share (s) which is allocated for energy related expenses (including running costs and investments) and previous assets (A_{t-1}) and energy related expenses:

$$A_t = (INC_t * s) - IC_{er,t} - EC_t - OMC_t + A_{t-1}$$ *Equation 3*

A, cumulated allocated energy related asset [EUR]; *INC,* household income [EUR]; *s,* allocation factor of total annual income on energy related expenses [%]; *EC,* annual running energy costs [EUR/a]; *OMC*, annual running operation and maintenance costs [EUR/a].

These cumulated assets in year t (A_t) represent the budget restriction, which the household faces. In addition, the household may take up a certain loan. The amount of the loan which the bank is willing to provide is assumed to be proportional to the cumulated asset and is represented by the variable l (share of the cumulated asset which can be gathered by a loan). Thus, the overall budget restriction in year t (B_t) may be written as:

$$B_t \geq IC_{er,t} + EC_t + OMC_t$$ *Equation 4*

with

$$B_t = A_{t-1} * (1 + l)$$

B; budget restriction [B]; IC_{er}, energy related investment cost of retrofitting measures [EUR]; *EC,* annual running energy costs [EUR/a]; *OMC*, annual running operation and maintenance costs [EUR/a]; l, loan [EUR].

3.1.2. Investment costs (IC). The total retrofitting investment costs (ICtot) in year (t) are determined by the sum of energy related investment costs (ICer) and the maintenance investment cost (ICman) for each retrofitting measure, which has to be carried out for reasons of security or aesthetics: building envelope (external wall, window, floor or roof) and active system (heating, cooling, domestic hot water) (i), considering the probability of material's aging process (pt) (see 3.2.) and a binary variable (xt), which indicates if the measure is performed or not:

$$IC_{er,i,t} = \sum_i [(1 - p_{t,i}) * IC_{man,i} + IC_{er,i}] * x_{t,i}$$ *Equation 5*[1]

where, $x_{t,i}$ = 1 or 0 and $p_t > 0.05$

[1] The approach could be extended by distinguishing different efficiency levels of different renovation measures (d.h. insulation thickness) by adding an additional index j for these levels, where the additional restriction has to be fulfilled that the sum over j of $x_{t,I,j} \leq 1$.

IC_{tot}, total investment costs [EUR]; IC_{er}, energy related investment costs of renovation measures [EUR]; IC_{man}, maintenance investment cost of renovation measures [EUR]; x, binary variable (1 or 0) [-]; p, probability of material's aging process [-]; A, annually allocated energy related asset [EUR].

The assumption behind this equation is, that the investment costs for the maintenance of a renovation measure (ICman,i) only has to be considered as an energy related expenditure, if there is no necessity to renovate a certain building component due to the life time. If the probability that a renovation measure has to be carried out is close to 1, then, ICman is not relevant for the energy related investment decision, because the measure has to be carried out anyway.

3.1.3. Energy costs (EC). The running energy costs of the active system (i) at the time (t) are related to the final energy demand (fed) and the prices (pr) of the corresponding energy source:

$$EC_t = \sum_i fed_{t,i} * pr_{t,i} \qquad \textit{Equation 6}$$

EC, energy costs [EUR/a]; *fed,* final energy demand [kWh/a]; *pr,* energy price [EUR/kWh].

If a retrofitting measure is carried out, the final energy demand is reduced and has to be recalculated. The energy savings achieved are presented by the factor f, which depends on the energy related investment costs IC_{er}:

for,

$$x_t = 0, \quad fed_{t+1} = fed_t$$
$$x_t = 1, \quad fed_{t+1} = fed_t * f(IC_{er,i}) \qquad \textit{Equation 7}$$

3.1.4. Operation and maintenance costs (OMC). The operation and maintenance costs for the active systems (i) at the time (t) are related to investment costs (IC) and the operation and maintenance factor (fOMC):

$$OMC_t = \sum_i IC_{er,t,i} * f_{OMC,i} \qquad \textit{Equation 8}$$

OMC, operation and maintenance costs [EUR/a]; IC_{er}, energy related investment costs of active system [EUR]; f; operation and maintenance factor [%].

3.2. Material's aging process probability (p)

The probability (p) of a retrofitting measures (i) at the time (t) is defined by the Weibull distribution of material's aging process [15]:

$$p_{i,t} = 1 - e^{-\left(\frac{t-t_{i,0}}{t_{i,L}-t_{i,0}}\right)^m}, \text{ where t, } t_0\text{, m>0} \qquad \textit{Equation 9}$$

p; probability of material's aging process*; m,* aging exponent *[-]; t_L,* technical lifetime [a]; *t_O,* period without failure [a]; *t,* time [a].

If the material is retrofitted, than the aging process restarts:

For:

$$x_{i,t} = 1, \quad p_{i,t+1} = 1 - e^{-\left(\frac{t-t_{i,0}}{t_{i,L}-t_{i,0}}\right)^m} \qquad \text{Equation 10}$$

3.3. Residual value (L)
The residual value at the time (t) of the retrofitting measures (i) is related to material's technical lifetime (t_L), depreciation time (t_P) and energy related investment cost:

for,

$t < t_{L,i}$: $L_T = \sum_i \sum_t IC_{er,t,i} * \frac{(T-t)}{t_{L,i}}$

$t \geq t_{L,i}$: 0 *Equation 11*

L, residual value [EUR]; total investment costs [EUR]; t_L, technical lifetime [a]; *T,* optimisation period time [a]*; t,* retrofitting time [a].

4. Conclusions

A literature review showed several approaches for optimisation models of building retrofitting. Despite their particularities in terms of energy performance calculation method and objective function, all methods consider that the retrofitting measures are performed at the same time, so called single stage retrofitting.

In this context, the present study proposes a framework on how to apply retrofitting optimisation models for step-by-step retrofitting approach by formulating a corresponding optimization problem. Our focus are owner occupied single family houses, and therefore, the optimisation framework considers the building owner's perspective. The proposed method aims at maximizing the net present value, which represents the balance between energy related expenditures, and existing assets for retrofitting (based on family's income and available budget).

In the step-by-step concept, a step consists of combination of one or more retrofitting measures at a point of time. A single stage approach can be broken down in numerous renovation steps: building envelope measures – roof, external wall, floor insulation and windows replacement- and active system measures for heating, cooling, ventilation, heat distribution, lighting and domestic hot water. In real-life, lock in effects and thermal bridges have to be take into account. Also, construction site preparation and scaffold costs also affect the aggregation of one- or two measures. Nevertheless, future studies should try to further identify retrofitting measures aggregation boundaries.

To define the timing of the each retrofitting step, the probability of material's aging process distribution [15] in combination with available asset was proposed. We assume that the budget restriction of the investments in maintenance renovation works is not correlated to the budget restriction of the energy related expenses. This might be a simplification, which will be revised in a later stage.

5. Discussion and future outlook

Future planned activities of this study will include testing and extending the optimisation model, as well as, applying its results to a building stock scale and analysing possible impacts of step-by-step renovation measures on the achievement of building stock's decarbonisation targets.

To guarantee accuracy, sensitivity analyses will need to include important parameters as income projection, energy price scenarios and policies.

Further plausibility analyses should include human behaviour aspects (i.e. rebound effect), market value of the building after retrofitting, ambitious of building energy codes in terms of energy efficiency, as unpredicted incomes and assets (e.g. bonus or inheritance).

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Towards a model for circular renovation of the existing building stock: a preliminary study on the potential for CO_2 reduction of bio-based insulation materials

Pittau F[1], Iannaccone G[2], Lumia G[2], Habert G[1]

[1] ETH Zürich, Institut für Bau- und Infrastrukturmanagement, Chair of Sustainable Construction, Stefano-Franscini-Platz 5, 8093 Zürich
[2] Politecnico di Milano, Department of Architecture, Built Environment and Construction engineering (ABC), Via G. Ponzio 31, 20133 Milano

pittau@ibi.baug.ethz.ch

Abstract. In the context of strategies for mitigating the impacts of climate change within European cities, increasing attention is being paid worldwide to the use of urban green infrastructure which, in addition to the potential for improving the quality of the urban environment, allow significant amounts of CO_2 to be removed from the air. However, considering the peculiarities of the dense European cities, most of the available surfaces in urban areas are the perimeter walls of buildings of considerable age that are in urgent need of measures to upgrade their energy performance. Based on this premise, this paper investigates the potential for CO_2 storage resulting from the application of energy retrofit solutions using biogenic insulating materials. Starting from the analysis of the demand for insulation materials necessary for the energy requalification of the residential existing building stock in 28 European countries, following the renovation target fixed by EU, the research analyses, through the adoption of a dynamic LCA approach, the environmental benefits of bio-based materials compared to traditional solutions. The use of these materials, especially if they are fast-growing - as the study shows - offers several advantages in terms of climate change mitigation by reducing the energy needs and CO_2 emissions of the existing building stock and increasing carbon storage capacity within cities. The results of this study are intended to provide a robust database on which to build a model of circular building renovation that takes into account the environmental long-term effects of measures for increasing energy efficiency of buildings.

1. Background

It is a well-established awareness that the construction sector and, more specifically, the building renovation sector plays a decisive role in the achievement of the European targets for the reduction of energy consumption and greenhouse gas (GHG) emissions. The main strategies implemented by the European Union are aimed, on one side, at increasing the number of buildings to be yearly renovated and, on the other side, at promoting deep renovation measures on the existing building stock [1]. The main objective is to decarbonise the building stock by 2050 by seeking a cost-efficient equilibrium between decarbonising energy supplies and reducing final energy consumption. A recent study confirmed that high energy efficient buildings after deep retrofit show multiple benefits at different scales: a considerable reduction in the overall energy demand and, consequently, a reduction of grid infrastructure and power system operational costs [2].

More than the 75% of the European building stock has been built before 1980, i.e. before the introduction of the first energy performance regulations in several EU countries [3]. Residential buildings account for the biggest segment of this stock and are responsible for the majority of the sector's energy consumption. Within the existing European stock, a large share (more than 40%) - widespread in urban areas - is built before 1960s with low insulation levels and old and inefficient systems [4]. A wide range of retrofit technologies are available and several studies have been carried out in order to identify optimized solutions in consideration of the cost-effectiveness, the improvement of energy performances and indoor comfort [5]. Because of the age of the European building stock and the new European regulations for improving the energy performance of existing buildings, there is a need of extensive solutions for the renovation of exterior walls as they offer a great potential of energy saving due to the decrease of energy losses on a greater surface, both in single housing and apartment blocks. On one hand, the renovation of residential building stock to reduce the primary energy demand represents a priority in EU-28, not only to address the carbon mitigation, but also to mobilize investments in construction [6,7]. On the other hand, when the primary energy demand of a building is reduced due to retrofitting, the contribution on carbon emissions due to insulating materials processing increases [8]. At European scale, an increased inflow of materials is expected for deep renovation scenarios in the coming years and the fossil carbon emitted by manufacturing of materials and construction might significantly affect the carbon saving from operational energy [9]. Thus, the carbon emission for the production of materials and construction is expected to slow down the transition to a low carbon society and significantly reduce the carbon budget available by 2050, i.e. the finite amount of greenhouse gases we can emit to limit global warming to 2 °C [10], ratified by the Paris Agreement as the maximum possible increase without drastic consequences for human life on the planet. In this scenario, the adoption of low carbon materials able to store carbon for a long time horizon is an opportunity that should be taken urgently in order to comply with climate change target [11].

The objective of this paper is to evaluate the global warming potential of different bio-based insulation alternatives when used for the retrofitting of existing facades compared to standard synthetic insulation. More specifically, in order to properly consider the biogenic carbon stored in the product, a dynamic time-dependent life cycle assessment has been introduced in order to verify the contribution of the different bio-based materials in affecting the radiative forcing over time.

2. Methodology

2.1. External insulation system for envelope retrofitting

In this study, five envelope retrofitting solutions have been identified considering their potential for application to the external walls of typical European residential buildings, in order to improve their thermal resistance. In particular, as illustrated in Figure 1, the selected alternatives include both systems with lightweight elements that can be installed on-site and large prefabricated modules, in order to take into account also high-quality renovation options [12].

The Functional Unit (FU) assumed for materials and life cycle impacts assessment (LCIA) is the same for all the investigated alternatives and is defined as follows:

- 1 m^2 of wall;
- U-value = 0.125 W/m^2K;
- non load-bearing structure;
- identical fire safety;
- 60 years lifespan assumed as the same of the reference service life (RSL) of residential buildings.

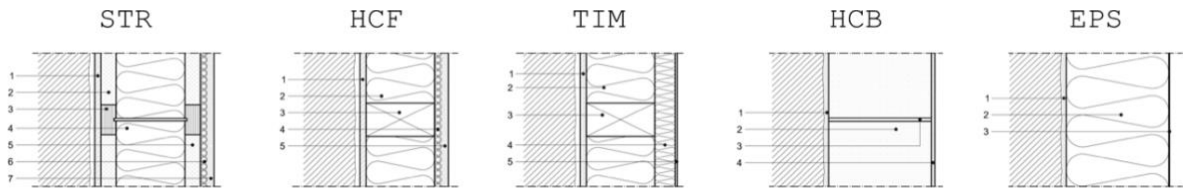

Figure 1. The five alternatives for the external insulation systems investigated in the study: STR (bio-based, prefabricated), HCF (bio-based, prefabricated), TIM (mixed mineral + wood, prefabricated), HCB (bio-based, on-site), and EPS (synthetic, on-site).

In the first four alternatives, different biogenic products are used for the thermal insulation and, in the case of prefabricated modules, for the structural elements as well. The thickness of the insulation for each alternative is a variable and has been chosen considering the required U-value of the walls in the different European Member State after renovation. In particular, for the identification of prevailing wall assemblies of existing building stock in EU, data from relevant databases have been considered, specifically the databases developed in the TABULA and EPISCOPE projects [13], and the information for the different States grouped according to seven prevailing climatic conditions in the framework of a geo-clustering approach [14].

STR – I-joist frame with pressed straw. An engineered I-joist frame is filled with straw which is pressed to a density of 100 kg/m3 to support a thick clay plaster layer mixed with straw on both sides. The structure is finished internally with an oriented strand board (OSB) to create a regular surface on the existing wall. After the assembly, the module is transported on the construction site and, once installed, is finished with a lime plaster on a reed mat.

HCF – Timber frame with injected hempcrete. A timber frame is filled with an insulation mortar of hemp shives bound with lime-based binder. The mass ratio of shives to binder is 1:1. Assembly and drying process is carried out off-site. Anchoring and plastering are executed on site.

TIM – Timber frame with mineral insulation. A timber frame is filled with a layer of glass wool. An additional wood fibreboard insulation is connected to the frame to increase the thermal performance of the wall and create a regular support for the external finishing.

HCB – Hempcrete blocks. After a preliminary preparation of the external surface of the existing wall, precast pre-dried hemp-lime concrete blocks are laid in order to wall up an insulation layer. A lime based plaster and render is applied as finishing.

EPS – Expanded polystyrene for external thermal insulation composite system (ETICS). An ETICS with polystyrene boards has been assumed as a reference system with an amount of bio-genic material equal to zero. EPS panels are applied on the existing wall, after the preparatory works on the existing wall surface, with an external render.

2.2. Dynamic Life Cycle Assessment

In order to analyze and compare the environmental impact of the different alternatives, a time-dependent life cycle assessment has been performed in order to proper account the biogenic CO_2. Normally, impacts of biogenic CO_2 are neglected in a traditional LCA since the same amount of CO_2 released from biogenic sources is assumed to be absorbed during the regrowth of the biomass, and the net emissions are therefore zero [15]. This widely used assumption about biomass carbon neutrality and climate neutrality has been increasingly criticized [16]. For this reason, a dynamic life-cycle assessment (DLCA) approach has been adopted for taking into account the timing of carbon uptake and GHG emissions, which is particularly relevant for bio-based products that temporarily store carbon and delay emissions [17]. The method was implemented taking into account only the GHG effect of CO_2 and methane (CH_4), since it was observed they contribute for the largest share of the radiative forcing impact due to the high amounts released in the process. A Time horizon (TH) of 200 years was assumed, in order to include into the calculation both short-term (2050) and long-term (2100) effects.

System boundaries. The LCA model was developed according to the standard EN 15804:2012 (CEN/TC350, 2012), and includes the following:

- product stage (modules A1-5) - extraction, transportation, production supply to the building site, and construction;
- usage stage (modules B1 and B4) – emissions by replacement of exhausted elements and uptake by the use of biomass and lime-based products;
- end of life (EoL) stage (modules C1-4) - wall demolition, transportation to waste treatment, sorting, waste processing, and final disposal.

Additional benefits, such as avoided virgin materials due to recycling or avoided emissions through energy recovery, are accounted for separately as additional loads and benefits beyond the system boundaries (module D).

Calculation model. The ΔR_T needed to meet the expected U-value limits in the future was evaluated for each European Member State, as well as the surface of the external walls that is expected to be yearly renovated. The two values were aggregated together according to the clustering process for each geocluster, and then correlated to the materials inventory for the five alternatives in order to define the annual material intensity. A life cycle inventory (LCI) from modules A1 to C4 was performed to calculate the impact inventory, measured in terms of kg of GHG emitted per year. In parallel, three different carbon sinks were modelled and included into the analysis in module B1: two sinks from biosphere (forest and crops) and one from techno sphere (lime), to take into account carbonation of lime-based products. On the base of the materials required, the annual carbon uptake, typically time depending, was measured and the resulting carbon removal were correlated to the GHG emitted by renovation of the stock to define a time depending matrix which was used as input to address the dynamic impact assessment. Finally, the results, expressed in instantaneous and cumulative radiative forcing, were converted into $kgCO_{2\text{-eq}}$ according to the IPCC method in order to measure the global warming potential (GWP).

End of life (EoL). Typically, the GWP calculation through a DLCA is particularly sensitive to the assumption concerning EoL treatment. A full understanding of the sensitivity of the results to the disposal scenarios (DS) is needed to succeed a careful interpretation [18]. At the EoL, the following five different waste treatments (WT) were assumed:

- WT1- inert landfill: considered for materials that do not release hazardous substances after building deconstruction;
- WT2 - sanitary landfill: considered as temporary storage for reactive materials as biogenic products;
- WT3 - composting facility: considered as alternative to WT2, where the full amount of methane produced during biological decay is captured and reused as bio-methane as substitution of natural gas;
- WT4 - municipal incineration: consists of incineration of waste with thermal energy recovery;
- WT5 - recycling: consists of generating new products from waste materials.

From the combinations of different waste treatments illustrated in Figure 2, the following three alternative disposal scenarios (DS) were defined:

- DS1: landfill;
- DS2: energy recovery;
- DS3: material recycling.

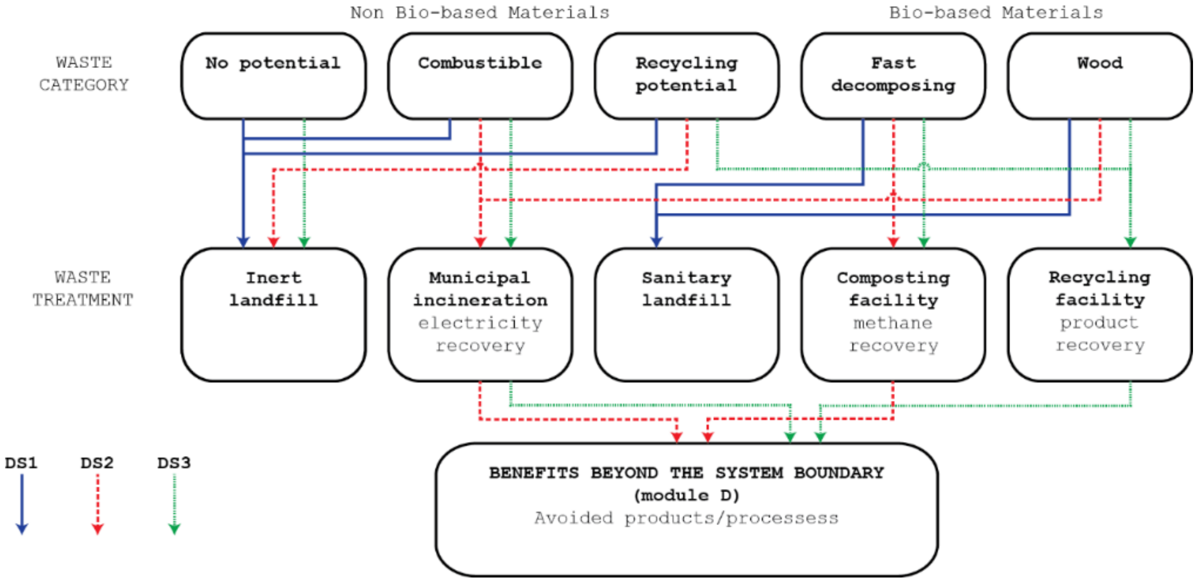

Figure 2. Waste treatments and disposal alternatives for each end of life disposal scenario [19].

3. Results

The instantaneous radiative forcing – which contributes to alter the Earth's radiative equilibrium, forcing temperatures to rise or fall - was calculated for each wall alternative and for the three DSs through the DLCA calculation model. The values of instantaneous radiative forcing calculated per year are summed to show the cumulative effect of the released emissions during the life cycles of the five construction alternatives. Finally, the results are converted into GWP according to the IPCC method in order to quantify dynamically the carbon emissions/removals.

The dynamic values of the GWP for each alternative and each DS are shown in Figure 3.

After an initial positive emission in 2018 of 7.64 Mt of $CO_{2,eq}$, the GWP impact of straw-based alternative (STR) rapidly decreases, with a carbon neutrality which is achieved after just 4 years. Then, the effect of removing carbon from the atmosphere continues with the same positive trend. It is expected that by 2050, almost 100 Mt of $CO_{2,eq}$ are removed from the air due to the massive use of straw. It is roughly equivalent to a reduction by 27% of carbon emissions from industrial processes and product use in 2015 in EU-28, or 23% of emissions from agriculture in the same year, which is equal to 3% of total carbon emissions from all sectors. In 2050, the materials required to renovate the residential building stock with HCF still lead to a positive emission, with a GWP of 3.55 Mt of $CO_{2,eq}$ that are expected to be cumulatively emitted since 2018. In 2100, the GWP registers a negative value, with a mean removal potential of almost 54 Mt of $CO_{2,eq}$, which is equal to a reduction by 17% of carbon emissions from industrial processes and product use, or 15% of emissions from agriculture in the same year or 2% of total carbon emissions from all sectors in EU-28 in 2015. A similar trend is observed for HCB, even if a negative GWP is achieved in 2050 due to the higher amount of carbon sequestered by hempcrete blocks. For the last two alternatives, no carbon removal is expected by 2100. Even if in TIM a large amount of bio-based material is used, the long time required to reabsorb the carbon in the forest by tree regrowth (a rotation period of 45-120 years was assumed in this calculation) drops down the positive effect of storing carbon in products.

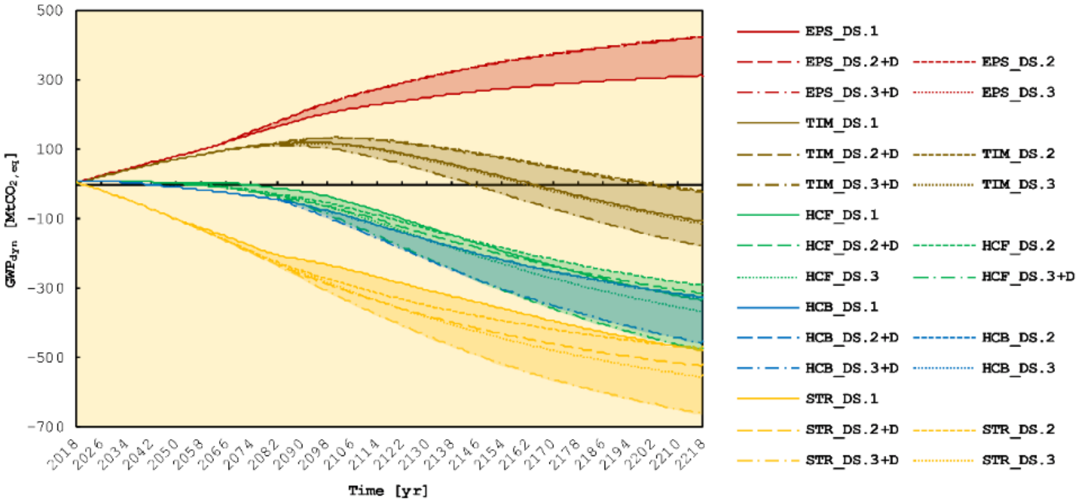

Figure 3. Dynamic GWP for all scenarios. DS1, 2, 3 stand for disposal scenario with landfill, energy recovery and material recycling respectively. DS +D stand for disposal scenario with module D and DS for disposal scenario without module D.

4. Conclusions

Fast-growing bio-based materials, such as hemp and straw, have a considerable potential of capturing and storing carbon when used as thermal insulation for renovating existing facades in Europe. Unlike forest products, they do not require long rotation periods, and the capacity for storing carbon increases when they are used as thick insulation for exterior walls due to the rapid CO_2 uptake in the crop fields. Among the five alternatives selected, STR showed the most promising potential, being the only one able to remove by 2050 3% of the $CO_{2\text{-eq}}$ emitted from all sector in 2015. The other two bio-based alternatives based on hemp start to be carbon negative slightly after 2050, with a carbon storage potential in 2100 of roughly 2% of the emissions from all sectors in EU-28 in 2015. Contrarily, timber-based construction always contributes to increase the emissions from renovation in a short and mid-term prospective, and the carbon capture and storage capacity of wood, if only timber is used in the structure, seems cannot be proposed as a valid strategy in Europe to contribute achieving the Paris Agreement targets. Clearly, EPS, which is nowadays the most used renovation system widely spread in Europe for energy retrofit, reduces the extra loads that the existing facades should support, but cannot contribute to actively remove CO_2 from the air.

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Implementation of Sustainable Development Goals in construction industry - a systemic consideration of synergies and trade-offs

Wieser A A[1], Scherz M[2], Maier S[2], Passer A[2] and Kreiner H[2]

[1] University of Graz (A)

[2] Working Group Sustainable Construction - Institute of Technology and Testing of Construction Materials, Graz University of Technology (A)

antonija_ana@hotmail.com, marco.scherz@tugraz.at

Abstract. According to sustainability research the world has exceeded four out of seven planetary boundaries. The areas of climate change, biodiversity loss, nitrogen cycle and land use have left the so called safe operating space for humanity. The built environment is one of the major contributors to environmental impacts. Especially the embodied energy during the construction phase of the built environment and the energy demands during the use of buildings contribute to a high energy and resource consumption. In the year 2015 the United Nations adopted the Sustainable Development Goals (SDGs), a universal development agenda, which goals need to be fulfilled by the year 2030 and by all UN countries worldwide. Amongst other countries Austria has adopted the 2030 agenda and has committed itself to the SDGs. Research objective was to explore the application of systemic approaches in the field of SDGs. The work presents a systematic literature review (SLR) and discusses an application of a qualitative system analysis (carried out with the tool iMODELER) on the SDGs. Results show how interdependencies among SDGs and among chosen concrete actions, e.g. for the built environment, can be visualized for a better systemic understanding. By visualizing synergies and trade-offs, effects of decisions taken can be estimated from a holistic perspective.

1. Introduction

According to ROCKSTRöM [1] three load limits of the earth system processes have already been exceeded. Namely the limits in the areas of climate change, the loss of biodiversity and the nitrogen cycle. The fourth area, namely land use, has also already surpassed the worldwide limits of ecological resilience [2]. The economist RAWORTH [3], takes the planetary boundary concept, expands it and introduces also socioeconomic indicators like education, health, gender equality and peace. In this way she defines a necessary bottom line for the social wellbeing of people on earth. The concept is called the ”Donut” [3]. There she defines the line which needs to be taken in account if humanity wants to stay within its safe limits, not only in ecological, but also in social terms. The described challenges and limits for our social and earth system wellbeing underlines the importance of the Sustainable Development Goals (SDGs), adopted by the United Nations in September 2015 [4], also called Agenda 2030. These Sustainable Development Goals comprise 17 goals, 169 sub-goals, and 232 indicators [5]. Amongst other countries, also Austria has committed itself to the SDGs [6].

1.1. Implementation of SDGs in Austria

In Austria, the mainstreaming approach is used to implement the SDGs. This means the Agenda 2030 is implemented on a federal level and every federal government department is responsible to implement the Agenda 2030 through relevant strategies and programs. On 12th January 2016, the working group ”Implementation Agenda 2030 for Sustainable Development” under the leadership of the Federal Ministry for Europe, Integration and Foreign Affairs (BMEIA), as well as with the participation of other ministries was established. Its task is to coordinate the preparation of the regular progress report complying with the internationally defined specifications on the basis of the agreed indicators as well as to coordinate the implementation priorities for the respective reporting period [7]. The mainstreaming approach as implementation strategy has been criticized by civil society [8] as well as by a report of the Austrian Court of Audit [9]. The civil society platform SDG Watch is advocating for the implementation of the SDGs and called in an open letter in January 2017 on the Austrian government and ministries to be more active in implementing the SDGs [10]. In the open letter, proposals for a better implementation of the SDGs in Austria, are formulated, for example a comprehensive inventory and gap analysis transparent reporting and the involvement of all stakeholders, is required [8]. From the science perspective, an important project to implement the SDGs in the Austrian higher education landscape is the project UniNEtZ, established by the network Alliance for Sustainable Universities. In this project Austrian universities aim towards cooperation for the SDGs on science and research level, furthermore the project tries to establish a better dialog between science-society-policy [11]. One main goal is the creation of an concrete action paper for SDG implementation in Austria, which will be presented to the Austrian government [12-13].

1.2. SDGs in construction industry

The SDGs concern many areas of society, including the construction sector. To achieve the goals of global sustainability in the sense of the SDGs, there is a need for redeveloping the construction sector. The construction sector is globally ”consuming 40 to 75 percent of the total value of materials extracted” [14]. According to figures mentioned in the International Resource Panel 2017 [15] buildings are also responsible for the use of 25 percent of global water. Furthermore the Global Status Report 2018 of the Global Alliance for Buildings and Construction [16] shows that 36 percent of final energy use in 2017 was caused by buildings and construction sector. This sector is also responsible for around 39 percent of emissions in the year 2017 [16]. Moreover estimated trends of the same report show that energy usage, besides improvements e.g. in building systems or building envelopes, is still growing. The emissions related to the buildings stagnate, due to the achieved energy efficiency in buildings as well as the decarbonisation of the power sector, and balance out development in population growth and the floor area growth. This means further reductions are necessary, if targets of the SDGs want to be achieved [16]. The Annex Report 57 of the International Energy Agency [17] is pointing out the factor that embodied energy and embodied energy emissions from construction industry constitute 20 percent of the global energy consumption and CO_2 emissions. This also implies that a reduction in embodied energy and CO_2 emissions can lead to a significant global decrease in energy consumption and CO_2 emissions. Another field where the built environment could act as driver is biodiversity, addressed in the SDG 15 - Life on Land [18].

The aim of this paper is to apply a systemic approach to identify building relevant actions and interactions between them based on the SDGs. As the SDGs have systemic interdependencies [19] and the Agenda 2030 has a systemic nature [20], the goals relate to each other and can create synergies and trade-offs among each other.

2. Applied methodology

The applied methodology described in this paper illustrates the state-of-the-art of the application of systemic approaches in context with SDGs (section 2.1) and shows how to link concrete actions to the SDG framework aiming to the identification and visualization of synergies and trade-offs (section 2.2) with the tool iMODELER (section 2.3).

2.1. Systematic literature review (SLR)

The literature research on systemic approaches in context of the SDGs was carried out by means of a systematic literature review and the snowball approach [21-22]. First, the following research questions were defined: ”Which systemic approaches in context of the SDGs exist?” and ”Why is a systemic approach indispensable for illustrating the interdependencies among SDGs?”. In order to answer these questions, a systematic literature review was conducted in the literature database ScienceDirect[1]. The search for relevant articles was restricted to ”Review article”, ”Research article” and ”Book chapters”. With the defined keywords in combination with the term Sustainable Development Goals the systematic literature review was carried out. Furthermore, only english-language literature was researched. The following table lists all keywords, which were used in combination with the term Sustainable Development Goals, including the number of articles found.

[1] https://www.sciencedirect.com

Table 1: Keywords of the literature research

Key word I	Key word II	Articles found
Sustainable Development Goals	interaction(s)	45
Sustainable Development Goals	trade-off(s)	41
Sustainable Development Goals	synergy / synergies	35
Sustainable Development Goals	links	28
Sustainable Development Goals	linkage	23
Sustainable Development Goals	relation	20
Sustainable Development Goals	correlation	13
Sustainable Development Goals	systemic	13
Sustainable Development Goals	connection	12
Sustainable Development Goals	interdependencies	8
Sustainable Development Goals	interconnection	8
Sustainable Development Goals	interrelationships	5
Sustainable Development Goals	intersections	4
Sustainable Development Goals	interrelations	0

2.2. Systemic approach and systems thinking

The roots of systems science go way back in time. With the statement "The whole is more than the sum of its parts" Aristotle already pointed out that it is not enough to know only the parts of a system, but that the relationship between these parts is crucial. Under the guise of systems science, numerous terms and fields have developed. Often, systems science is divided into systems theory, systems analysis and cybernetics [23]. The insights gained from systems theory and cybernetics led to numerous interdisciplinary approaches. Particularly noteworthy is the approach developed by FORRESTER [24] called System Dynamics to better understand complex systems regarding their nonlinear behaviour. COLLSTE et al. [25] describe system dynamics as "a systems analysis approach that is used to study behavioural patterns of systems". Meanwhile, we look back on more than 50 years of systemic understanding and system dynamics [26]. Systemic thinking, in contrast to analytic thinking, is contextual, which in turn means that systems can only be understood by placing them in an overall context. At the same time, people can not consider the effects of more than four interacting factors at once [27]. This raises the challenge or difficulty of a lack of human understanding for interactions of factors in systemic approaches [28].

Problem-solving methods from the past, due to interconnectedness, complexity, feedback, etc., are no longer adequate for the problems of today's generations. The adaptation of new ways of thinking does not fall victim to the intellectual deficiency of humanity, but rather to the difficulty of storing thought patterns applied over centuries [29]. The first limitations of systemic thinking take place at the latest at the beginning of compulsory education. Through a strict separation of subjects the first interconnections are hidden. Much more seriously, these delimitations of the individual subject areas are then operated in the later school levels and universities. By neglecting the interactions between the subsystems, overarching medium and long term impacts are not visible. Because of the segregation of the individual things according to disciplines and areas of life and the oblivion of the connecting relationships that exist in reality, we lose our cybernetic understanding [30].

Sustainable construction - i.e. taking account of environmental, economic, sociocultural, functional and technical aspects in the planning and construction of buildings - not only represents a megatrend in the construction industry, but in recent years, notably through the signing of the Paris Climate Agreement [31] as well as various progress reports [32-34] already anchored in everyday practice.

Especially in the context of sustainable construction, the importance of systemic approaches in an early design stages, is growing [35-36]. The complexity of construction projects is high, so that their underlying dynamics is difficult to understand [28], [37]. Systemic effects can be modeled and effects can be shown that have not been pointed out yet. This can also lead to systemic improvement processes [38]. Another reason for a systemic approach in the construction sector is construction management itself. Generally a lack of methods for the management of necessary lifecycle processes, difficulties arise in the operationalization of integral planning or imprecise stakeholder requirements. These different goals should be optimally considered through systemic approaches, which in turn can lead to increased building quality in terms of sustainability and process optimization and thus to financial and time savings in the planning and the life-cycle of a building [39].

2.3. SDGs and their systemic nature

The systemic approach plays a role as well for the SDGs. They are integrated [4] and have a systemic character and relate to each other [19-20]. The SDGs are a relatively new and an extensive framing concept. This is the reason why there is only little literature specifically on SDG interactions available so far [40-41]. Therefore tools to analyze their complexity, as well as for enhancing their implementation, are important. To understand and unlock their full potential synergies and trade-offs of SDGs need to be analyzed and integrated in policy frameworks out of a holistic perspectives. As there is "a lack of science-informed analysis of interaction across the SDG domains" [20] more systemic science-based analyses can help to develop more coherent and effective decision-making [20]. Furthermore with the application of a systemic approach interactions can be understood and feedback loops between SDGs and their targets and sub-targets can be managed [42].

ALLEN et al. [19] indicate that in the SDG implementation lacks analytical tools and lack instruments to help countries' to assess interactions of SDGs as well as to optimize and understand the systemic impact of the various interventions. Also in the SDG practice of countries gaps are shown, which hinder the transformative potential of the SDGs. Reasons for this is a lack of skills and lack of awareness in system thinking and systems analysis, as well as the lack of SDG tailored systemic tools [19]. Furthermore, also BAI et al. [43] see the opportunity to exploit potential and positive synergies for the SDGs in the use of a system approach. Therefore a systemic view on the SDGs, their synergies and trade-offs connected with the constructed environment is necessary.

2.4. A qualitative systems analysis with the tool iMODELER

The iMODELER is a tool for qualitative explorative cause and effect modeling. With the iMODELER it is possible to visualize complex systems and show interconnections between factors. The connections are shown with arrows between different factors, marked with pluses or minuses, to show a positive or negative correlation. It is a model helping to understand complexity and complex systems with the advantage of relative simplicity compared to quantitative modelling. The applied software can be used for environmental, economic and social problems at regional or national level. It also allows for participatory modelling with different stakeholders with the benefit of not missing potentially important factors. Beside visualization, also analysis of systems is possible with the goal to reach improved planning, communications as well as decision-making and communications. Other use cases of the tool, if data is available, are test scenarios or as a simulation tool [37], [44].

With regard to the SDGs, NEUMANN et al. [44] have already tried to model the SDGs with their systemic interdependencies on a general level. Building on this approach, this article specifically places SDG 11 at the center of the model and visualizes the effects of concrete actions related to the construction industry.

3. Results

This section presents the results of the SLR and the application of the tool iMODELER for the identification and visualization of synergies and trade-offs among SDGs. The developed model represents an exemplary demonstration for the application of a systemic approach for the causal loop investigation of concrete actions based on SDGs. The focus in the illustrated example was directed to the SDG 11.

3.1. Systematic literature review (SLR)

The systematic literature review (SLR) shows that so far some of the authors use systemic approaches to explore the interconnections within the SDGs as well as certain topics.

Figure 1 shows the number of found articles by keywords indicated in table 1 split up by the year of publication. In the years after the adaption of the Sustainable Development Goals in 2015 by the United Nations [4] the numbers of publications levels off.

In the SLR a number of 263 article entries was found. After checking for double entries, 158 papers were identified. In a second step the entries were filtered, first by title, then by abstract and finally by the full article. The SLR showed that interconnections within SDGs were researched with different methods, also systemic approaches. Moreover literature poses that there should be more research to explore the interactions of SDGs and processes behind them, as well as synergies and trade-offs among the SDGs, to progress toward the achievement of the SDGs [45], [46], [47]. Some papers found through the SLR were not addressing the topic of SDG interconnection at all.

In general literature from different disciplines and journals was found, e.g. from the sustainability or environmental sciences, marine research, engineering or agriculture. The SLR results showed that different

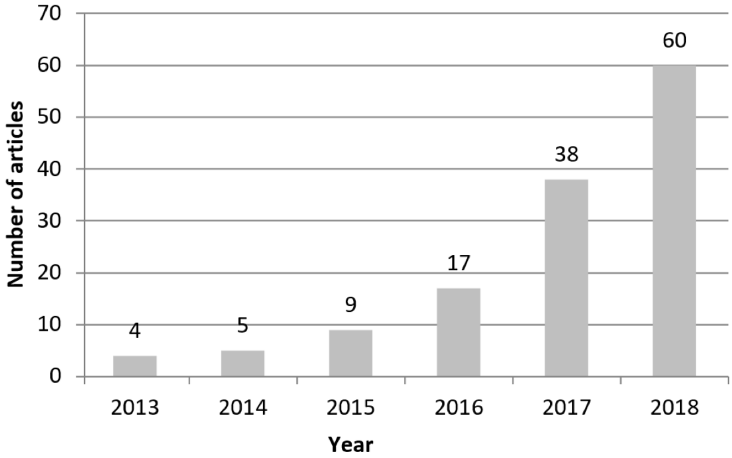

Figure 1: Number of SDG-related articles by the year of publication

authors, depending on their background and discipline, apply different, also non systems-oriented methods and tools to identify SDG interactions and connected synergies and trade-offs.

The thematic topics of the articles addressing SDG interconnections varied as well. Specific topics like salinization or SDG sub-targets like water quality were chosen as a starting point for the exploration of interdependencies among SDGs and the relevant topic. Synergies and trade-offs were not addressed in all papers specifically, sometimes the focus was e.g. just on trade-offs. Furthermore no paper was addressing SDG interdependencies specifically related to the built environment.

The following table 2 lists the titles of the relevant articles as well as their authors and their year of publication. Furthermore, the addressed SDG(s) within the articles are illustrated.

With the SLR only one scientific database has been researched, but for the exploration of the SDGs also grey literature needs to be taken into account. That is why also a snowball sampling was carried out.

One key paper found by snowball sampling, was the article of ALLEN et al. [19]. This paper provides an overview and analysis of expert literature (science-based) and guidelines (evidence-based) for SDG implementation worldwide. In an analytical framework 17 relevant papers as well as eight relevant guidelines and toolkits were identified and analyzed. One criterion was systems thinking and system analysis: in all eight guidelines or toolkits systems thinking and system analysis were applied. Moreover, 12 out of 17 papers used systems thinking. Further applied approaches identified in the expert literature were ”nexus approaches, quantitative modeling, indicator-based-assessments and benchmarking, scenario analysis and MCA[2] decision-frameworks” [19] .

[2] multi-criteria analysis

Table 2: List of relevant articles of the SLR and snowball approach

Article title	Author	Year	Adressed SDGs
Water quality and its interlinkages with the Sustainable Development Goals	Joseph Alcamo	2019	SDG 6, and SDGs 2, 3, 7, 14, 15
Analysing trade-offs between SDGs related to water quality using salinity as a marker	Flörke et al.	2018	SDG 2, 6, 7, 12, 15,
Defining and advancing a systems approach for sustainable cities	Bai et al.	2016	SDG 11, but more cities in general
More than Target 6.3: A Systems Approach to Rethinking Sustainable Development Goals in a Resource-Scarce World	Zhang et al.	2016	SDG 6 and other SDG
A rapid assessment of co-benefits and trade-offs among Sustainable Development Goals	Singh et al.	2018	SDG 14 and other SDGs
Trade-offs between social and environmental Sustainable Development Goals	Scherer et al.	2018	SDG 1 and SDG 6, 10, 13, 15
From goals to joules: A quantitative approach of interlinkages between energy and the Sustainable Development Goals	Santika et al.	2019	SDG 7 and other SDGs
Connecting SDG 14 with the other Sustainable Development Goals through marine spatial planning	Ntona Mara and Morgera Elisa	2018	SDG 14
Articulating natural resources and sustainable development goals through green economy indicators: A systematic analysis	Merino-Saum et al.	2018	SDGs and topic natural resources
Dynamic modeling approaches to characterize the functioning of Health Systems: A systematic review of the literature	Chang et al.	2017	No specific SDGs
Distilling the role of ecosystem services in the Sustainable Development Goals	Wood et al.	2017	SDG 1, 2, 3, 6, 7, 8, 9, 11, 12, 13, 14, 15
Building Urban Resilience for Disaster Risk Management and Disaster Risk Reduction	Etinaya et al.	2017	SDG 11
Towards a governance heuristic for sustainable development	Müller et al.	2015	No specific SDGs
SDG synergy between agriculture and forestry in the food, energy, water and income nexus: reinventing agroforestry?	van Noordwijk et al.	2018	No specific SDGs
The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency?	Ringler et al.	2013	No specific SDGs
National pathways to the Sustainable Development Goals (SDGs): A comparative review of scenario modelling tools	Allen et al.	2016	No specific SDGs
Toward a systemic monitoring of the European bioeconomy: Gaps, needs and the integration of sustainability indicators and targets for global land use	O Brien et al.	2017	No specific SDGs
Towards integration at last? The sustainable development goals as a network of targets.	Le Blanc David	2015	SDG 12, 10 other SDGs
Modeling and measuring sustainable wellbeing in connection with the UN Sustainable Development Goals	Costanza Robert	2016	SDGs and topic of wellbeing
Evaluating agricultural trade-offs in the age of sustainable development	Kanter et al.	2018	SDG 2
Initial progress in implementing the Sustainable Development Goals	Allen et al.	2018	No specific SDGs (Review)
Map the interactions between Sustainable Development Goals	Nilsson et al.	2016	All SDGs
Policy coherence to achieve the SDGs: using integrated simulation models to assess effective policies	Collste et al.	2017	SDG 3,4,7
Connecting the sustainable development goals by their energy inter-linkages	McCollum et al.	2018	SDG 7 and other SDGs

3.2. Application of the systemic approach

As part of the UniNEtZ project, several expert workshops in the area of SDG 11 were held. The aim of these workshops was to develop concrete actions for the Austrian Federal Government in order to contribute to the achievement of the Agenda 2030. In these workshops, first subject areas by experts were defined to holistically cover the targets of SDG 11. In the expert workshops it turned out that there are numerous interdependencies among these subject areas and subsequently between SDG sub-targets and SDGs. In figure 2 the process model is illustrated. In the center of the model is the factor SDG 11. For an initial modeling, the following assumptions were made, which also stem from the framework of the SDGs:

- all SDGs have an equivalent meaning and thus a same weighting[3]
- the targets and indicators were taken as defined by the United Nations
- all targets have an equivalent meaning and thus a same weighting
- interdependencies among the targets were not considered
- interdependencies among the indicators were not considered
- defined subject areas were linked to the indicators only

[3] although is not necessarily the case in reality

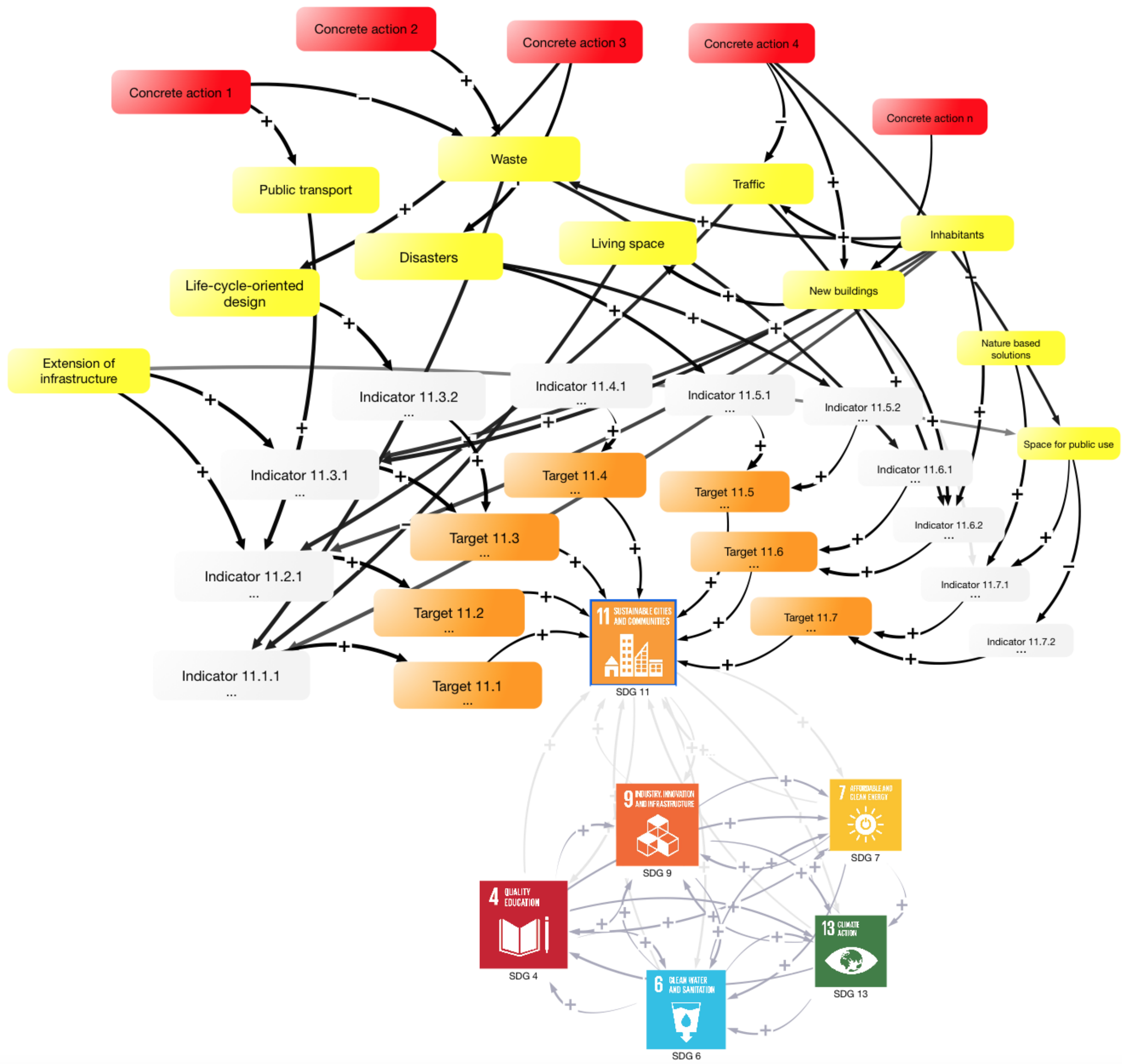

Figure 2: Interdependencies among defined subject areas within SDG 11

In iMODELER direct relations between factors have to be considered. This method is called know-why method [48] and concludes four know-why questions:

- What leads directly to more of a factor?
- What leads directly to less of a factor?
- What might lead directly to more in the future?
- What might lead directly to less in the future?

In the illustrated example (figure 3) an increased fulfillment of target 11.1[4] and target 11.6[5] directly causes to SDG 11. By analogy, the increased fulfillment of the Indicator 11.1.1[6] leads directly to an increased fulfillment of target 11.1.

Further examples for the interpretation of the model:

- more inhabitants lead to more traffic
- more inhabitants lead to more waste

[4] By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums

[5] By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management

[6] Proportion of urban population living in slums, informal settlements or inadequate housing

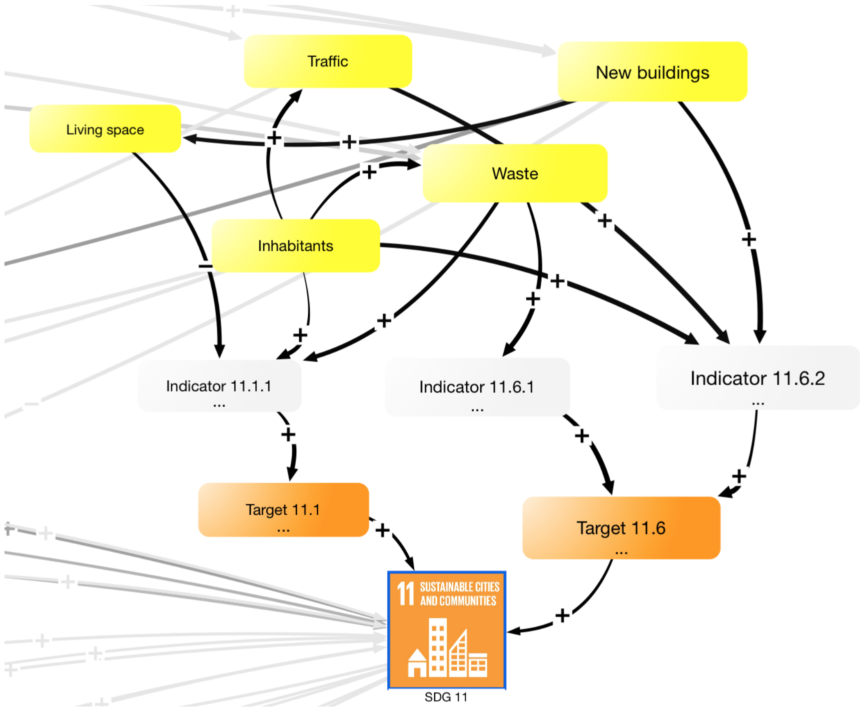

Figure 3: Exemplary illustration of synergies and trade-offs - an excerpt of the model

- more waste leads to more urban solid waste (indicator 11.6.1[7])
- more inhabitants lead to more fine particulate matter (indicator 11.6.2[8])
- more traffic leads to more fine particulate matter (indicator 11.6.2)
- more new buildings lead to more fine particulate matter (indicator 11.6.2)
- more new buildings lead to more living space

As shown in figure 3 concrete actions were linked to the defined subject areas. These concrete actions may influence the subject areas in positive or negative ways. To visualize the interdependencies of single actions or to identify the most useful action for SDG 11 or for one of the targets or indicators, the iMODELER is a helpful tool.

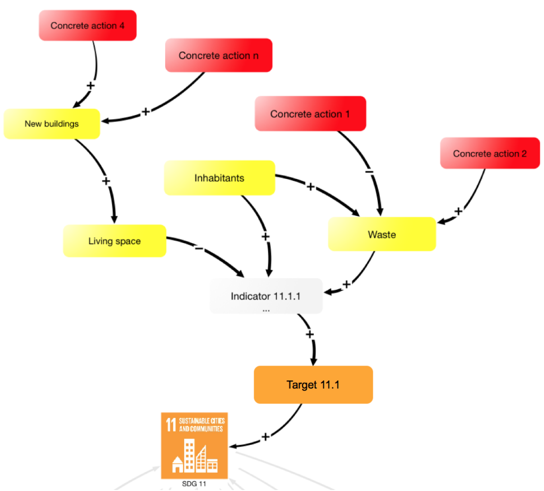

Figure 4: Target 11.1 in the center of the model

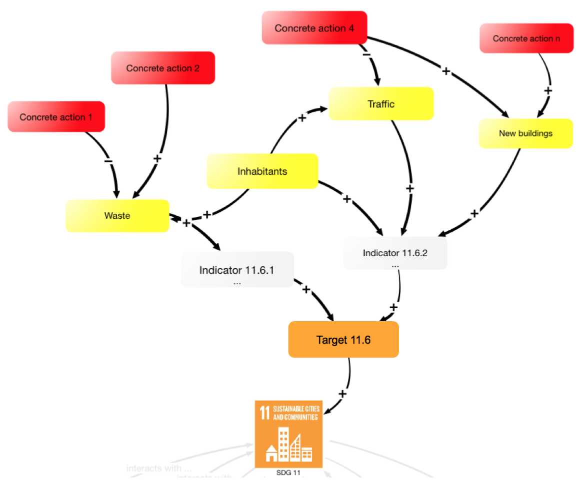

Figure 5: Target 11.6 in the center of the model

[7] Proportion of urban solid waste regularly collected and with adequate final discharge out of total urban solid waste generated, by cities

[8] Annual mean levels of fine particulate matter (e.g. PM2.5 and PM10) in cities (population weighted)

In figure 4 and figure 5 the comparison of influences on exemplary factors is shown. To visualize the systemic effects of concrete actions the tornado chart was used. In order to analyze the influencing factors for a selected target factor, the target factor must be placed at the center of the process model. The tornado chart shows positive and negative influences between the respective actions as well as synergies and trade-offs resulting from this consideration.

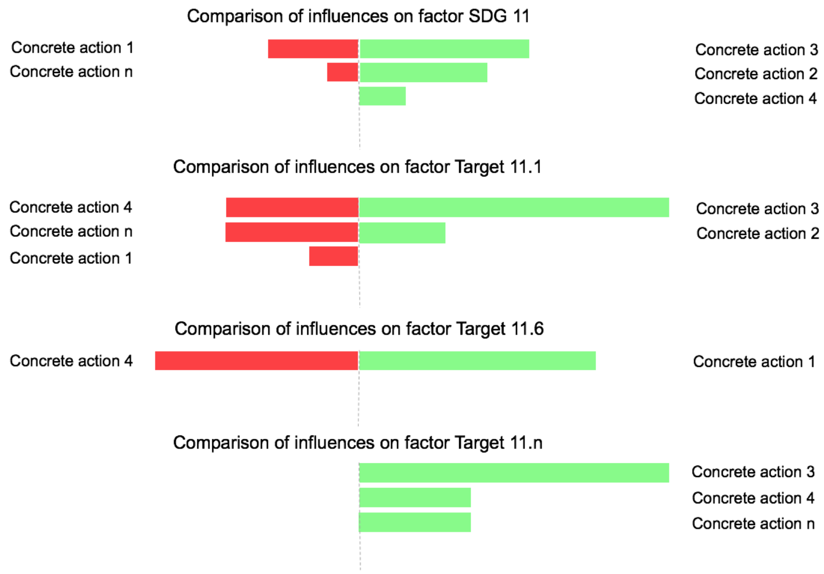

Figure 6: Concrete actions and their synergies and trade-offs shown as tornado chart

Behind the calculation of the effects is an extensive algorithm. The calculation of the tornado chart is done by multiplying the weights of influences between two factors. Starting points of the calculations are loops of inventory factors, which allow an exponential increase of influences in self-reinforcing loops. In order for the potential effect of loops to become clear, they run through the time steps (short-term, medium-term and long-term) twice.

For decision makers, this implies that action 2 and action 3 should be executed first. These actions have no negative effects on any of the centered target factors. Action 4 has a positive impact on the entire SDG 11 but has a negative impact on sub-target 11.1 and on sub-target 11.6. That implies that action 4 must have positive impacts on other sub-targets (not illustrated in figure 6) . If action 4 will be taken decision makers have to estimate how strong the negative effects on sub-targets 11.1 and 11.6 are and whether these have negative effects in the medium or long term. If decision makers only consider sub-target 11.6 and therefore executes action 1, this would lead to a negative impact on the entire SDG 11. With the systemic consideration within the tool iMODELER, these occurring synergies and trade-offs can be quickly identified and visualized.

4. Discussion

This article shows no analyses of concrete actions nor a recommendation for necessary actions to fulfill SDG 11. Rather it recommends a systemic approach supported by the iMODELER to handle the complexity of SDGs and their numerous subtargets. The detailed analyses of actions and their effects is currently under development in the UniNEtZ project. In Austria the implementation of SDGs shall be implemented on federal level. To coordinate the preparation and implementation the Federal Chancellery and other Austrian ministries established an Implementation Agenda 2030 for Sustainable Development. Civil society criticizes the way and intensity of this implementation process executed by the Austrian government and ministries. It is an important topic in regard to SDG implementation and policy. The development of the SDG indicators is already given, nevertheless the completeness and meaningfulness of many indicators can still be improved. The special focus in this work on SDGs in construction industry reveals that there is a need for a complete redevelopment of the construction sector because of its high energy and material use. The systematic literature review shows that literature on the topic of SDGs and interactions has increased in recent years from 4 articles in the year 2013 to 60 in the year 2018. Literature on the systemic nature of the Agenda 2030, and especially on synergies and trade-offs, is still in its infancy. In this relation insights gained from systems theory and cybernetics concepts play an important role in thinking and understanding of interconnections between different aspects and factors.

For the definitions of the SDGs and targets the linking between subtargets is a difficult step because targets are formulated very generally. Even when the SDGs are considered equivalent, the most important SDGs and targets for Austria, e.g. in regard to the building sector, should be identified. The definition and introduction of subject areas is a first attempt to make the model more comprehensible and tangible. In this manner new topics can be added and the extensibility of the model is possible. In any case before implementation the identified measures should be analyzed in regard to their impact. Based on several expert workshops in the area of SDG 11 the qualitative exploration of the interdependencies among SDG targets and related sub-targets and indicators as well as the levels of influence between immediate actions was exemplarily performed with the tool iMODELER.

5. Conclusion

We as a global society face great challenges which can only be solved together. With the SDGs we now have an agenda that addresses them in a comprehensive framework. That is why the Agenda 2030 can be chosen as a starting point to transform society in a sustainable way and it should also be used in science as well as in practice. High energy consumption, CO_2 emissions and material consumption are a problem in the Austrian building sector and must also face its responsibilities. Although it seems difficult, as there are multiple reinforcing and nested interactions among the SDGs, it is important that the Austrian building sector and its actors take into account systemic thinking and systemic approaches to contribute to the SDGs. Moreover approaches like the UniNEtZ project which aims for better science-society-policy dialogues should be implemented and used more often to bring different stakeholders together to identify common solutions supported a comprehensive and integrated know-how, towards the implementation of SDGs. Research recommendations are that the interdependencies within the Agenda 2030 should be explored in a systemic way for the Austrian implementation of the SDGs especially regarding the construction sector and the built environment. The tool iMODELER can help to pave the way for decision makers and assist them with decision-making as well as an argumentation and visualization tool e.g. for presentations. This must happen soon because as the Agenda 2030 should be implemented and reached by the year 2030, it must be clear that this is a very short timespan from this moment on. The research also shows that the iMODELER tool is a reasonable tool to model interdependencies among SDGs, their targets and indicators and helps to visualize synergies and trade-off between different actions connected to them. This tool can support decision makers to opt for the action with the least trade-offs and the most synergies with other SDGs. With regard to the pressing challenges the world and humanity is faced at the moment, such as the huge environmental impact of the buildings and construction sector, there is a need to rethink and redesign the sector to contribute to the SDGs, also in Austria. The Agenda 2030 is an opportunity to lead and initiate a change in this sector. Moreover this work shows that it is essential to work with systemic thinking and systemic approaches towards the implementation of the SDGs, demonstrating a complex and integrated framework, to address challenges of our time until the year 2030 in the optimum way. The tool iMODELER offers decision makers in Austria an option to visualize actions, which will e.g. developed by the UniNEtZ project, and their synergies and trade-offs. In a second step in this way immediate actions can be better prioritized and the actions with the highest synergies and least trade-offs can be chosen.

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Retrofitting strata property - a tool supporting long-term retrofit strategy

Ehrbar D, Heim D, Mayer A-T, Schwehr P

Lucerne University of Applied Sciences and Arts, Competence Center Typology & Planning in Architecture (CCTP), CH-6048 Horw

doris.ehrbar@hslu.ch

Abstract. Strata property - ownership of apartments or townhouses consisting of private and commonly owned building components and areas - was established in Switzerland in 1965 and since has become very popular. But, well-needed retrofit work of these buildings is often postponed and long-term retrofit strategies are rarely considered. However, the low retrofit rate must increase to meet the global energy goals. Interviews and workshops with relevant actors showed that missing financial means are not the key issues for the low retrofit rate. Major challenges arise from a broad set of issues, such as difficult processes, unclear responsibility, insufficient communication, missing building information or underestimation of the commonly owned building components. "Luzerner Toolbox" provides eight folders that address the key clusters of challenges. Central to this toolbox are Excel-based tools, which transform accurate technical and financial information into a visual format. An ample diagram illustrates the remaining lifetime of the building parts and a graph relates upcoming retrofit costs and the annual payments into the contingency reserve fund with a forecast of the contingency reserve fund. As such, these tools assists in scheduling appropriate retrofit measures and establishing a balanced financial planning. But, various actors have reported that the retrofit timetable is too complex to be used in management firms. Feasibility studies and further research of their specific needs and work processes are needed to refine the tool accordingly. In a further study, interviews with management firms and architects are conducted to determine the key factors of a useful tool.

1. Introduction

In Switzerland, strata property – apartments or townhouses that consist of private and commonly owned spaces and building parts – was established in 1965 and since has become very popular. In canton Zurich for example, strata property has become an important form of home ownership. Between 1990 and 2014, strata property increased from 4.5% to almost 15% of the total number of apartments while the share of single-family houses remained stable at about 17% [1]. The reason for the success of strata property might be found in the low interest rates along with the increasing property prices. This situation allowed to purchase this limited form of home ownership at an affordable price. And, strata property owners profit from the various advantages of home ownership, such as independency from landlords, investment of capital or freedom to design their own home according to their needs and wishes.

When buying strata property, owners often do not consider the challenges deriving from the building, the organization or the corporation. They focus on their new (privately owned) property. As members of the corporation they are – in collaboration with the other owners – also responsible for the commonly owned spaces or building parts. The commonly owned property, which includes facade, roofs, windows, elevators, underground parking lots or outdoor spaces account for more than half of the property [2]. And, it has to be maintained and retrofitted periodically, until the building reaches the end of life. Missing financial means - which was believed to be the key problem – is not the only reason for the low retrofit rates or postponed retrofit measures of strata property [3]. Major problems arise from a broad set of issues, such as difficult processes, unclear responsibility and communication, missing information on the building and its physical state or underestimation of the commonly owned areas.

Other countries report analogous challenges in retrofitting or dissolving strata property. However, due to the different laws in place, they manifest in different management issues and legal problems [4, 5]. Do to the long lifecycle of buildings, the challenges in Switzerland arise in the retrofit of buildings rather than the dissolving of buildings. As buildings get older and owners change, it gets more and more difficult to find majorities for well needed retrofit measures. The reasons are multifaceted: overall goal of the strata property isn't defined, there's not enough money into the contingency retrofit fund and the inhomogeneous strata property corporation is not willing to pay well needed retrofit measures with extraordinary payments. This leads to the fact, that the effort to manage strata property becomes more and more difficult and unprofitable, the older a buildings gets. As a consequence, management firms more and more withdraw from managing strata property as experienced employees that are skilled to handle the multi-faceted decision-making processes can rarely be found.

Over time, these multifaceted challenges may negatively influence the success story of strata property in Switzerland. Even more, the low (energetic) retrofit rate of the growing number of strata property works against the Swiss federal energy strategy 2050 [6], which assigned the energetic retrofit of the building stock to be one of three key actions. Statistical numbers show that the Swiss building stock still consume about 45% of the total primary energy consumption [6] and, the retrofit rate of the building enclosures remained at about 1% [7]. If the federal goal will be met, both, the energy consumption of the buildings and the low retrofit rate of the buildings have to be increased.

Considering the intrinsic challenges, management of strata property may no longer be seen as the purely administrative task of the commissioned management firms. Strata property corporations will be forced to set up comprehensive management structures, which include all relevant actors and pursues distinct long-term strategies for the maintenance and retrofit of strata property. To do so, property managers and owners must become aware of the multifaceted challenges. And, they must have user-oriented guidelines and tools that enable to set up long-term strategies for the operation, maintenance and retrofit of strata property. Finally, owners must get comprehensive information to take well founded decisions, which help to preserve (or increase) the value of their property and, to improve the energetic performance as asked by the federal energy strategy.

2. Challenges in retrofitting and managing strata property

The research project "long-term strategies for the retrofit of strata property" [8] invested the key challenges of strata property in Switzerland and developed user-oriented guidelines and tools to support long-term strategies for the maintenance and retrofit of strata property. The research based on interviews with relevant experts in planning, building, retrofitting and managing strata property, financial and legal experts, and members of associations as well as workshops with strata property owners.

The interviews with the experts and the workshops with owners of strata property confirmed the results of preliminary work [3]. Challenges are not only found in the retrofit of strata property. They are multifaceted and for example arise from missing information on the building and its physical state at time of purchase, owners underestimating the share of the commonly owned building parts and spaces, insufficient reserves in the contingency reserve funds, lack of knowhow referring to maintenance and retrofit, difficult decision-taking processes, little willingness of the inhomogeneous corporation to approve long-term retrofit strategies, unclear responsibilities and mandates of management firms or little interest of strata property managers to take on the responsibility for technical management.

Figure 1 shows that the key challenges and milestones related to maintenance and retrofit of strata property includes the entire lifecycle of a building as well as all key actors [9]. To structure further work, the challenges were assembled in six superior clusters, which encompass "planning and building", "establishment and purchase", "management and operation". "retrofit", "strata property corporation" and, "cancellation" of strata property. The key challenges of the six clusters are discussed in [10].

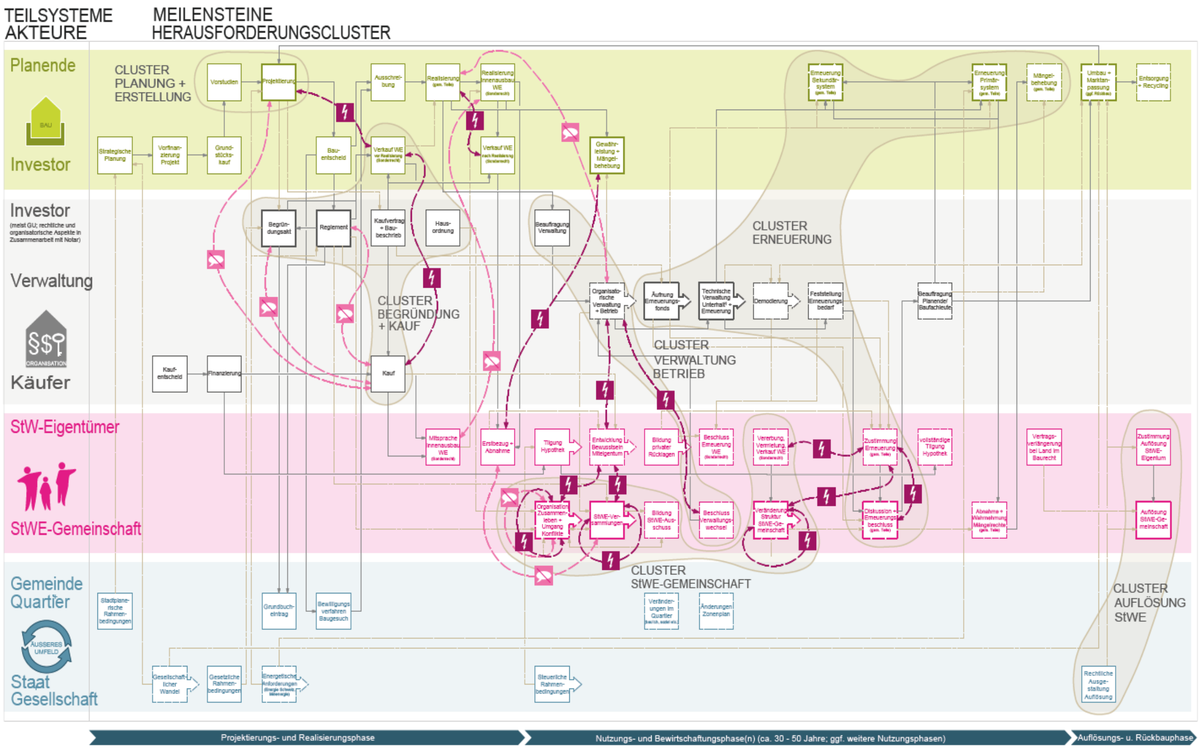


Figure 1. Scheme of the lifecycle of a strata property with challenges in maintenance and retrofit

3. Guidelines and tools for owners, corporations and managements

The interviews and workshops with key actors showed [8], that interdisciplinary work is necessary to overcome the multi-faceted challenges as shown in Figure 1. This means, that property managers – who mostly have a commercial background –need to collaborate with building professionals to manage the needs of technical management. However, this is only possible, if owners attach importance to that work and in consequence, assign the respective mandate and pay for it.

"Luzerner Toolbox" (Lucerne toolbox) [11] consists of 8 folders, which cover the most critical challenges assigned to the management of strata property. They provide useful background information and hands-on tools to manage long-term retrofit strategies of strata property. Folder 1, "Information for strata property", provides basic information on the challenges of strata property. Folder 2, "Optimized maintenance process for strata property", summarizes the key aspects of an optimized maintenance process. The visualization of the lifecycle includes milestones and decisions to be taken by different actors. Folder 3, "Tools for retrofit planning", explains the intention of the three Excel based tools as well as their use and function. Folder 4, "Exemplary rules and goals for strata property", provides guidelines and exemplary paragraphs that help to establish long-term retrofit planning in the regulations. Folder 5, "Specifications for the management of strata property", gives examples on how to stipulate the technical and administrative mandate. Folder 6, "Communication and conflict management in strata property", describes typical decision taking processes and provides guidelines on how to prevent and overcome conflicts. Folder 7, "Incentives for the retrofit of strata property", displays potential incentives that might be considered when retrofitting building and infrastructure. Folder 8, "Planning and design recommendations for strata property", provides guidelines for the planning and design of strata property, aiming at easing maintenance and retrofit as well as avoiding conflicts among owners.

3.1. Tools for the retrofit planning

Folder 3, "Tools for retrofit planning" [11], addresses owners and management firms as well as planners and architects. The three Excel based tools, "Tool A – retrofit timetable", "Tool B – forecast of contingency reserve fund" and, "Tool C – overview over retrofit measures" are designed to foster the planning and communication of long-term retrofit strategies.

The information, which is implemented into of "Tool A – retrofit timetable" and "Tool B – forecast of the contingency reserve fund", provides the base for the "Forecast of contingency retrofit fund" (Figure 2). It gives a graphic overview of the annual payments into the contingency reserve fund (blue line) as well as the relation between retrofit costs (black columns) and the long-term forecast of the contingency reserve fund (red line). If retrofits would be done as recommended by the retrofit timetable in Figure 2, the annual payments would not be sufficient without the three extraordinary payments.

This graph (Figure 2) is the core part of Folder 3, as it allows to displays all relevant information in a well-understandable, visual form. Even more, the graphic overview allows planners and architects or property managers to simulate and communicate consequences of different retrofit strategies or varying financing models. This helps strata property owners to make up their mind and to take well-founded decisions on how to maintain the common parts of the property.

Once the information is implemented, the tools should be actualised on a regularly bases. This might include an inspection of the building and critical building parts to determine the remaining lifetime. Being informed of the retrofit schedule as well as upcoming retrofit measures and the respective costs allows property managers to regularly communicate this issue. It also allows to take enough time for the complex decision taking process. Furthermore, clear and understandable information provides confidence and fosters strata property corporations to set up a long-term vision for the retrofit strategies.

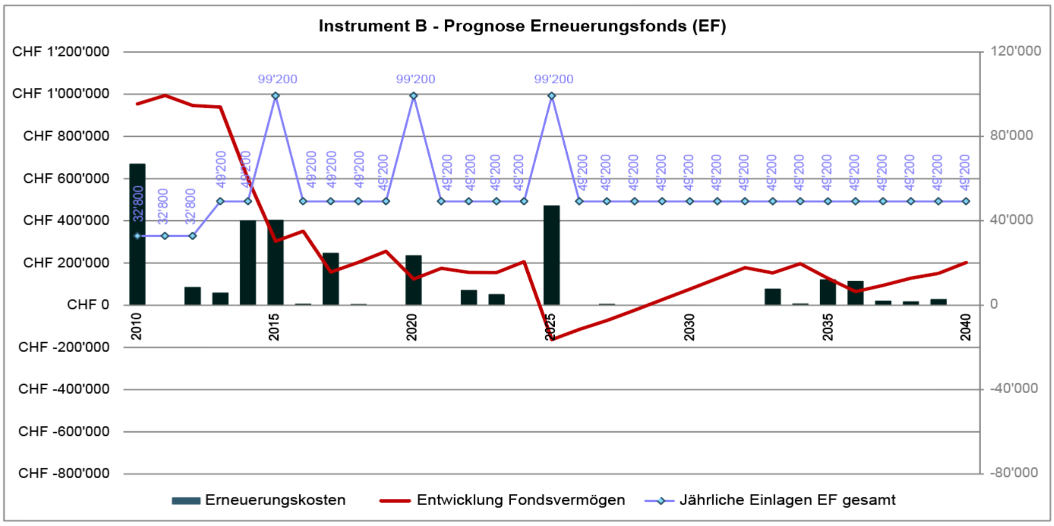


Figure 2. Forecast of contingency retrofit fund

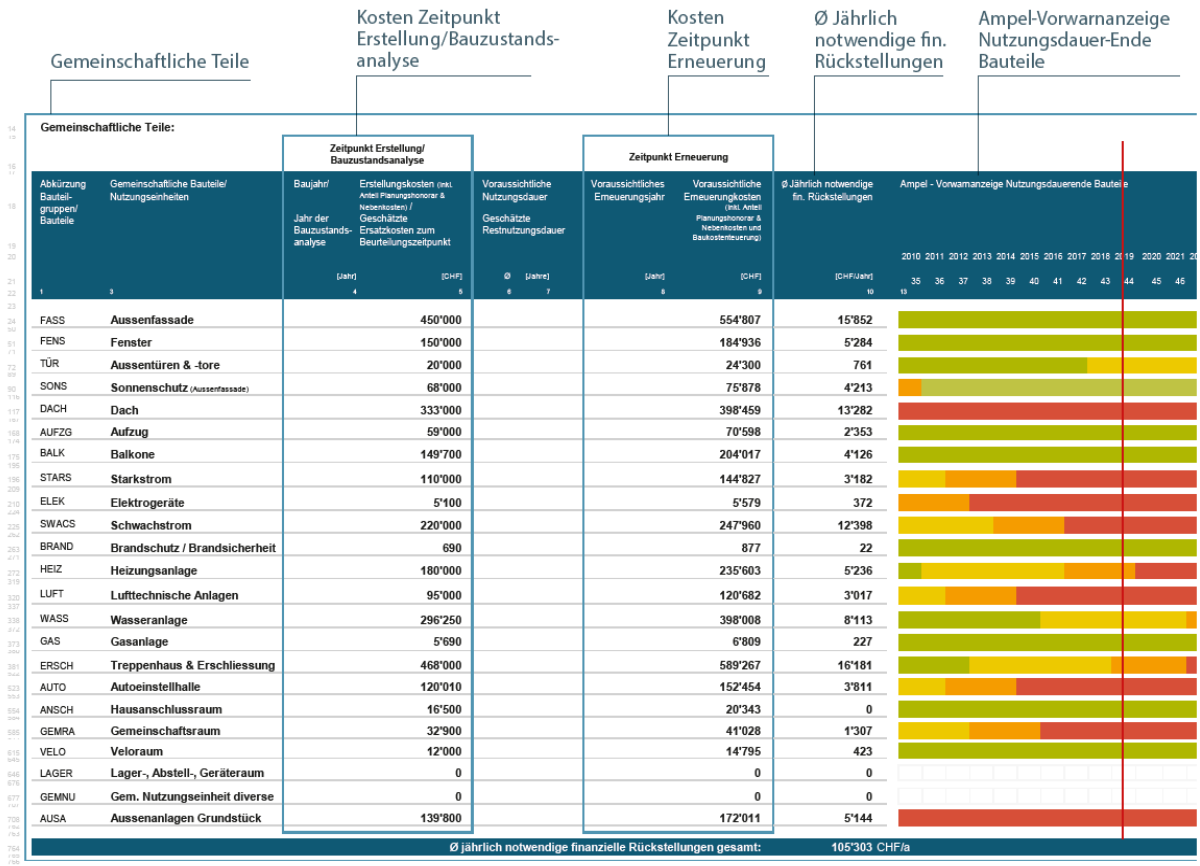
3.2. Retrofit timetable (Tool A)

The retrofit timetable [12] bases on average retrofit costs published by Swiss Centre for Building Realisation [13] and the expected, average lifetime of building parts published by Swiss Homeowners Association [14]. The structure follows the Code for Building Costs [15].

The header of the retrofit timetable [12] includes year of construction, year of first retrofit timetable, year of current investigation and, average increase of building costs (Figure 3). Within a row, column 1 shows the code of the building part followed by its name, year of construction and respective building costs, the average lifetime of the building part or an estimation of the remaining lifetime as well as the year of retrofit or replacement and respective costs.

The entry information in the header and the information on the building parts (column 1 to 8) generate the necessary annual provisions needed to retrofit or replace a building part at the given time (column 9). The total of the average annual costs for the retrofit of the single building parts is shown at the bottom of the table. The remaining lifetime of the building parts is illustrated in an ample diagram on the right hand side of the entry mask. The colours of the ample diagram indicate how urgently a building part should be renovated or replaced. Green colour means, the renovation is not expected in the next 10 years. Yellow and orange indicate that a building part will have to be renovated or replaced in about 5 – 10 years and 2 – 4 years, respectively. Red colour means that the average lifetime is one year or less and an on-site check is strongly recommended.

The tool allows to work on different levels of detail. Level 1 (Figure 3) shows the primary building parts or spatial units (e.g. windows, staircase), whereas the respective ample displays the subordinate building part with the shortest remaining lifetime. This level of detail is only to be used to communicate rough first overview. Level 2 consists of subordinate building parts (e.g. windows of apartments, windows of staircase, etc.) and Level 3 splits the building part or spatial unit up in further sub-items (e.g. wooden windows of apartments in upper floors, wood-metal windows in apartments of ground floor or double-glazed windows of staircase, etc.). It is recommended to work on Level 2 or 3. The more detailed the entry information is, the more accurate is the information on the remaining lifetime of the building parts and the respective costs for retrofit or replacement.



Gemeinschaftliche Teile:

Abkürzung Bauteil-gruppen/ Bauteile (1)	Gemeinschaftliche Bauteile/ Nutzungseinheiten (3)	Zeitpunkt Erstellung/ Bauzustandsanalyse: Baujahr/ Jahr der Bauzustands-analyse [Jahr] (4)	Zeitpunkt Erstellung/ Bauzustandsanalyse: Erstellungskosten (inkl. Anteil Planungshonorar & Nebenkosten) / Geschätzte Ersatzkosten zum Beurteilungszeitpunkt [CHF] (5)	Voraussichtliche Nutzungsdauer Ø (6)	Geschätzte Restnutzungsdauer [Jahre] (7)	Zeitpunkt Erneuerung: Voraussichtliches Erneuerungsjahr [Jahr] (8)	Zeitpunkt Erneuerung: Voraussichtliche Erneuerungskosten (inkl. Anteil Planungshonorar & Nebenkosten und Baukostenteuerung) [CHF] (9)	Ø Jährlich notwendige fin. Rückstellungen [CHF/Jahr] (10)
FASS	Aussenfassade		450'000				554'807	15'852
FENS	Fenster		150'000				184'936	5'284
TÜR	Aussentüren & -tore		20'000				24'300	761
SONS	Sonnenschutz (Aussenfassade)		68'000				75'878	4'213
DACH	Dach		333'000				398'459	13'282
AUFZG	Aufzug		59'000				70'598	2'353
BALK	Balkone		149'700				204'017	4'126
STARS	Starkstrom		110'000				144'827	3'182
ELEK	Elektrogeräte		5'100				5'579	372
SWACS	Schwachstrom		220'000				247'960	12'398
BRAND	Brandschutz / Brandsicherheit		690				877	22
HEIZ	Heizungsanlage		180'000				235'603	5'236
LUFT	Lufttechnische Anlagen		95'000				120'682	3'017
WASS	Wasseranlage		296'250				398'008	8'113
GAS	Gasanlage		5'690				6'809	227
ERSCH	Treppenhaus & Erschliessung		468'000				589'267	16'181
AUTO	Autoeinstellhalle		120'010				152'454	3'811
ANSCH	Hausanschlussraum		16'500				20'343	0
GEMRA	Gemeinschaftsraum		32'900				41'028	1'307
VELO	Veloraum		12'000				14'795	423
LAGER	Lager-, Abstell-, Geräteraum		0				0	0
GEMNU	Gem. Nutzungseinheit diverse		0				0	0
AUSA	Aussenanlagen Grundstück		139'800				172'011	5'144
	Ø jährlich notwendige finanzielle Rückstellungen gesamt:							105'303 CHF/a

Figure 3. Tool A – Entry mask for data referring to the retrofit timetable

If the initial building costs are not available and it is not clear what physical state the building and its building parts have, it is not possible to fill in the retrofit timetable. In order to get reliable information, it is recommended to mandate building professional with the setup of the renovation timetable.

3.3. *Forecast contingency retrofit fund*

The forecast of the contingency retrofit fund [12] requires basic information on the building (year of construction, insurance value, owner quotas) and financial information, such as first year of investigation and respective balance of contingency retrofit fund, current year of investigation, year with first payment and annual payment into the contingency retrofit fund, interest rates on the reserves in the contingency fund as well as minimal or maximal balance of the contingency retrofit fund. The forecast of the contingency retrofit fund table (Figure 4) transforms and displays the information relevant long-term strategies for the retrofit of strata property. These are the annual payment into the contingency retrofit fund (column 3), extraordinary payments (column 4), the average annual retrofit costs (column 10) and the development of the contingency retrofit fund (column 11).

Gebäudealter [Jahre] 1	Jahr 2	Jährliche Einlage EF [CHF/Jahr] 3	Ausserordentliche Sonderzahlungen 4	Jährliche Rendite Einlagen [%] 6	Erneuerungskosten [Summe pro Jahr in CHF] 10	Entwicklung Fondsvermögen [CHF] 11
30	2005	16'400	0	3.00%	0	1'601'456
31	2006	32'800	0	2.75%	187'500	1'491'698
32	2007	32'800	0	2.50%	17'100	1'545'510
33	2008	32'800	0	1.25%	0	1'598'039
34	2009	32'800	0	1.00%	72'000	1'575'147
35	2010	32'800	0	1.00%	670'000	954'027
36	2011	32'800	0	0.75%	0	994'228
37	2012	32'800	0	0.50%	85'690	946'473
38	2013	49'200	0	0.25%	59'000	939'162
39	2014	49'200	0	1.25%	401'112	599'604
40	2015	49'200	50'000	1.25%	403'974	303'565
41	2016	49'200	0	1.25%	6'345	350'830
42	2017	49'200	0	1.25%	247'960	157'070
43	2018	49'200	0	1.25%	5'469	203'379
44	2019	49'200	0	1.25%	0	255'736
45	2020	49'200	50'000	1.25%	235'603	123'770
46	2021	49'200	0	1.25%	0	175'132
47	2022	49'200	0	1.25%	71'976	155'160
48	2023	49'200	0	1.25%	52'360	154'554
49	2024	49'200	0	1.25%	0	206'301
50	2025	49'200	50'000	1.25%	472'027	-162'707

Figure 4. Tool B – Entry mask referring to the contingency retrofit fund

3.4. *Suitable packages of retrofit measures*

According to the ample diagram of "Tool A – retrofit timetable" (Figure 3), planners and architects can set up suitable retrofit packages, which can be realised in accordance to the timetable. All the relevant information, such as a preview of upcoming renovation periods along with respective retrofit measures and retrofit costs, current state of planning as well as state of decisions and required quorum, can be documented in "Tool C - overview of retrofit measures" [16]. The exemplary structure is meant to support the communication with the strata property corporation and to plan the complex decision making process. Furthermore, it supports owners in coordinating private retrofit work with the common one. Regular update is necessary to keep the tool up to date and reliable.

4. Implementation of tools

Feedbacks of experts and strata property owners have shown, that the tools of folder 3 "Tools for retrofit planning" are of great interest for the planning of long-term retrofit strategies. However, they state that the handling of "Tool A – retrofit timetable" is too complex. It is assumed that this feedback bears two major barriers. First, the detailed information, which is has to be compiled and entered into the tool, requires in-depth knowhow on maintenance and retrofit. Second, the implementation of the broad set of data is time consuming. And, the compilation and entry of the data is not covered by the mandate. Thus, it is necessary to do further work on the role of the management firms as well as on the optimisation of the retrofit timetable.

Research on the role of management firms on energetic retrofit has shown [17] that management firms have a great impact on the renovation of strata property. They often initiate and accompany retrofit measures. In doing so, they evaluate the needs of the corporation, call the experts (e.g. architects) and establish the contact among the relevant actors. Also, they must inform the strata property corporation and, withstand the high expectations of the owners. However, management firms cannot cope with all these requirements. This role goes beyond their core business and, it would require additional organisational and financial effort. For these tasks, they only have a vague or no mandate at all.

"Tool A – retrofit timetable" is based on the work environment of planners and architects. And, it is meant to provide accurate information for setting up long-term strategies for strata property. A reduction of the level of detail has direct impact on the accuracy of the information. Other tools, such as "Stratus" [18] or "Cost Planning for Retrofit" [19] rely on the insurance value or the construction costs of the building, the major building parts as well as rough values for its lifecycle and the respective building costs. As such, they generate a fast overview over the critical building parts and the cost for retrofit. But, this information does not consider the design and construction of the building, nor to the actual state of the building parts. It may only be used for a fast and rough overview of the major building parts. Also, it is not clear, how the privately and commonly owned parts of the building are split. Considering these facts, the new research project will have to get insight into the work processes of planners and property managers and evaluate the appropriate level of accuracy before the tool is overworked accordingly.

5. Discussion

Research has shown, that there is in-depth disciplinary knowhow on how to retrofit building and to calculate the respective retrofit costs as well as to achieve long-term maintenance and retrofit strategies. But, the problem lies in inadequate mandates, inflexible processes and the way key actors collaborate and communicate. A closer collaboration between planners, management firms and the strata property corporation would generate multiple benefits. Within this core team of experts, planners or architects would have a mandate for the technical issues, such as the periodic evaluation of the state of the building, the set-up and maintenance of the retrofit timetable, the overview of the retrofit measures and assist, if necessary, with the technical management. Management firms would be in charge of the administrative and technical mandate and, the corporation board would represent the interests of the strata property corporation. Together, the core team could set up recommendations for the long-term retrofit strategy of the strata property. They also inform the corporation on the strategies and the current state of planning. This approach can help to establish a broad support of the retrofit strategies and to avoid precipitate actions as well as uncoordinated and costly retrofit measures. But, this process can only be initiated, if the strata property corporation sees the benefits and approves the mandates.

Given the fact that processes and mandates are adapted, "Tool A – retrofit timetable", must not be simplified, but, set up a connection between the work environment of planners and architect and the one of the property management firms.

6. Outlook

As property prices rise, the popularity of strata property will further increase in Switzerland. But, the increasing demand of strata property bears the risk that more and more existing multi-family houses are sold to strata property corporations. As these buildings are not planned for strata property and have passed a good part of the lifecycle, special attention has to be given to proper management and communication. Major retrofit – along with major costs – will most probably come up in only a couple of years. At that time the challenges and the effects of discordant strata property will no more be limited to the actors involved.

Considering the growing issue, it might become necessary that the intrinsic challenges are addressed by a broader circle of actors, such as banks, home owner associations or the federation. Banks might consider alternative financing models for strata property owners that cannot increase the mortgage. The strata property association could provide guidelines and exemplary regulations that help strata property corporations to establish long-term retrofit planning in the regulations or, they could intensify further education of strata property owners or property managers. And, last but not least, federal laws and provisions could enforce appropriate and prompt retrofit.

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Mobilizing Low Carbon Transition: Transnational Practice of Energy Efficiency in the Urban Building Sector

Feng K, Schmidt J A

Institute of City Planning and Urban Design, University of Duisburg-Essen, Universitätsstraße 2, 45117 Essen

keru.feng@gmail.com

Abstract. In many countries worldwide, low carbon sustainable transition has been planned and implemented through decoupling the economic growth from GHG emissions. Some nations are leading the scene by developing corresponding low carbon development strategies and policy measures to encourage socio-technical innovations. One of the key areas for low carbon urban development is the energy efficiency in buildings. The tendency of the rapidly growing population and urbanization asks for better narratives and practices improving the built environment. Cities and countries are keen on learning from best practice. Through international joint development projects, the "knowledge resources" - transnational, governmental, NGOs, practitioners, and academic actors - are disseminating the low carbon urban development ideas globally. What drives a successful translation of knowledge emerged from one social, economic, cultural, political, climatic and geographical context into a new one needs better clarification. This study explores the process of global circulation of sustainable innovation from a mobility and transition perspective. A conceptual framework is explored and tested through analysing the Passive House concept transferred from Germany to China. The study shows how the succinct form, co-evolving and re-contextualising attributes are key factors in circulating urban sustainability across context. Acknowledging the notion of adaptation and mutation in the translation process is a first step to address the discrepancies between the knowledge lending and receiving side, and further to foster the transformative learning.

1. Introduction

In the international community, transformative actions have been planned and implemented in many countries endeavouring climate change mitigation through decoupling the economic growth from greenhouse gas emissions [1]. They generate proven synergies with Sustainable Development Goals (SDGs) [2]. It is widely acknowledged that a socio-technical transition is necessary for an ecological friendly sustainable development [3]. One of the key approaches for climate mitigation is the energy efficiency and renewable energy in building sector [2], which accounts for 31% of global energy use, and 23% of global energy-related GHG emission [4]. The tendency of increasing population and urbanisation asks for better narratives and practice for better built environment. The largest energy saving potential is in heating and cooling demand, largely due to building envelope improvements and energy-efficiency and renewable energy adoptions [1, 2]. As a result, low-energy, low-carbon design and construction concepts such as ultra-low-energy buildings, passive houses, and plus energy buildings are receiving growing interest globally.

While the COP21 climate negotiations adopted the first ever global climate deal, some nations are already leading the scene by taking corresponding low carbon development strategies through socio-technical innovations. In building sector, socio-technical changes have been observed, for example the development goals and policy measures are promoting the increase of renewable energy equipment in China [5] and net zero-energy building (nZEB) in Europe [6].

Countries are keen to learned from “best practices”. Through international practical networking and cooperation, the “knowledge resources” - transnational, governmental, NGOs, practitioners, and academic actors - are disseminating the low carbon urban development ideas globally. However, what makes an idea of low carbon innovation globally transferable? How is the knowledge adapted during the process of translating from the emerged context to the adopted one? What makes a success/failure of transferring low carbon development model into a new geographic, social, political, economic, cultural context?

This study explores a theoretical tool drawn from the literature of knowledge mobility and transition studies, and further investigates the translating process of Passive House concept from Germany and Europe to China.

2. Conceptual Framework

The knowledge circulation process is conceptualized in the literature of policy mobility from international development experience. The conceptual framework drawn from the policy mobility literature helps to understand how policy ideas flow transnationally, interacting with the local actors and adapting into a new context [7, 8, 9]. It addresses the “struggles involved as particular ideas are drawn into—localized—in new situations” [11]. The result is co-evolving of the ideas as they travel into the new social, cultural, institutional, and economic situations [10]. It brings up the questions of the actual impact by disseminating the “best practices” or sustainable development models. It highlights the traveling process as the processes of disseminating, translating and adapting [12], addressing the driving forces from both idea lending and receiving contexts [13]. It interprets the process of policy/knowledge transferring with the notion of mutual learning [14]. The green innovation is subject to a re-combination with pre-existing on-site knowledge that can lead to further innovations [15].

Recently, the growing interest in green innovation, climate change and sustainable development has been drawn on transition studies, which focus on interaction of social and technological changes [15]. The discussions help to identify the drivers and barriers of low-carbon sustainable transitions in the urban system, particularly on the topics of transport, energy and building sector [15, 16, 17, 18]. The transition process is conceptualized by the multi-level perspective model (Figure 1, [19]). It identifies three hierarchic and co-evolutionary levels to analyse the complexity of changes in socio-technical systems: 1. A micro-level of niches, where innovations occur e.g. experimental projects or policies, inventions, and community initiatives; 2. A socio-technical regime where the dominant standards, norms, structures, institutions or market rules are stabilised over time; 3. A socio-technical landscape level, where changes usually take place slowly in this wider context including cultural norms, values, demographic trends or political strategies [19].

Experiments can trigger social change. Experimental niches are protected from the normal rules, for example pilot projects or special subsidy programs. These niches are tested and developed. Successful ones can be translated to the regime level and formulate new regular conditions. The ones who cannot trigger aligning changes at regime and landscape level will fail. The three levels are co-evolving and subject to external driving forces [15, 19, 20]. For example, the oil crisis and Chernobyl nuclear disaster triggered the transformative power for the Energiewende (German energy transition).

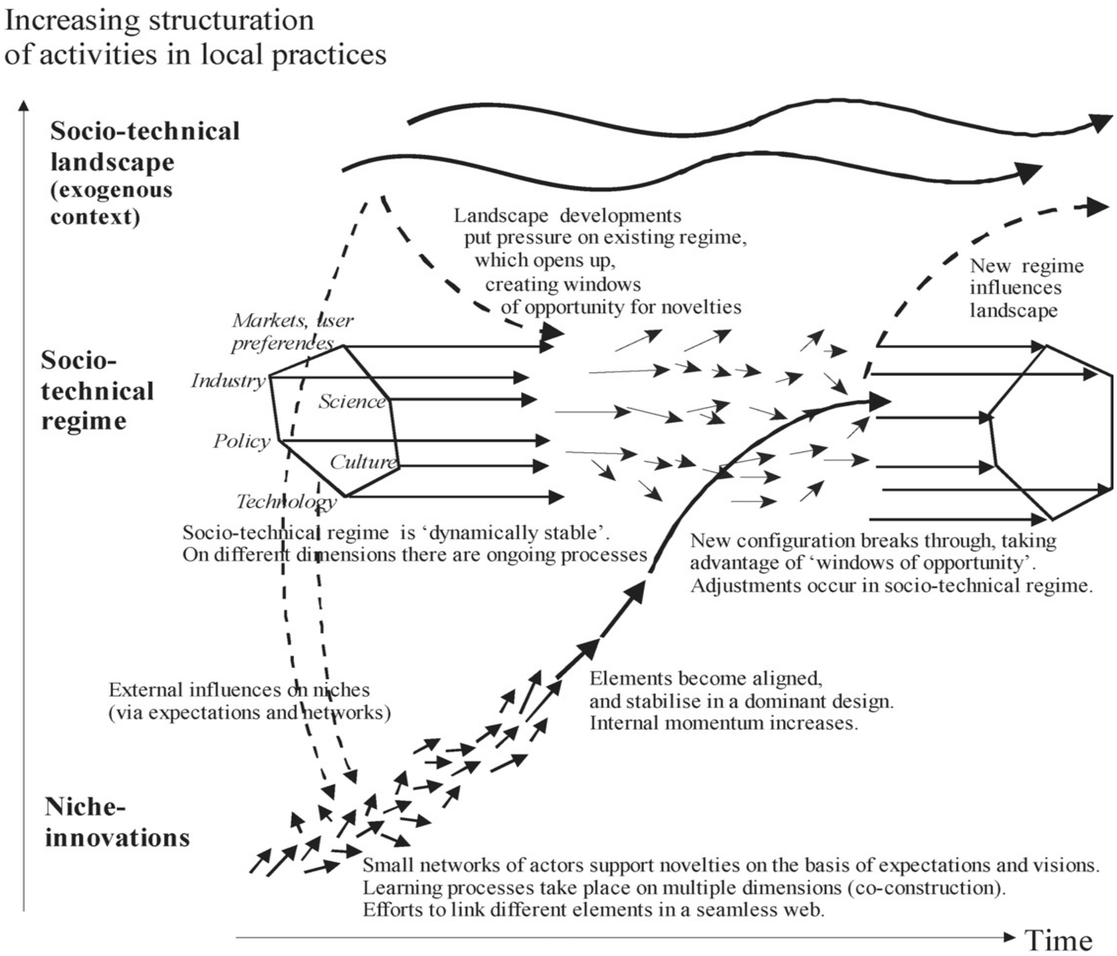

Figure 1. Multi-level perspective on transitions (source: [20])

Affolderbach and Schulz (2016) further explored the synergies of the transitions and policy mobility framework by proposing the concept of "mobile transitions". Transition studies focus on the impact of local experimental niches on the local or national socio-technical regime, which lead to transformation. Policy/knowledge mobility framework offers better understanding of the traveling process of ideas cross-locally or transnationally. Combining the transition with mobility frameworks can provide a better understanding of overall process of cross-local knowledge translation [15].

Based on the conceptual framework of policy mobility and transition studies, this paper examines the case of European low-energy building experiment of the Passive House, and its translation into Chinese context. The data sources include design documents, technical reports, policy documents, academic publications, conference presentations, websites and media articles.

3. Passive House in Germany: From Experiment to Standard

The Passive House concept was developed in 1980s when the oil crisis triggered economic depression and environmental social movements in Germany and Europe. Nationwide, there was growing concern on energy security and climate change. The civil society, policy, and culture were synchronously moving towards an ecological modernisation [21, 22]. The strategy underlying the Passive House experiments was to create a low energy, low emissions, resource efficient building through strict heat conservation: thermal protection and heat recovery. While some of the passive house principles have been applied over the world in vernacular buildings and research projects, the Passive House concept is considered being created by Professor Bo Adamson of Lund University (Sweden), and Dr. Wolfgang Feist of the Institute for Housing and the Environment (Germany) in 1988 [23]. The approaches of Passive House are excellent insulation, prevention of thermal bridges, airtightness, insulated glazing and heat recovery ventilation. The concept is designed to fit central European climate with no necessity for active heating facilities [24].

The concept was materialised in 1991 in the city of Darmstadt to the result of passive house feasibility research funded by the Hessian ministry for economics and technology. A Passive House Developers Society composed of four families, with Dr. Feist's among them, was formed in the city quarter of Kranichstein and commissioned the architects Bott, Ridder and Westermeyer to build a row of four family houses. Each of the 156m² apartment was designed with perfect thermal features in roof, exterior wall (275mm EPS), basement ceiling and windows (triple-pane low-e glazing), together with heat recovery ventilation, ground heat exchanger for preheating the fresh cold air and solar collectors for hot water supply. The maximum heating loads in Kranichstein passive house was 10 kWh/(m²a), which saved 90% energy than conventionally built houses [24].

Although there was local political support from Hessen state and Darmstadt city government, established policies and funding incentives to support this development did not pre-exist, until later in 1990 KfW bank began to provide low-interest loan to encourage energy saving projects [24]. There was reluctance from the private owners to invest into such buildings: the price is relatively high although 50% of the building cost was covered by the state of Hessen; energy was not so expensive as it is today; there was no mandatory regulation for such low-energy building [26].

In 1996, Passive House Institute (PHI) was found to further research, develop and promote the Passive House model. The technical and economical practicality of implementing Passive House standard was tested through the European sponsored research project - Cost Efficient Passive Houses as European Standards (CEPHEUS). In 1997, European Commission funded 262 passive houses projects in Austria, Switzerland, Germany, France and Sweden, and to present the result in the Expo 2000 in Hannover. The passive house built by PHI is located in Kronsberg district of Hannover, beside the site of EXPO 2000. Through the CEPHEUS project, the Passive House concept demonstrated itself to be technically and economically feasible across Europe [27, 28].

Since then, the Passive House concept was "traveling" widely, applied not only in buildings but also in urban districts, for example the Bahnstadt residential area in Heidelberg [29]. Currently there are approximately 25,000 passive houses in the world and 80% of the projects published by PHI are built in Germany and Austria [30].

The Passive House concept includes three formulations: Passive House standard, Passive House Planning Package (PHPP) design tool and the certifications to buildings and components. The framework also supports the policy goal of energy efficiency. In Germany, KfW bank provides funding support for the passive house construction and retrofit [31]. The international consultants, academics, NGOs began to introduce Passive House as a good practice toward low-energy, low carbon sustainable urban development to other places around the world [32, 33, 34, 35, 36].

Passive House developed as a traveling concept, was evolving as the result of interacting with the local and global actors. At the beginning, the Passive House standard is designed to fit central European climate and the requirements are on space heating demand ≤ 15kWh/(m²a), primary energy demand (for all energy services) ≤ 120 kWh/(m²a), and airtightness (Ionescu et al., 2015). Later the cooling demand requirement of ≤ 15 kWh/(m²a) was read in the Passive House standard, responding to the hot climate zones. In 2010, European Union issued updated Energy Performance in Building Directive [37], which introduce the nearly-Zero-Energy Building (nZEB) as goal for all new buildings by 2021 and for new public building by 2019. Meanwhile, the energy efficient innovations in construction industry further developed, for example the Plus-Energy-Building concept [23, 38]. In 2014 PH standard is re-classified as PH Classic, PH Plus, PH Premium, and EnerPHit for retrofitting exiting buildings [39]. In the new rating system, the primary energy demand is replaced by PER (Primary Energy Renewable) to support the energy transition agenda in Germany and worldwide. The PER calculates energy demand in detail through PHPP, responding to each of climate zone globally. The component requirements are correspondingly adapted to the climate zone and cost efficiently optimised for the applied zone [40].

Passive House was developed as a nearly zero energy building model. The experiment was driven by engineering pioneers to test the technical principles, design options, design tools and to develop the cost-effective solutions, which could be promoted and adapted in a wider socio-technical context [24].

4. Passive House in China: Disseminating, Translating and Adapting

China has ratified the Paris Agreement and is engaged in its post-2020 nationally determined contributions (NDCs) to mitigate and adapt to climate change. In China, the building sector accounts for 28% of the energy consumption, and the number is rising due to the growing population, rapid urbanisation and industrialisation [41]. The resource and energy security concerns brought China's growing emphasis on energy efficiency in the 11th, 12th and the current 13th National Five-Year Plan. From 1986 to 2015, China issued about 44 building energy efficiency-related standards [42], and since 2002 initiated series of energy efficient and green building pilot projects [43]. Policy implementation, financial incentives, accelerated approval processes, and priority of land allocation boosted the investors' interest in developing energy-efficient profile properties and therefore increasing their competitiveness [43, 44].

Additionally, the Chinese government considered the energy efficient and green building technologies as pathways to modernise Chinese building industry [45, 46, 47]. Energy efficient and green profile projects also helped to attract international financial and technical support and increase attraction for foreign business and investment [45]. Moreover, solar and wind energy had rapidly development in China thanks to the policies and subsidy programs [48]. The launching of emissions trading system in 2017 and potentially later carbon tax helps to trigger greater demand for renewable energy and energy efficient technologies [49], [50]. Passive House's suitability to adopt renewable energy [51] aligns with China's strategy to increase the market demand for energy-efficient and renewable energy products and services.

The first passive house in China was the Hamburg House built by Hamburg city in Shanghai World Expo 2010. The 2,094 m^2 exhibition centre was designed to meet the German Passive House Standard and Hamburg HafenCity Environmental Standard, aiming to promote the best practice of the "European Green Capital 2011" [51]. During the Expo, the dissemination of passive house concept was facilitated through relative events and mass media attention. But translating the idea into Chinese context confronted difficulties due to its requirement to transform local existing regulations, construction process and production. After the Expo, the Hamburg city government did not further fortify the translation process on Passive House [52].

The translating process was greatly facilitated through the "German-Chinese Working Group for the Promotion of Energy-Efficient Building" partnered by the Ministry of Housing and Urban-Rural Development of China (MoHURD) and the German Energy Agency (dena) established in 2006. Dena worked directly with the socio-technical system through political dialogue, knowledge transfer and strategic market development [53], with benefit from the long-term political support and national branding programs such as "Sustainability - Made in Germany", "GreenTech – Made in Germany", and "Energy Efficiency – Made in Germany" [54, 55, 56]. Under this partnership, dena and the Science Technology and Industrialization Development Center (CSTC), an affiliation of MoHURD, jointly developed pilot projects with low-energy and passive house approaches. in 2012, a 6718m^2 high-rise residential building in Qinhuangdao city of Hebei province was built as the first pilot Passive Ultra-Low-Energy Building [57]. Thermal performance of the building envelope is excellent with passive design approaches such as thermal-bridge-free well-insulated (220 mm EPS) exterior wall, triple glazing low-e windows, air-tightness, and energy recovery ventilation system. The energy demand for heating and cooling is 16 kWh/m^2a, primary energy demand is 102 kWh/m^2a. The project was nation-wide promoted as a show-case of successful knowledge transfer on German energy-efficient technologies, products and construction processes with potential to proliferate on the large scale in China [52]. Subsequently Hebei province released the first voluntary passive building standard guideline based on German passive house standard: Design Standard for Energy Efficiency of Passive Low-Energy Residential Buildings in 2015 [57, 58]. Later that year, based on the passive house experiment through transnational cooperation e.g. with Germany and US, MoHURD issued trial version of Technical Guidelines for Passive Ultra-Low-Energy Green Residential Buildings [59]. At provincial level, policies, financial incentives and standards are developed in Beijing city, Hebei, Shandong, Henan, Heilongjiang, Jiangsu and Jiangxi provinces [52].

In 2016, the concept of passive house appeared in the Guidelines on Urban Planning and Development released by Communist Party of China Central Committee and the State Council [60]. Regulations released by State Council set the tone of rules, standards, plans and financial incentives released by ministries, for example MoHURD and Ministry of Finance [61]. Thus, this policy document is considered as an evidence to mainstream the Passive House concept in energy efficient buildings in China.

In 2017 MoHURD issued 13th Five-Year Plan for the Building Energy Efficiency and Green Building Development [62]. Referring to the international narratives, the nearly-Zero-Energy Building (nZEB) has become a crucial concept, targeting on building over 10 billion m^2 pilot nZEBs by 2020. Recently, MoHURD is developing the National Technical Standard of Nearly-Zero Energy Building. The framework directly referred to the experiments of Passive House pilot projects. For example, the airtight building envelope is required although it is still new to Chinese construction process and no Chinese standard on air tight construction exists yet [63, 64, 65].

Nationwide, there are more than 100 projects built through passive house approach. Some are awarded certificates based on different standards, namely the Passive House Certificate, Sino-German Energy-Efficient Buildings and CPBA Certificate (Table 1). The Passive House concept can be adapted to the rich Chinese vernacular architectural styles and different climates. Although most of the certificated passive low-energy buildings are in severe cold and cold climate zones, there are also trial adaptions to the hot summer-cold winter and hot summer-mild winter climate zones. Passive House approaches have been adapted to local context and are moving towards creating a new socio-technical regime.

Table 1 Certificated passive low energy building in China by 2017

Certification	Quantity	Awarded by	Standard	Description
Passive House Certificate	20	Passive House Institute, Germany	Passive House Standard	Category: office building, residential building, industrial building, exhibition enter, health centre, and kindergarten in China's 4 climate zones
Sino-German Energy-Efficient Buildings – Passive Low-Energy Building Quality Certificate	30	Dena and Science Technology and Industrialization Development Centre (CSTC) (affiliated to MoHURD)	Sino – German Energy Efficiency Standard	Category: office building, residential building, exhibition centre, school in China's 4 climate zones
China Passive Ultra-Low-Energy Buildings - CPBA Certificate	34	China Passive Build ing Alliance (affiliated to China Association of Building Energy Efficiency)	Technical Guidelines for Passive Ultra-Low-Energy Green Residential Buildings (MoHURD)	Category: office building, residential building, exhibition centres, health centre and kindergarten, covering 4 climate zones in China

(Source: [66, 53, 52])

The recent Passive House urban district development in Gaobeidian, which locates 100km south of Beijing, tests the practicality of proliferating the Passive House principles in China at large scale.

Bearing the same name after the German Passive House district Bahnstadt in Heidelberg, the Bahnstadt Gaobeidian includes 30 high-rise buildings, several multi-story and single-family buildings in over 1,000,000m^2 [67]. Implementing the world's largest Passive House settlement project in China requires to overcome the discrepancy between PH standard and Chinese construction routines, to develop construction knowledge and capacities to apply PH technology in large scale projects, and to formulate economically feasible solutions, which are by no mean guaranteed through the knowledge gained from successfully implemented small pilot projects [68].

The adaption of the Passive House approaches to the Chinese context was supported greatly by active dialogues with the local actors (local administrators, professionals, construction supervisors and component producers) through seminars, conferences, training programs and study tours, facilitated by German consultants, academics, NGOs and development agencies [53, 69, 70, 71, 72]. It encouraged to foster a context-oriented passive house development model and nurtured the mutual learning process.

The Passive House's process of translating into local context also confronted difficulties. For example, the current regulation on floor area calculation doesn't allow the extra insulation thickness to be deducted from floor area, which can be discouraging to the private energy efficient property development [52]; Evidenced by documents, experts are holding different arguments if the passive house concept is suitable to be adapted in Chinese climate zones with hot summer, and there exist few closely monitored and proven evidences in China; Both construction and industrial production capacity is increasing but slowly [73]; The Chinese culture is not yet co-evolving with the technical change. For example, 20 out of the 21 Chinese passive houses published by PHI are consulted by planners, architects and engineers with German background. To the most of Chinese developers, the Passive House is merely "a mirror image of German Passive House technology in China" [74].

5. Discussion and Conclusions

The Passive House concept developed from the experiments in Germany and Europe successfully disseminated and translated into Chinese practice. The standard criteria are smooth to be circulated with its simple and concise narrative character, which merely requires control for heating, cooling, primary energy and airtightness. The challenges are on implementation which inform the existing routines, regulations and culture of building industry. However, the provided design tool (PHPP) to support the design choices, educational and networking programs facilitating the planning decision making, and PH certification for incentives and promotion significantly increase the capability of the Passive House to be translated and inhabited into the new context. It shows that the translatable knowledge distilled from an experiment needs to be clearly defined and succinct. Its form should be able to overcome the context (socio-technical regime and landscape) from which the knowledge emerged and re-align with the context into which it is translated.

The narrative of Passive House appears to be evolving, on account of changing climate and energy policy narratives, market trends, knowledge transferring actors, and practice evidences. Through the translating process the Passive House framework interacts with the socio-technical regime on the recipient side. For the transnational practitioners, it presents the necessity to recognise this eco-evolving nature throughout the translation process. In the cross-local practice, the contexts (socio-technical regime, landscape and their driving forces) from both knowledge supplying and demanding sides should be full addressed and understood, if improved outcomes are to be achieved.

Combining mobility with a transition conceptual framework is very useful to clarify the overall translating process of knowledge distilled from experiments in the original socio-technical context into a new one. It extends the notion of "adaptation" and "mutation" in the mobility conceptual framework. This study is limited to the documentary evidence on general base. Further endeavour should be to develop a clearer conceptual model to better articulate the translating process. Detailed case studies based on stakeholder interviews and document reviews should be conducted on the translating process of Passive House from German and Europe to China, in order to examine the theoretical framework with detailed empirical evidence.

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Strategies for a sustainable energy transition: the case of the housing sector in Graz, Austria

Hohmann B

University of Graz, Institute of Geography and Regional Science, Heinrichstrae 36, 8010 Graz

bernhard.hohmann@uni-graz.at

Abstract. To facilitate a sustainable energy transition, the housing sector needs to be considered as a whole. Consequently, buildings as well as spatial structures have to be sustainable. Buildings, new and existing, need to be energy efficient, low carbon, considering diverse demands, while also providing a healthy indoor environment and a high quality of life. Spatial structures have to be efficient through compact development, supporting the transition to a post fossil society and mobility regime, that also provide high quality public spaces. In a transdisciplinary approach, strategies and policies, relevant for the case of Graz, Austria, were analyzed. Challenges and potential solution approaches were identified in a theory discussion, considering spatial development and construction aspects. A resulting set of measures to support the necessary sustainability transition is evaluated and iteratively enhanced by qualitative expert interviews with relevant stakeholders, i.e., researchers, practitioners and the administration. The aim of this research is to come up with a set of policy recommendations for decision makers. First results of this work in progress are already available and presented in this paper.

1. Introduction

In order to avert drastic consequences of climate change, the 2 °C target, also embraced by the Paris Agreement [1], needs to be met. This is only possible if GHG emissions are significantly reduced to achieve the energy transition to 100% renewables. Participating countries have set themselves individual goals, which will be hard to attain, but still even need to become more ambitious. Furthermore, climate change is not the only challenge that needs to be tackled. Brand argues, that the situation can be rather described as a multiple crisis, which requires a profound social change [2]. The Sustainable Development Goals (SDGs) [3] are a key global governance approach, that tries to tackle this complex situation comprehensively, covering not only climate action, but all kinds of social aspects as well. The SDG 11 *Sustainable Cities and Communities* is of special importance, as buildings are a major contributor of GHG emissions due to their high energy consumption.

According to the Energy Efficiency Plan of the EU [4], buildings account for 40% of the total final energy consumption in the EU. More than 80% of this energy demand is caused by heating and domestic hot water. In addition, construction and renovation processes also contribute to energy demand. Moreover, the location of a building indirectly also influences the amount of emissions, as it impacts mobility patterns of occupants and infrastructure extent.

As a result, buildings in loosely populated suburbia are generally responsible for a significantly higher energy consumption, due to less efficient mobility patterns than homes in urban areas. Furthermore, considerably more resources have to be spent (energy and money) on the construction and maintenance of the necessary infrastructure in dispersed areas. Therefore, it is crucial to consider the spatial dimension of the housing sector, to decrease its impact on energy consumption. Consequently, it is favorable to promote measures that lead to denser structures, which can also be socially beneficial and integrative.

Individual buildings, on the other hand, raise questions, such as, how they should be built, heated, cooled or ventilated, in order to facilitate a switch to renewable energy supply, to increase their energy efficiency and to decrease energy and resource consumption. Moreover, a distinction is necessary between new constructions, with significantly more degrees of freedom, and existing buildings that need to be refurbished, insulated or adapted. All these discussions must not neglect the social dimension of sustainability and thus, consider the needs of and impacts on the residents, providing a high quality of life.

Graz, as a medium sized European city, serves as a case study for this research. Until 2030, the city is expected to grow dynamically within the city limits by 18% (based on 2014), i.e., approximately 48,000 additional inhabitants with an according need for new housing [5]. Furthermore, the historic center of Graz is an UNESCO World Heritage site, which limits growth and redensification options in the downtown area, as well as energy efficiency measures.

The aim of this research is to generate a set of strategic principles and specific measures that can guide the housing sector in Graz on a path of a sustainable energy transition. The suggestions consist of top down measures (i.e., legislation, tax or subsidies), but also consider bottom-up approaches, such as the strategic enforcement of increased participation. The generation process of this set of recommendations, as well as the whole research design and methodology is outlined in Section 2. A system model describing the relations of stakeholders and the connection to the research process is presented in Section 3. The preliminary set of recommendations is discussed in Section 4, while the current state of this research in progress, next steps and future work, will conclude this paper in Section 5.

2. Research Design

The underlying hypothesis of this research is that: strategies, regulations and incentives, concerning the housing sector in Graz, have to be significantly improved to promote a sustainable energy transition. This leads to the research question: how to adapt strategies, regulations and incentives (subsidies and tax), to enforce the right measures to promote a sustainable energy transition? To answer this question, a transdisciplinary approach was chosen, as discussed in Section 2.1. The applied mixed methods multi actor process is presented in Section 2.2.

2.1. Transdisciplinary Approach

As stated by Stiess et. al. [6], few fields of action are as complex as the area of housing and construction. Ecologic, economic, social and institutional dynamics are interconnected in numerous ways, causing interacting and overlapping effects. Therefore, an adaption of the building stock requires the consideration of a multitude of actors of different fields and contexts. In addition, various professional perspectives and conflicting goals need to be incorporated. According to Stiess et. al. this integration effort can only be tackled by applying a transdisciplinary approach. First, disciplinary knowledge of fields, such as construction, architecture or urban planning need to be analyzed and combined to a coherent concept. Second also the relevant actors for an according implementation of the proposed measures need to be included in the research process [6].

Consequently, a transdisciplinary approach is chosen to answer the present research question. Moreover, this work has the aspiration to not only analyze this complex field, but also to trigger change to make the current situation more sustainable. It is hence based in the field of critical geography, which traces back to Max Horkheimer's critical theory and assumes, that everything that influences human life is man-made and thus changeable [7]. This connects to the realm of the transformative paradigm, as outlined by Creswell [8]. It is based on the critical theory and underlines the self-conception of researchers who feel to have a responsibility to dedicate their work to serve aims of social justice and sustainability. Within this worldview, research is commonly collaborative, based in political domains and power and justice-oriented. Most importantly, however, it is change-oriented which implies a transdisciplinary approach, including multiple actors from politics and society into the research process.

As discussed by Jahn and Keil [9], the transdisciplinary research process is not a clearly defined procedure. Within the field, different discourses focus on more science or more practice focused branches. In general, transdisciplinary research aims on generating scientific solutions for societal issues. This can appear in the form of an intervention in public discourses or an increased expert knowledge. On the other hand, also scientific results are created, e.g., new transdisciplinary models or detailed problem descriptions. The transdisciplinary integration describes the process from the constituted societal problem to an elaborate societal solution. For the necessary sustainable solutions, segmented disciplinary and common knowledge are not sufficient. Therefore, a reflected synthesis of the different solution approaches is necessary and leads to a systemic problem solution of the societal problem. In addition, this synthesis of different knowledge creates a new comprehensive theoretical structure [9]. A general model of a transdisciplinary research process, differentiates three stages [9].

(i) A common object of research has to be constituted by combining different disciplinary knowledge with practical issues, commonly involving the relevant actors. This leads to the research questions.

(ii) Relevant disciplinary knowledge is generated and integrated.

(iii) In the transdisciplinary integration, practical solutions are generated and a new transdisciplinary knowledge base is created. This stage summarizes the results of the previous stage and verifies the validity and relevance of the proposed solution approaches, by, e.g., conducting expert interviews with the relevant stakeholders. This creates strongly integrated objects, e.g., strategies or specific measures. Thus, added value is generated for each involved actor and beyond by creating a base for potential future cooperation and research.

In this research disciplinary knowledge from the fields of architecture, construction engineering, geography and spatial planning are integrated to take a broad perspective on the role of the housing sector in Graz, in a sustainable energy transition. This scientific knowledge is combined with the practical experience of relevant stakeholders (i.e., experts) to generate a new transdisciplinary knowledge base and come up with a set of possible measures to transform the status quo sustainably. The process of this multi actor mixed methods approach is discussed in Section 2.2.

2.2. Methodology

In accordance with the transdisciplinary research approach discussed in Section 2.1, the methodology follows a three stage process.

1.) First, an analysis of global challenges and possible solution approaches was conducted in which the goal of a sustainable energy transition was focused on the housing sector. In combination with feedback from exploratory interviews with researchers of the respective disciplines and practitioners, this lead to the research question.

2.) Against the backdrop of the theory discussion, a qualitative analysis of strategies and policies, concerning the national, the provincial and the local level of administration, relating to the housing sector in general or concerning the spatial development dimension, was conducted. The documents were processed and coded using MAXQDA [10] to systematically identify relevant text passages, by using different sets of search strings. Out of these relevant text passages, challenges and possible solution approaches were extracted. This process lead to a first set of specific measures, as well as, more general strategic recommendations. Scientific experts of the fields of architecture, civil engineering and spatial planning were asked for their opinion on these proposals. In these semi-structured qualitative expert interviews, the suggestions were discussed and graded to identify the most relevant measures.

3.) This reduced set is currently being evaluated in interviews with practical experts, i.e., developers, cooperative housing associations, architects or civil engineers. In the next step, feedback from administration officials is obtained. Finally, the resulting set of recommended strategic principles and specific measures is presented to political decision makers.

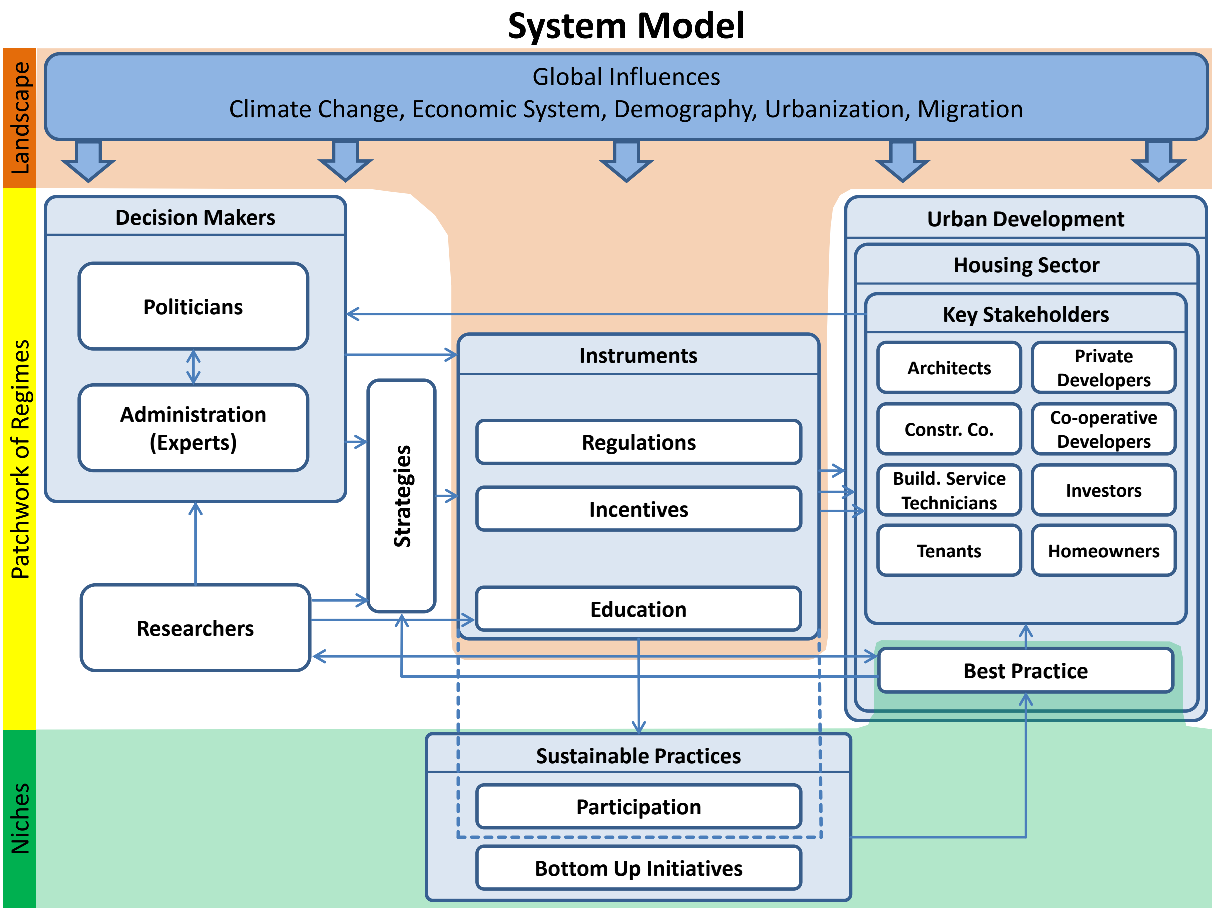

Figure 1. System Model visualizing the relations of the relevant stakeholders and instruments to promote a sustainable transition of the housing sector. The tiering on the left side corresponds to the multi level perspective (cf. Section 3). Source: own design.

3. System Model

To visualize the relations of the relevant stakeholders and instruments to influence the transition, a system model was iteratively developed and validated in cooperation with scientific experts. The system model depicted in Figure 1 also connects this research with the multi level perspective (MLP), introduced by Geels [11]. The MLP, is a model to describe socio-technical transitions which differentiates three levels. In this broad framework, a so called *patchwork of socio-technical regimes* is influenced by *niche innovations* and an *exogenous landscape*. Socio-technical regimes propose, that process technologies, practices and scientific knowledge are socially embedded in a network of actors, institutional structures and infrastructures. Niches are sources of radical change, located at the micro-level, that can lead to incremental or substantial regime change. The exogenous landscape represents external factors which can not be controlled by individual actors, but influence the regime level. Pressure from the landscape can open a window of opportunity in the patchwork of regimes, in which niche innovations have the potential to establish themselves as alternative paths within the system. In contrast, the current regime will try to resist fundamental changes [12]. Therefore, attention has to be focused on how to destabilize current regimes, as the system needs to be transformed towards sustainability.

In the present case the exogenous landscape is, on the one hand, represented by global influences that can not be altered by the patchwork of regimes, i.e., climate change, the economic system, demography, urbanization or migration. On the other hand, the landscape can be interpreted as to additionally include regulations, incentives and education. These instruments, which can be influenced and altered by key stakeholders, can put pressure on the regimes of the housing sector or urban development. This way, sustainable practices, which represent the niches in the MLP, can potentially establish themselves in a window of opportunity in the current patchwork of regimes. These sustainable practices can be participatory processes that respect actual needs of occupants, or bottom up initiatives that try to trigger change to establish sustainable practices. In part these sustainable practices already materialized as best practice examples, which are part of the current patchwork of regimes, but still represent niches.

The system model includes the relevant stakeholders identified in this research process. The instruments, which can be utilized to put pressure on the system to initiate a sustainable transition, are determined by politicians and administration officials who decide and prepare new legislation. These decision makers can be influenced by scientific expert opinions of researchers. Both stakeholder groups influence strategies, which serve as principal guidelines of how the instruments should gradually develop. Moreover, researchers have a direct influence on education, but only indirectly on regulations or incentives. The instruments, are interpreted as part of the landscape environment for the housing sector and urban development, that influences the behavior of the key stakeholders within these regimes, i.e., homeowners, tenants, investors or practitioners, such as architects, construction companies, building service technicians or developers.

Consequently, this system model also refers to the research design and the three stage methodology, as described in Section 2. 1.) Global challenges and influences are analyzed, which represent the exogenous landscape. 2.) The instruments are analyzed to identify challenges and potential improvements, to put pressure on the system to trigger the opportunity for a change towards sustainability. The identified ameliorations (i.e., strategic principles and specific measures) are evaluated and enhanced by the relevant scientific experts. 3.) Next, practitioners commit their perspective on the reduced set of suggestions. In the final step, the resulting set of measures is presented and discussed with administration officials and political decision makers to initiate this process of a sustainable transition.

4. Strategies and Policies for a Sustainable Energy Transition

As discussed before in Sections 2 and 3, the research process generates a set of recommended strategic principles and specific measures. In this section preliminary results are presented. The qualitative analysis of strategy and policy documents (39 relating to the housing sector in general and 24 concerning spatial development), resulted in a first set of 96 recommendations and additional general challenges. These were discussed and iteratively improved in qualitative interviews with scientific experts, who also graded the specific measures and strategic principles. This way the vast amount of suggestions was reduced to a set of 50 most important recommendations (stage 2). Currently, this set is evaluated by practical experts, i.e., developers, cooperative housing associations, architects or civil engineers and in a next step, feedback from administration officials and political decision makers will be obtained (stage 3). The preliminary recommendations are summarized and structured in regulations, incentives, measures concerning education and strategic principles (in correspondence with the system model in Figure 1).

4.1. Regulations

Regulations are a key instrument to secure sustainable development in a top-down manner. For a long term sustainable development, the mandatory use of LCAs in the construction of buildings, is a key requirement. Furthermore, immediate bans on fossil energy sources for the supply of new buildings, obligations to implement passive cooling (shading) on all new buildings or an immediate total ban on split system air conditioning devices in new constructions are important measures to avoid long-term lock-in effects. Another relevant measure would be the mandatory implementation of low-temperature radiant heating and cooling with thermal component activation in new constructions. To ensure a healthy indoor environment and to prevent rebound effects the introduction of mandatory training offers (e.g., the correct use of heating or ventilation systems) by developers for occupants in new highly energy efficient buildings could be a beneficial measure. In addition, mandatory post occupancy evaluations in new apartment buildings and evaluation of the results by the facility management could also improve the actual performance of buildings.

Another key topic to increase sustainability is the promotion of reuse instead of demolition and replacement. This could be supported, if in case of a replacement, the gray energy of the demolished building would be added to the LCA or the energy performance certificate (EPC) of the succeeding building. In case of historically important buildings, reuse also implies the preservation of building culture. In case of willful neglect of such buildings, it could be beneficial to introduce a confiscation option for the community (with compensation). The densification of urban spaces to promote compact development could be fostered by allowing developers to exceed the maximum density in refurbishments as well as new constructions, if a green building certificate is obtained to prove compliance with sustainability criteria.

In order to foster inclusive and collaborative planning, it is suggested to specifically dedicating a certain share of building land in new developments (e.g., in land-use plans), for co-housing initiatives, as it is practiced for instance in Vienna. Moreover, obligatory additional community areas in new housing projects could help to support social integration. The rate of sustainable refurbishments could be increased by the introduction of mandatory higher rates for the creation of reserves (in condominiums), dedicated to the sustainable implementation of a refurbishment, respecting construction methods, materials or a well-considered decision process (proved by a LCA). Furthermore, it would be helpful to adapt the apartment property law (*Wohnungseigentumsgesetz*) in a way to prevent that one owner can block the implementation of a refurbishment. A reform of the tenancy law to create equal conditions for all tenants, or an adaption of rents in social housing, depending on income with periodic updates, to avoid that wealthy tenants occupy needed social housing, could lead to a more just space and cost distribution in the housing sector.

For a sustainable spatial development, a mobility transition to a post-fossil society is necessary. Thus, restrictions for motorized individual transport are necessary, i.e., no subsidies for still individual car based e-mobility, reduction of the number of public car parking spaces and of public investments in road infrastructure. In addition, a reduction of mandatory minimum numbers for the construction of car parking spaces for new buildings, and introduction of upper limits would be beneficial. At the same time, the mandatory minimum number of bicycle parking spaces for new constructions, with a focus on roofed parking, also considering bicycle trailers and cargo bicycles, need to be increased. The introduction of a separate *location factor* for buildings or an extension of the EPC by spatial factors (e.g., proximity of public transport or local suppliers) could raise awareness about the benefits of centrality. A stricter enforcement of the demand of the construction law, that the design of a building has to fit the present street-, town- and landscape, could help to make the urban environment also visually more attractive. Moreover, sprawl could be reduced by mandatory mixed-use multi-story developments on supermarkets and the introduction of tight maximum absolute limits of the plot size for new single family homes, corresponding to the local settlement structure.

4.2. Incentives

In contrast to regulations, incentives (which can be alternative or complementary measures) can help to softly promote a sustainable transition. New incentives, promoting innovative participatory housing approaches, e.g., co-housing, could be introduced as a part of the housing subsidies of the province. The subsidies for reuse and refurbishments could be extended to also cover community areas. In turn, the support for new detached single family homes in urban areas could be scrapped to reduce space consumption. Furthermore, a mandatory consideration of the embedding in the neighborhood and the surrounding public space should be tied to the granting of subsidies.

In order to increase the number of sustainable refurbishments, further investment incentives for owners (subsidies or tax reliefs) to refurbish sustainably (proved by a LCA) should be created. The introduction of specific subsidies for an accompanying process in refurbishments of condominiums, could increase participation and raise awareness, facilitating a more sustainable implementation.

Another suggestion is the coupling of interest rates of building savings contracts (*Bausparvertrag*) and correspondent loans to the gained CO_2 emission savings of a refurbishment. Generally it is suggested to establish more incentives on all levels of administration to facilitate reuse rather than demolition and replacement, as well as the introduction of distinct incentives to promote densification in the process of a refurbishment. Incentives for extensive greening of roofs, on the other hand, could alleviate some of the negative effects of higher densities.

The transition to renewable energies could be accelerated by the introduction of a tax on CO_2 emissions in combination with an eco-social tax reform. Specifically targeting heating systems, a tax on these CO_2 emissions, which is progressively increasing over time, could motivate users to switch their heating system. In addition, subsidies for heating systems with thermal component activation that can be used also for cooling (thermo-active ceilings) potentially raise awareness and avert the further increase of the number of inefficient cooling devices.

To make the space and cost distribution more fair, incentives and suitable general conditions could be created to motivate older people to give up unneeded space (e.g., move to a smaller, more convenient flat or share the house). Moreover, a vacancy tax in urban areas could help to activate vacant flats. In order to promote central living and make it more affordable than the suburban, a progressive tax on land, as a function of the utilization ratio of land and the quality of the location (e.g., centrality) could be introduced. Another beneficial measure would be, the introduction of cost transparency in the construction and maintenance of public infrastructure and a splitting of costs according to the principle that the responsible party has to pay.

4.3. Education

Educational measures aim at raising awareness and the dissemination of professional knowledge, in this context. These measures also positively influence the *Sustainable Practices* addressed in the system model in Section 3. In order to spread knowledge about the latest innovations, best practice and lessons learned on housing among professionals, including relevant research results of other fields (e.g., sociology, psychology, ethnology or geography), it is suggested to establish a suitable medium for that purpose. Additional awareness raising campaigns to promote energy efficient behavior would be beneficial. Likewise the rate of sustainable refurbishments could be increased through, e.g., information about saving potentials in connection with the issuing of energy performance certificates, under the condition that issuers are continuously trained on up-to-date sustainable solutions. An introduction of a summary in construction processes, listing all materials used in a construction process, including their components, properties and impacts on health and the environment, could potentially help to establish awareness about the impact of construction.

4.4. Strategic Principles

In addition to the specific measures that can be attributed to regulations, incentives and educational measures, also more general strategic principles have resulted from the research process. The fostering of the implementation of flexible floor plans of flats in combination with a participatory planning process can help to promote a more just space and cost distribution, as people are more flexible to give up unneeded space, without the need to move. Rebound effects in new highly energy efficient buildings could be averted by a good facility management that monitors energy consumption and contacts occupants in case of irregularities. A general strategic preference of low-tech solutions in construction could significantly help to save resources. For a sustainable spatial development, car free cities with spacious pedestrian zones and high quality public spaces have to be fostered. Furthermore, the increased consideration of local waste heat potentials (e.g., for district heating or local heat supply) needs to receive more attention to promote a sustainable energy transition.

5. Conclusion

So far, the underlying hypothesis, that strategies and policies, concerning the housing sector in Graz have to be significantly improved to promote a sustainable energy transition (cf. Section 2) was acknowledged by all scientific experts. The preliminary results presented in Section 4 are currently under evaluation by practitioners. In the next step they will be discussed with administration officials of the local and provincial government. After this, it will be possible to answer the research question more comprehensively, with the final set of recommendations. Moreover, it will be possible to analyze a second research question, i.e., whether there is a knowledge gap of what is sustainable, among the relevant stakeholders (i.e., architects, developers, construction companies, investors, building service companies, home owners, tenants politicians or administration) and, if yes, how to improve this situation.

The results of this work are specifically concerning the case of the city of Graz. The general approach of the applied research design (cf. Section 2) and the iteratively developed system model (cf. Section 3), could also be transfered to other cases beyond Graz. 1.) The general research question can be directly transfered and possibly adapted to another local context. 2.) A basis for such a transdisciplinary research process can be created by the combination of an analysis of the relevant local policy documents and a state of the art theory discussion. The identified challenges and possible solution approaches are evaluated together with according scientific experts. 3.) Also the expertise of local practitioners and decision makers needs to be included, to produce a set of recommended specific measures tailored to the particular situation. Consequently, this approach can be utilized to support a sustainable transition of the housing sector, also in other local contexts.

Planned future work is to present the final results of this research to local decision makers, to support the targeted transition process. The establishment of an urban lab to acquire deeper insights, to come up with new research results and to foster a dialog among relevant stakeholders, is also planned.

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Energy transition and technical energy regulations in the building sector

Knoeri C, Schwarz M, Nakhle C

ETH Zürich, Group for Sustainability & Technology, Weinbergstrasse 56, 8092 Zürich

cknoeri@ethz.ch

Abstract. Energy demand from buildings accounts for about 31% of global final energy demand and 23% of global energy-related carbon emissions. Technical energy regulations or building energy codes - policies that set minimum requirements for energy in buildings – have proven effective and efficient in decarbonizing the building sector. However, despite their long history and success, policymakers increasingly recognise that TERs in their current design have reached a point of diminishing returns. This study evaluates five countries with innovative building energy codes – Denmark, France, England, Switzerland, and Sweden – through reviewing legal documents and conducting expert interviews with researchers, practitioners, and regulators. Our results highlight the implementation challenges of innovative building energy codes and we provide learnings in form of six design principles.

1. Introduction

The building sector accounts for about 31% of global final energy demand and 23% of global energy-related carbon emissions [1]. While buildings provide a remarkable potential for energy savings and carbon emission reduction [2], many energy-efficient opportunities are not realized despite being economically superior compared to their carbon-intensive alternatives. Technical energy regulations or building energy codes (BEC), which set minimum requirements for energy in buildings, have proven effective and efficient in reducing energy demand and carbon emissions in the past – for example, up to 22% energy savings in Europe [3] and China [4].

However, despite their success and long history, BECs in their current design have reached a point of diminishing returns [5]. Literature outlines the following five reasons: First, BECs traditionally focused on prescriptive requirements such as minimum U-values. Second, current BECs regulate the energy demand during the use phase of buildings, and thus neglect embodied energy (i.e., energy used to produce construction materials). While this is appropriate for conventional buildings with up to 90% of their lifecycle energy use during their operational phase, net-zero energy buildings have up to one-third of their energy use, and up to half of their carbon emissions embodied in their materials [6]. Third, most BECs still allow fossil heating systems, which are subsequently still the prevalent technology in many industrial countries, despite economically superior renewable alternatives. Fourth, most BECs regulate building design and construction based on calculated energy use but not measured energy use, despite an average difference between calculated and measured energy use at 34% [7] – termed as 'performance gap'. Fifth, while stipulating requirements for retrofits, with retrofitting rates below 1% per year in many countries [8], a fast decarbonization of the entire building stock is unlikely.

Although literature highlights these challenges of current BECs, it lacks providing a comprehensive analysis of how to overcome these challenges and thus achieve a low-carbon building sector. Further, due to being mandatory for the entire sector, BECs' implementation has been outlined as a key issue [9]. This study aims to address this gap by evaluating how policymakers can design and implement innovative BECs that address challenges of their predecessors. To do so, we first elaborate on the five challenges of current BECs –in the following termed 'key leverage points'. We then review five countries with innovative building energy codes – Denmark, France, England, Switzerland, and Sweden – applying archival data and expert interviews with academia, industry, and regulators.

2. Methodology

We aim to increase our understand on how policymakers can design and implement innovative BECs that address key leverage points in three parts

Part 1 - Key leverage points: We first analyzed the few existing review studies on BECs, which mention several limitations current BEC designs have. We then consolidated and extended the findings from the review paper with a forward and backward search from the review literature and an independent keyword search.

Part 2 – State-of-the-art of building energy codes: First, we identified and selected innovative BECs that address key leverage points. To do so, we collected innovative BECs in a 'long list'. We then applied two selection criteria: BECs are already in the process of their implementation and in countries that have similar climatic conditions. The former is required as most challenges of BECs disclose during their implementation – for example, politicians might set ambitious targets and introduce new laws but fail to implement them. The latter is required as climatic conditions influence the sources of energy demand that regulation needs to address. We ultimately selected Denmark, France, England, Switzerland, and Sweden. Second, to understand selected innovative BECs, we scanned through the relevant legal documents for building regulation (707 pages) and validated our understanding with secondary literature. For comparing BECs, we developed a categorization framework that covers the essentials of previous, prevailing, and innovative BECs (in total 63 indicators). We validated the filled framework concerning comprehensiveness and correctness in several rounds with building and energy experts.

Part 3 - Implementation challenges of innovative BECs: To discuss the challenges that disclose during their implementation, we conducted 18 semi-structured interviews (Table 1). To account for different perspectives, we conducted interviews with researchers, practitioners, and regulators. We selected the interview partners through targeted snowball sampling. In the first round, we identified experts by drawing on secondary data of BECs, industry reports, and academic publications in this field. In the second round, we then asked interviewed experts for recommendations for other experts. We conducted the interviews between March 2018 and January 2019. The response rate was 24% (researchers 33%, practitioners 20%, regulators 22%). We validated our findings by asking the interviewed experts to check their interview summary and the final case summaries, including the statements of the other experts.

Table 1*: Data Sources across Cases*

		Denmark	**France**	**Switzerland**	**England**	**Sweden**
Interviews (minutes)	Researchers	Professor (61)	Professor + Director (53 + 82)		Director (40)	Senior Researcher (65)
	Practitioners	Energy (written)	Buildings (41)	2 x Buildings (34 + 24)	Buildings (54)	Consultancy (63)
	Regulators	Advisor (49)	Director (63)	3 x Director (52 + 54 + 73)	Director (93)	Advisor (58)
	Total	110	239	237	187	186
Legal Documents (pages)		137	140	98	167	165
Secondary data		e.g., scientific publications on building regulations, summaries of innovative BECs				

3. Results

3.1. Part 1 - Key Leverage Points

In the following, we will briefly summarize the five identified key leverage points for decarbonizing the building sector:

(i) In many countries, BECs have been effective in '*Improving Energy Efficiency*' in buildings [10]. Historically, most energy-efficiency gains came from mandating better thermal insulation of the building envelope and installing energy-efficient building technologies for heating. While this was achieved mainly by increasing the stringency of prescriptive requirements, there are limits to which this approach can achieve energy savings, resulting in diminishing returns for each incremental improvement. For example, adding insulation material to an uninsulated wall reduces heat loss by about 75%, while adding the same amount of insulation material again only results in 11% more reduction [5]. In turn, a shift from a traditional focus on prescriptive requirements for individual building parts (e.g., U-Value) to performance metrics for the entire building energy (e.g., primary energy demand) is necessary. Besides performance and prescriptive requirements, BECs can also limit service capacities such as maximum electricity or natural gas supply [11].

(ii) Current BECs neglect '*Considering Embodied Energy*' while concentrating on energy consumption during the use phase of buildings and thus neglect embodied energy. While this might be appropriate for conventional buildings with up to 90% of their lifecycle energy use during their use phase, net-zero energy buildings have up to one-third of their energy use, and up to half of their lifecycle carbon emissions embodied in their materials [12]. Further, energy-efficient buildings often use many energy-intensive materials [13]. Also, the transport of materials significantly affects the amount of embodied energy; for example, while timber originating from sustainable forestry is almost carbon-neutral, due to its energy-intensive transport, the embodied energy varies drastically depending on its destination [14]. Further, the recyclability of building materials contributes to the overall reduction of a building's embodied energy [14]. BECs can help to reduce the embodied energy and carbon by taking a lifecycle perspective for performance metrics, thereby providing a more holistic picture of a building's energy consumption.

(iii) A complete decarbonization of the building stock requires '*Integrating more Renewable Energy*'. While some BECs already prescribe the use of renewable energy, most still allow fossil heating systems, which are the prevalent technology in the building stock [15], despite energy-efficient alternatives are available. BECs could increase the share of renewables in four different ways: First, increasing the stringency of performance metrics that are based on primary energy demand or carbon emissions. Such a performance metric could also be extended to neighborhoods and districts, which facilitates the cost-effective integration of renewables. Second, prescriptive requirements can directly stipulate the use of renewable energy, indirectly increase the share of renewable energy – for example, through mandatory feasibility assessments of renewables – or directly ban fossil fuel technologies such as gas and oil boilers.

(iv) While on paper new buildings are increasingly energy-efficient, '*Closing the Performance Gap*' – the difference between the calculated and the measured energy use – is crucial as this gap amounts to 34% on average [7] but can even increase up to 300% [16]. Causes of this gap are manifold, for example, wrong estimates of the energy-use behavior of occupants, deviations to as-planned building properties such as insulation and air permeability, rebound effects, and unfamiliarity of occupants with complex energy efficient technologies. BECs can contribute to close the performance gap by, first, improving the compliance check through additional testing of the constructed building (e.g., blower-door test) or checking compliance based on measured energy performance. Second, BECs can stipulate training and tools for building developers and owners.

(v) With retrofitting rates below 1% per year in many industrialized countries [8], many of today's existing buildings will also exist in 2050 and beyond, making a fast decarbonization of the entire building stock challenging; BECs should therefore particularly focus on '*Accelerating Retrofits*'. Besides less stringent requirements for retrofits compared to new constructions, BECs can accelerate retrofitting by, first, stipulating retrofitting of buildings during a change of ownership or occupant – during such special occasions energy efficiency measures are typically more profitable – and, second, providing a long-term perspective on minimum energy requirements that existing buildings have to meet. Such a long-term perspective would serve as a roadmap, making it easier for building owners to make retrofitting decisions involving time horizons of a decade or more.

3.2. Part 2 – State-of-the-Art of Building Energy Codes

In this second part we briefly outline the common denominator – or state-of-the-art – in BECs in the selected countries adressing the five key leverage points outlined above (Table 2).

(i) To improve energy efficiency, all selected cases implemented a performance metric, mostly considering primary energy demand. Further, all cases kept prescriptive requirements for the envelope efficiency or a second performance metric for total heating demand. Such a 'double metric' allows the countries to, first, minimize building energy demand and, second, minimize the use of resources or carbon emissions to cover the remaining building energy demand. England and Switzerland add requirements for individual building technologies and Switzerland and Sweden limit the capacity for heating power. Only France includes a requirement for summer comfort – the temperature on the hottest five days is not allowed to exceed a certain threshold – and only Denmark pre-announces future energy efficiency requirements.

***Table 2**: Overview of the state of the art in the topic of technical energy regulations.*

		Denmark	France	England	Switzerland	Sweden
Improving Energy Efficiency	Performance	Yes	Yes	Yes	Yes	Yes
	Prescriptive	Yes	Yes	Yes	Yes	Yes
	Capacity	-	-	-	Yes	Yes
Considering Embodied Energy	Performance	-	Yes (pilot)	-	-	-
Integrating more Renewable Energy	Performance	Yes	Yes	Yes	Yes	-
	Prescriptive (direct)	Yes	Yes	-	Yes	-
	Prescriptive (indirect)	Yes	-	Yes	-	-
	Prescriptive (ban)	Yes	-	-	Yes	-
Closing the Performance Gap	Compliance Check	Yes	Yes	Yes	Yes	Yes
Accelerating Retrofits	when retrofitting	Yes	Yes	Yes	Yes	Yes
	to retrofit	-	Yes	-	-	-

(ii) So far, no country considers embodied energy in their BECs. However, France announced to include embodied energy to be part of the next regulation in 2020. This regulation will include embodied energy in the existing primary energy metric and will put an additional focus on embodied carbon.

(iii) To integrate more renewable energy in buildings, all selected countries adopted a performance metric that supports the use of on-site and off-site renewables. While all other countries focus on primary energy demand, England adopted a performance metric based on carbon emissions. Also, all countries except Sweden adopted additional prescriptive requirements for the use of renewable energy. Denmark, France, and Switzerland directly stipulate the use of renewable energy. Further, Denmark and Switzerland include technology bans and Denmark only restricted the extension of their distribution network of fossil fuels. Also, Denmark and England take an indirect approach by stipulating an assessment of renewables in regards to their technological and economic feasibility.

(iv) To close the performance gap, all selected countries check compliance with the technical energy regulations before the start of the construction as part of the building permit process and directly after the construction as part of the building decommissioning. Further, all countries except Switzerland also conduct an airtightness test. Further, England requires building owners to provide occupants with a set of operating & maintenance instructions, and Sweden includes a compliance check based on measured data after two years of occupation.

(v) To accelerate retrofits, all selected countries except Sweden include less stringent requirements for retrofits compared to new constructions and allow buildings that are retrofitted to opt for compliance based on prescriptive requirements. Both less stringent requirements and the option for prescriptive requirements reduce costs for retrofitting buildings. Besides such requirements that aim at buildings that undergo a retrofit, France follows a unique approach and pushes for mandatory retrofitting of buildings. So far, they prohibit the sale of social housing with high-energy demand, thus hoping for an increase in the retrofitting rate of social houses.

3.3. Part 3 – Innovative Building Energy Codes and their implementation challenges

In this final part of the results we look at innovative BEC approaches in the five countries and what have been the challenges when implementing them.

Denmark - Increasing energy efficiency through pre-announcing energy standards: Denmark reduced the energy use of buildings drastically by pre-announcing future BECs, thus providing long-term regulatory certainty for the building industry. The building industry perceived the pre-announcing as a strong signal that drives innovation and cost reductions, and therefore, advocated for it. Knowing that a voluntary energy standard will become mandatory, companies had time to develop and exploit investments in new technologies, materials, and construction methods. Ambitious building owners, too, advocated for the announcement of future regulation as it provides a target to aim at. However, Denmark stopped making BECs even more stringent as the requirements did not prove to be cost-effective; yet, concerning building sustainability, they might again pre-announce regulations in the future.

France – Considering embodied energy in central performance metric & Accelerating retrofits through situational retrofitting obligations: France will include embodied energy in the next update of the thermal regulations for buildings. However, the introduction of embodied energy is challenging, requiring extensive prior testing and continuous learning. Further, integrating a lifecycle perspective of buildings' energy use is expected to transform the French construction industry. Besides embodied energy, another target of French policymakers is to accelerate retrofitting the existing building stock, for example, by mandating all private residential buildings to achieve steadily increasing energy levels over the next decades. However, while ambitious targets and laws exist, decrees to turn the targets into specific policy measures are lacking because the retrofitting obligation causes additional upfront costs for building owners and is premised on the French Energy Performance Certificate, which is perceived as unreliable by the population.

England – Increasing the share of renewables through adopting a carbon emissions metric: England adopted a CO_2 performance metric to align requirements for buildings with national targets and international commitments. As a result, carbon-friendly technologies have been heavily adopted; shortly, the decarbonization of the electricity mix will pronounce this technology impact. However, the carbon emission metric is perceived increasingly critical because, first, reducing carbon emissions does not necessarily result in energy-efficient buildings and, second, primary energy factors are more stable than carbon emission factors. England is likely to shift towards a primary energy metric, also because the EU pushes the use of primary energy as part of its harmonization efforts.

Switzerland – Increasing the share of renewables through prescriptive requirements: Switzerland increases the share of renewables in buildings through two specific requirements: One requires new buildings to produce a certain amount of electricity on-site, the other requires residential buildings that have an oil or gas boiler to install a heating system based on at least 10% renewable energy in case of a boiler replacement. Both requirements – despited perceived to be very effective in pushing more renewables into buildings – are heavily debated. Mandatory on-site electricity production is perceived as technology specific and as challenging to achieve in the case of compact buildings. Renewable heating might result in high investments costs for homeowners.

Sweden – Closing the performance gap through compliance based on measured buildings' performance: Sweden aims to close the performance gap by checking compliance based on the measured building's performance two years after its occupation. This compliance path is viewed differently by building developers, owners, and municipalities. Larger actors seem to prefer the measured over the calculated compliance check, while for smaller actors, this is typically vice versa. This might be because, first, the available and required measurements are often different; the smaller the building, the less precise the measurements and, in turn, the larger this difference. Second, sanctioning the building owner in case of non-compliance two years after the building's occupation is a delicate task for smaller municipalities; keeping the file open for two years requires more personnel capacities. Sweden plans to address the second challenge by, first, shifting the authority for the final compliance control from local municipalities to the regulator and, second, combining the compliance check with the issuing of the energy performance certificate, which has already previously done by the regulator's energy experts.

4. Discussion

In the following, we synthesize the key findings across the five case studies. We derive six policy design principles from the challenges regulators were facing across our selected case studies when implementing innovative BEC designs. Despite the broad variety in innovative approaches addressing very different aspects of buildings' energy use, the challenges faced showed a surprisingly similar pattern. Table 3 lists the six key learnings – or policy design principles – derived and illustrates them with examples from the cases.

(1) To keep the additional burden for building owners at bay, policymakers should design BECs as cost-effective as possible, thus only mandating what is economically beneficial – e.g. being net present value positive – to consumers but fails to diffuse in the market. This is especially important as many of

the mandated efficiency technologies require comparable high upfront investment compared to their fossil counterparts.

(2) Creating long-term regulatory certainty – e.g. through preannouncing of regulatory changes – provides a fair planning horizon for the building industry, in turn, spurs innovation, drives down technology costs and, ultimately, allows for stricter BECs.

(3) Avoiding technology-specific requirements allows all buildings to comply. However, even de facto not technology-specific regulations – such as a requirement for onsite electricity generation – might leave homeowners with very limited choice given the current technology landscape.

(4) Anticipating the impact on various actors the adoption of new BECs might have is crucial for a broad acceptance of the regulatory change; regulatory change is often particularly challenging for small actors. This has been observed across the board from small construction firms via homeowners to small municipalities struggling with the implementation.

(5) Ensuring sufficient knowledge about the regulatory innovation before implementing it, helps policymakers to improve its design (e.g., identify cost-effective stringency levels) and to justify its implementation (e.g., refer to front-runners who prove cost-effectiveness).

***Table 3**: Overview BEC Design Principles and Design Recommendations*

Design Principle	BEC Design Examples
Keep additional burden for building owners at bay	▪ Include technical feasibility & cost-effectiveness tests ▪ Combine BEC with additional policies such as zero-interest financing to lower the burden of upfront investment cost.
Create long-term regulatory certainty	▪ Align BEC with national energy & climate targets ▪ Pre-announce next BECs ▪ Integrate continuous improvement process
Avoid technology-specificity	▪ Ensure multiple technology options are available when increasing stringency levels ▪ Set performance based targets for retrofits
Anticipate the impact new regulations have on actors	▪ Support the building industry through reducing unnecessary soft costs ▪ Support building owners decision-making through providing information ▪ Support authorities through disburdening them from capacity-intensive compliance control
Ensure sufficient knowledge about innovative design	▪ Pre-announce next BECs ▪ Conduct multi-stage test programs ▪ Build upon voluntary labels ▪ Learn from frontrunner legislation
Integrate BECs in the local context	▪ Leverage the existing infrastructure ▪ Consider the level and pace of ongoing grid decarbonization ▪ Leverage domestic resources ▪ Consider the quality of domestic building industry ▪ Check political feasibility

(6) While learning from frontrunner firms and legislation helps to design BECs that enjoy broader acceptance, policymakers have to adapt these learnings to the local context, which includes existing infrastructure, level and pace of grid decarbonization, domestic resources, quality of domestic building industry, and current politics.

In summary we can say that the mandatory nature of BECs as a policy instrument seems to directly lead to the first four design principles derived, which all ensure that the broad range of actors in the sector are able to cope with the new regulation. With increasing distance from the traditional regulations – e.g. when including embedded energy – extensive testing becomes crucial. Further, despite the general findings, adapting an innovative approach to the context of the local building industry, infrastructure, electricity grid, and political system has been found challenging in all cases. Finally and beyond this study, BECs are only one of a mix of policy instruments (e.g. labels, subsidies, tax incentives etc.) which all have to work in concert to achieve a most efficient and effective transformation of the building stock.

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Achieving net zero status in South Africa

Terblanche R

School of Construction Economics and Management
University of Witwatersrand, 1 Jan Smuts Avenue, Johannesburg, 2000, South Africa

rolien.labuschagne@wits.ac.za

Abstract. The purpose of this research is to determine how net zero buildings in South Africa can achieve net zero status. Net zero buildings are defined as energy efficient buildings with energy supply from renewable sources on-/ or off-site or through offsets. The Green Building Council South Africa launched and certified the first four buildings in South Africa under its Net Zero Pilot Certification scheme in October 2017. Net zero status can be achieved in waste, water, carbon and ecology respectively. The concept of net zero buildings is thus new to South Africa and certain barriers needs to be overcome. A semi-structured questionnaire was sent out to developers in order to establish the perceived barriers by developers. Net zero buildings still needs to be commercially justified in South Africa. Cost and lack of incentives are definite barriers. The National Building Regulations of South Africa is a barrier to the development of net zero buildings as is does not require buildings to aim for net zero status. Requirements from national authorities could greatly impact changes in the approach to developments. There is a knowledge gap in the construction industry of sustainable and net zero buildings in South Africa regarding the benefits, implementation thereof as well as the actual costs.

1. Introduction

The United Nations Environment Programme (UNEP) reports that the built environment contributes approximately 40% to global energy consumption and approximately 36% in greenhouse gas emissions [1]. Recently, developing countries, such as South Africa, has become known for rapid urbanisation. [2]. Urban areas not only see an increase in the carbon dioxide emission but also see a decrease in biodiversity and the effects of the Urban Heat Island effects [3]. Johannesburg, a metropole in South Africa, has been ranked as one of the most polluted cities in the world. This is due the heat island trapping dust from mining and other pollutants. According to the World Health Organisation, Pretoria is the second most polluted city in South Africa, followed by Cape Town and Durban [4]. Internationally, the growth of cities, known as urbanisation, establishes by means of high rises, inward compacting and or outward expansion. [5]. Nonetheless, urbanisation in African cities manifests as uncontrolled spatial expansion, known as urban sprawl. Recent studies on African cities found that urban sprawl subsequently causes unsustainable land use, and often consumes bordering urban areas and converts non-urban land, primarily agricultural lands, into urban developments [6]. As such, it is imperative that African countries, such as South Africa, re-evaluate development strategies by introducing sustainability.

Some sustainability strategies, for example greenery systems, have been around for centuries to reduce and mitigate the negative effects of the built environment on the surrounding environment and biodiversity [7]. Although they have been around for centuries, green infrastructure systems is relatively new to the South African industry [8], and adaptation to sustainable strategies are slow. The latest sustainable strategy is net zero developments. Understanding if and how net zero developments are introduced in South Africa, and knowing how South Africans can achieve net zero status developments, could inform and encourage the industry. The objectives of this study is thus to define net zero developments, determine the status quo of net zero developments in South Africa, the involvement of building regulations of the latter and to determine the difficulties that South Africans face with the implementation thereof. As such, the main aim is to understand how developments in South Africa can reach net zero status.

2. Building regulations in South Africa

The national building regulations of South Africa does not include any reference to vegetation, greenery or net zero energy usage [9]. As such, it is not compulsory by national regulations to develop sustainable or net zero buildings in South Africa. Nonetheless, South African cities have influence over building energy usage, and thus energy-related emissions, through the building plan approval process, building inspectorate and regulatory functions. Local authorities in South Africa introduce their own by-laws regarding green and sustainable buildings. A range of options regarding the minimising of energy usage by buildings are being explored. These include by-laws that are more stringent than the national building regulations on building energy efficiency. Stringency would increase in order to meet the net zero or low-carbon target by 2030/2050. Incentives for developing more energy efficient buildings are also being considered. Four of South Africa's metros (Johannesburg, eThekwini, Tshwane and Cape Town) are aiming to implement innovative programmes and certain policies that strive towards net zero carbon emissions from newly-developed buildings by 2050 [10]. The City of Johannesburg has a Built Environment Guideline which will be simplified and reused for awareness-raising. eThekwini (Durban) aims to incentivise green developments. City of Cape Town wants to update their Resource Efficiency Criteria for Development guideline and incorporate low-carbon conditions. The City of Tshwane (Pretoria) requires that all new city-owned buildings must achieve at least a five star Green Star rating and their Green Building By-law document will be updated to incorporate a zero carbon target [11]. In South Africa, the Green Building Council of South Africa (GBCSA) is the main driver of green developing principles [12].

3. Green Building Council South Africa

The GBCSA is a member of the World Green Building Council and was founded in 2007. The aim of the GBCSA is to develop green building solutions to drive the revolution of the South African developing industry towards sustainability. In addition, the GBCSA and focus on green building training and certification. The GBCSA certified the first four buildings in South Africa under its Net Zero Pilot Certification scheme in October 2017 [13]. In the pilot programme, four developments were awarded a net zero certificate. These four developments are the first and only net zero certified buildings in South Africa currently. The developments are the Estuaries Plaza in Century City situated in Cape Town, which received a net zero water certification, the Vodafone Site Solution Innovation Centre in Midrand situated in Johannesburg, which received a net zero certificate in both carbon and ecology, Greenfields Industrial Park in Cape Town and Two Dam Sustainable in Montagu, which both received a net zero carbon certificate [14].

The GBCSA categorizes net zero buildings into the following four categories: carbon, water, waste and ecology. Each categories has its own definition. A net zero carbon building is defined as: "A building that is highly energy-efficient, and the remaining energy use is from renewable energy, preferably on-site but also off-site where absolutely necessary, so that there are zero net carbon emissions on an annual basis." A net zero water building is defined as: "A building that is designed, constructed and operated to greatly reduce total water consumption, and then use harvested, recycled and reused water such that the amounts of water consumed is the same as the amounts of water that is produced." A net zero waste building is defined as: "A building that reduces, reuses, and recovers its waste streams to convert them to valuable resources with zero solid waste sent to landfills over the course of the year." A net zero ecology building is defined as: "A building that does not reduce the ecological value of the site during development for Greenfield sites [15]."

4. Comparing definitions of net zero across the world

Various definitions and understandings of net zero buildings emerged worldwide. Net zero as defined by Europe, The United States, Brazil and the World Green Building Council will be compared.

4.1 Europe

According to Article 2(2) of the Energy Performance of Buildings Directive (EPBD) of Europe a nearly zero-energy building (NZEB) is defined as "a building that has a very high energy performance, as determined in accordance with Annex I which translates to the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby". Each European country, as part of the EPBD recast into national legislation, can adopt a unique national definition of NZEB. Subsequently, variances exist among the NZEB definitions within the European Union, the calculation methods as well as the type and level of requirements [16].

4.2 The United States

The National Institute of Building Sciences in the United States defined "a zero energy building (ZEB) as an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy" [17].

4.3 Brazil

The Green Building Council of Brazil defines a net zero energy building as a development that proves that the consumer site of the annual operating energy is reset by a combination of high energy efficacy and energy generation from renewable sources [18].

4.4 World Green Building Council

The World Green Building Council (WGBC) defines "a net zero carbon building as a building that is highly energy efficient and fully powered from on-site and/or off-site renewable energy sources". Canada, Brazil, Australia and South Africa launched the net zero initiatives in 2017 [19].

4.5 Comparison

South Africa is on par with some developed countries regarding the implementation of net zero buildings. It is however, still a fairly new initiation in South Africa. The definitions as given by Europe, United States, Brazil and the Green Building Council all comes down to buildings that are energy efficient and that uses renewable energy resources, where the energy used by the building does not exceed the energy generated by the renewable resources. The GBCSA, however, created four separate categories for net zero status: water, waste, carbon, and ecology. The carbon category relates to the definitions given by Europe, United States, Brazil and the Green Building Council. The water, waste and ecology categories are other means for South African developers to achieve the net zero status.

5. Barriers and solutions to the implementation of net zero buildings in South Africa

Although various benefits have been identified for sustainable buildings, stakeholders, particularly in Africa, have not yet realised the claims as such [20]. Barriers to implement net zero buildings in South Africa includes the perception of costs being higher than it is in reality as well as the lack of incentives [21]. South Africa has a water shortage problem and could be considered a barrier when it comes to developing green buildings, as green building are often seen as rich in vegetation [22]. While African urbanisation has mostly been criticised extensively for its apparent failure to contribute to a sustainable built environment [23], inadequate guidance is accessible to African governments, policy creators and planning institutions, in respect of how best to deal with these concerns [24].

The average premium cost to build a four star Green Star SA rated building is 5.5% on the total building cost and 6.6% for a five star Green Star SA rated building [25]. The average premium costs for developing a net zero building in either of the four categories given by GBCSA (carbon, water, waste and ecology) has yet to be researched.

If a sustainable industry has not been established, a premium cost exist to overbridge the unknowns and lack of technology available. For example, retrofitting buildings with greenery systems in South Africa. Van der Walt [26] did a cost benefit Analysis for retrofitting an existing building with a green roof system excluding any external incentives or policies i.e. the "do nothing" approach. He found that a retrofitted green roof system will not be feasible in South Africa, as the owner of the building will never be able to recover these expenses. The same cost benefit analysis was done, however incentives and benefits were taken into consideration. The results indicated that a retrofitted building only becomes feasible with the following incentives and polices: if the green roof system reduces the building's energy consumption by not less than 3%; the municipality subsidise 80% of the green roof's installation costs and; there is a reduction of property tax by 2% during the green roof's lifespan. Given these circumstances, a building owner will have a repayment period of 7 years [26]. As such, South African developments are currently relaying on the change of policies and the availability of incentives in order to develop feasible sustainable buildings. That being said, local governments in South Africa are presently dealing with the concept of local economic development (LED), which is perceived as a tool that can support the development of sustainable buildings. LED are progressively becoming a centralised tool while local governments are faced with the challenge of developing sustainable housing that will succeed in improving the quality of lives, economic growth and provision of local needs. [28]. Therefor there is movement towards sustainability in South Africa. The solution provided by Holliday Schmidheiny and Watts is to drive markets in favour of sustainability, leveraging the power of innovation and global markets for the benefits of everyone – including developing countries [29].

The primary reasons for introducing environmentally friendly measures in hotels in South Africa, found by Ismail and Rogerson, were to lessen the hotel's carbon footprint, to decrease costs and to boost the image of their brand [27]. Hence we see that there are motives for South African developments to follow sustainable strategies.

6. Research Methodology

A mixed method approach was used in order to gather perspectives [28] of developers. A semi-structured questionnaire was emailed to ten developers. The ten developers where selected on a non-probability basis. Five developers responded. The respondents have between 12 and 30 years of experience as developers. Their input is thus deemed as valid and reliable.

7. Analysis of semi-structured questionnaire

The respondents were asked if they have ever developed a net zero building as defined by the GBCSA. None of the respondents have developed a net zero building before. The perceived barriers as set out by the respondents were the following: The 4 Star green star rating is commercially justified; cost, (both the cost of implementation as well as the price sensitivity of the market), scarcity of resources and technology, client's perception of value, lack of incentive/encouragement from the local authorities to promote/include this at the planning phase; completely unfamiliar to net zero developments. The literature review indicated that the barriers of implementing net zero buildings in South Africa includes: lack of incentives; lack of knowledge regarding net zero buildings by the developer, lack of knowledge regarding net zero buildings by the construction professionals; the perception of cost related to the development of net zero buildings; the actual cost for the development of net zero buildings; water shortage in South Africa; maintenance cost and the National Building Regulations. The respondents were asked to rate barriers given on a Likert scale of one to five, where one is seen as not a barrier at all and five is perceived as a major barrier. The bar graph below shows the extent to which a barrier is involved.

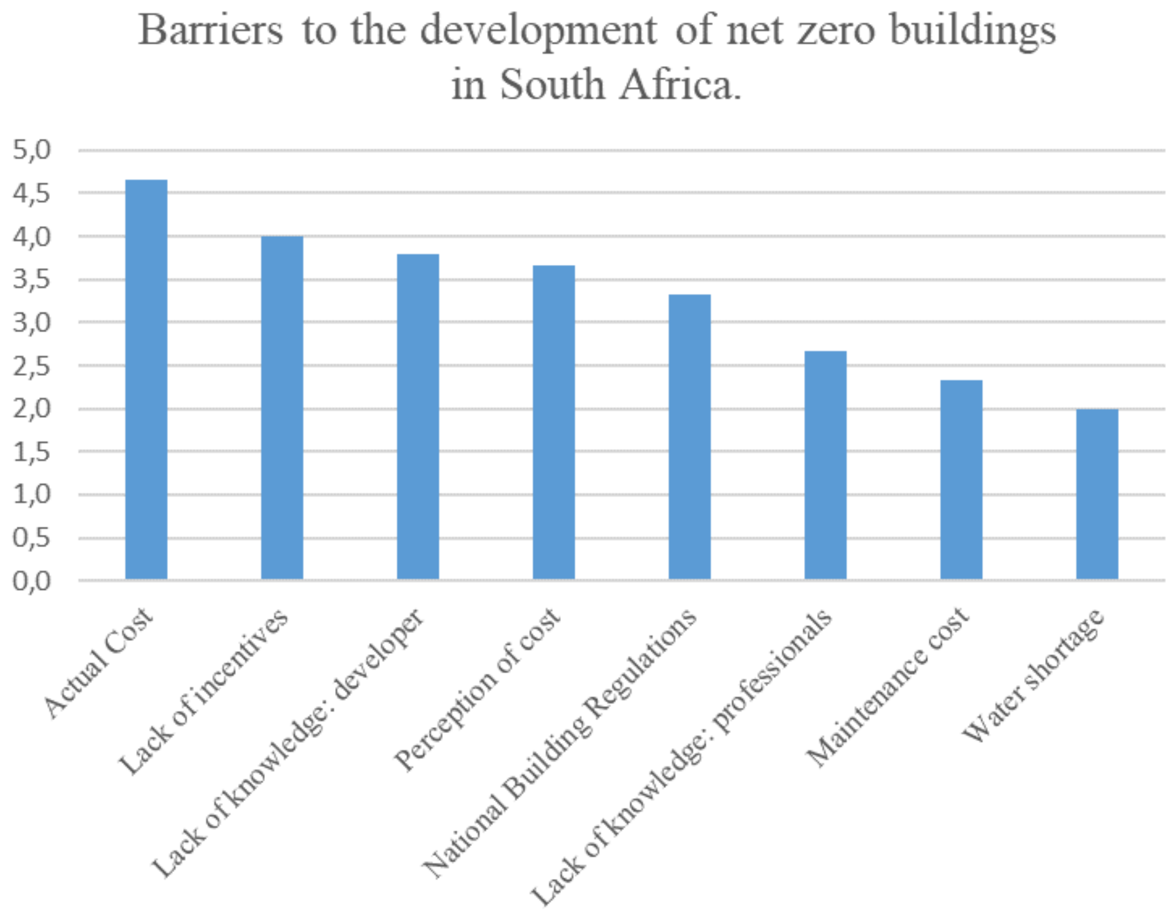

Figure 1: Barriers to overcome in order to achieve net zero status in South Africa

South African developers considers the cost of developing a net zero buildings as the major barrier. Lack of incentives is ranked as the second highest barrier. The third and fourth highest barriers are seen as the lack of knowledge by developers and the perception of costs respectively. The national building regulations and the lack of knowledge by professionals are both perceived as a moderate barriers. Maintenance cost is perceived as small barrier, which means if the design is done correctly, the maintenance could be kept to a minimum. Water shortage in South Africa is not a barrier to the development of net zero buildings in South Africa.

8. Conclusion

Cities, especially African cities, are in need of sustainable developments and the net zero criteria is providing the opportunity thereof. The national building regulations of South Africa does not include any reference to vegetation, greenery or net zero energy usage, however, local authorities introduce their own by-laws regarding sustainable development. Four of South Africa's metros (Johannesburg, eThekwini, Cape Town and Tshwane) are working towards the implementation of policies regarding sustainable development. The GBCSA is a members of the World Green Building Council and has awarded the net zero status to four buildings to date. The definitions as given by Europe, United States, Brazil and the Green Building Council all comes down to buildings that are energy efficient and that uses renewable energy resources, where the energy used by the building does not exceed the energy generated by the renewable resources. The GBCSA, however, created four separate categories for net zero status: carbon, water, waste and ecology. The carbon category relates to the definitions given by Europe, United States, Brazil and the Green Building Council.

Net zero buildings still needs to be commercially justified in South Africa. Cost is a definite barrier for the development of net zero buildings, thus incentives could increase the interest thereof significantly. The National Building Regulations of South Africa is a barrier to the development of net zero buildings as is does not require buildings to aim for net zero status and it is recommended that the National Building Regulations are adjusted accordingly. Requirements from national authorities could greatly impact changes in the approach to developments. The knowledge gap in the construction industry of sustainable and net zero buildings needs to be closed in South Africa regarding the benefits, implementation thereof as well as the actual costs. If installations are done with minimum maintenance in mind, then the maintenance barrier could become redundant. South Africa faces the above mentioned barriers and solutions as a developing country. The same barriers could be issues in other developing countries and the same solutions could be of help to other developing countries.

This research is limited to South Africa and is limited by the small amount of feedback received. It is recommended that more interviews or semi-structured questionnaires are gathered for an in depth and comprehensive conclusion. The research is also limited by the lack of previous research done on net zero buildings in South Africa and further research in this general area in South Africa is recommended. Further research on the premium costs of net zero carbon, water, waste and ecology in South Africa should be done. Future research could also focus on South African credit institutions, fund companies and insurance companies which can possibly acknowledge net zero building developments for sustainable financing instruments, sustainable fund management or insurance offers and support their development with incentives.

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A top-down approach for setting climate targets for buildings: the case of a New Zealand detached house

Chandrakumar C[1,2], **McLaren S J**[1,2], **D Dowdell**[1,3], **Jaques R**[3]

[1] New Zealand Life Cycle Management Centre, c/o Massey University, Private Bag 11222, Palmerston North 4442, New Zealand
[2] School of Agriculture and Environment, Massey University, Private Bag 11222, Palmerston North 4442, New Zealand
[3] Building Research Association of New Zealand (BRANZ), Judgeford, Porirua 5381, New Zealand

C.Chandrakumar@massey.ac.nz

Abstract. Climate change mitigation requires the construction of low/zero-carbon buildings, and this is a challenge for designers. The use of Life Cycle Assessment (LCA) provides useful information to support eco-efficiency improvements and therefore, to reduce the climate impacts of building designs. However, it does not provide information about whether a proposed design aligns with achieving the global climate target of limiting global warming to below 1.5°C or 2°C. This study, therefore, introduces an LCA-based top-down approach for setting climate targets for the whole life cycle of buildings in terms of greenhouse gas emissions. It involves assigning a share of the 2°C global carbon budget for 2018-2050 to a country, to the construction sector of the country, and finally to a building. The approach includes a stock model that accounts for the projected growth in the number of buildings and associated climate impacts in a country up to 2050. The proposed approach was applied to a detached house in New Zealand, the most common residential building type in the country; it was found that the climate target of a New Zealand detached house over a 90-year lifetime is 71 tCO_2eq. This modelling approach has potential to guide designers and other interested stakeholders in development of building designs enabling the building sector to operate within a selected global climate target (such as the 1.5°C or 2°C target).

1. Introduction

The construction sector fulfils several human needs (e.g. provision of housing, hospitals, schools and transport infrastructure), but mostly at the cost of a range of environmental impacts including climate change [1, 2]. For example, the sector uses 40% of global energy and therefore contributes around 30% of global greenhouse gas (GHG) emissions annually [1]. At the same time, due to the growing population and economic activities, the demand for construction is rapidly increasing globally and this will lead to more climate impacts in the future. Thus, it is timely to consider the issue of climate change mitigation for the construction sector.

Efforts to mitigate climate impacts from this sector in the past have tended to focus on the use phase of buildings. However, as energy use in the operation of buildings becomes more efficient and there is greater uptake of renewable energies, researchers are becoming more interested in opportunities to reduce the so-called “embodied GHG emissions” associated with the manufacturing of construction materials and to the construction, maintenance and end-of-life of buildings [3]. This requires analysis of the climate impacts associated with buildings (including materials and elements) throughout the complete life cycle [4, 5]. Life Cycle Assessment (LCA) accounts for all inputs, outputs and flows within the complete life cycle of a building and can be used for this type of analysis [6, 7]. Evaluating the climate impacts of a building using LCA is, however, not sufficient to mitigate climate change globally [3, 8], as LCA only provides information about the climate impacts of a building relative to another building and does not provide information about the building's performance in terms of any global climate target (or threshold) [9-13]. For example, building X may be considered better than building Y if it emits less GHG emissions over its lifetime; however, it may be that neither of them can be considered sustainable if their GHG emissions are more than their assigned shares of the global carbon budget. This insight has led researchers to focus on the development of benchmarks using a top-down approach [3-5, 14, 15]. A top-down benchmark, in general, aims to cascade global climate targets down to sub-global levels [5].

Some researchers have already calculated top-down benchmarks for buildings. For example, Zimmermann et al. [4] suggested that the climate impacts of a global citizen should be limited to 1 tonne carbon dioxide equivalent per capita per annum [$tCO_2eq/(c.a)$] by 2050 to stay within the 2 degree Celsius (°C) climate target, according to the *2000 Watt society vision* [16]. They subsequently set a climate target for a Swiss single-family house based on the relative share of household expenditure for residential buildings in Switzerland, following the sharing principle of *final consumption expenditure* [17]. Following this method, the climate target of a Swiss single-family house was 370 kilogram $CO_2eq/(c{\cdot}a)$ [$kgCO_2eq/(c{\cdot}a)$]. Another similar top-down approach, also based on the 2000 Watt society vision [16], was recently developed for Switzerland [3]. However, when assigning a share of the carbon budget (of 1 $tCO_2eq/(c.a)$ in 2050) to a residential building, Hollberg et al. [3] rather used the *grandfathering* sharing principle [13, 17], which assigned a share of the carbon budget to the residential sector based on its relative contribution to the national GHG emissions. According to this approach, the climate target of a Swiss single-family house was 360 $kgCO_2eq/(c{\cdot}a)$.

In another study, Brejnrod et al. [8] defined climate targets for a single-family house in Denmark (for the year 2010). They calculated the carbon budget available for a global citizen in 2010 (985 $kgCO_2eq/(c{\cdot}a)$ for 2°C and 522 $kgCO_2eq/(c{\cdot}a)$ for 1 Watts per square meter [Wm^{-2}] targets), and assigned a share of it to a Danish single-family house using the sharing principle of final consumption expenditure (i.e. the relative share of household expenditure for housing), as was previously done in [4]. Following this method, the climate targets of a Danish single-family house were 110 $kgCO_2eq/(c{\cdot}a)$ and 58 $kgCO_2eq/(c{\cdot}a)$ for 2°C and $1Wm^{-2}$ respectively. Given the aim of the study was only to calculate GHG emissions reduction targets for existing buildings (in the year 2010), no climate targets for future buildings were recommended. Similar efforts to propose climate targets for commercial buildings exist [e.g. 5, 14]. For example, Russell-Smith et al. [14] estimated a target of 2.29 tCO_2eq/m^2 for the whole life cycle of a commercial building in the USA, considering a 50-year lifetime. The target was based on the GHG emissions projections in the IPCC Fourth Assessment Report [18], which recommended a 70-80% GHG emissions reduction below 1990 levels by 2050 in order for buildings to operate within the 2°C climate target. Likewise, using a similar approach of Zimmermann et al. [4], Hoxha et al. [5] proposed climate targets for a set of commercial buildings in 2050, including offices (14 $kgCO_2eq$ per square metre floor area per annum [$kgCO_2eq/(m^2{\cdot}a)$]), restaurants (20.3 $kgCO_2eq/(m^2{\cdot}a)$), food stores (19.8 $kgCO_2eq/(m^2{\cdot}a)$) and hotels (11.7 $kgCO_2eq/(m^2{\cdot}a)$).

Overall, although studies defining climate targets using a top-down approach for both residential and commercial buildings in different countries exist [e.g. 3, 4, 8, 15], no similar study is available for New Zealand. The climate targets proposed in other studies are not generalizable given the large variations in the construction materials, climate conditions and energy mix in different parts of the world. Moreover, the existing studies are limited in several aspects. In particular, while all the existing studies have considered population growth when setting climate targets for buildings in 2050, none of them has modelled the growth in the number and size (i.e. floor area) of buildings nationally and/or globally (through to 2050). However, temporal aspects such as the growth in the number and size of buildings are critical in determining the available share of the global carbon budget of a building, and should be addressed when setting climate targets for future buildings. Also, many of the studies have proposed a single climate target value for the whole life cycle of a building, and it would be challenging for building designers to use the proposed target as a guide in the design process given the lack of transparency regarding environmental hotspots. This study, therefore, developed an LCA-based top-down approach to propose a climate target for the whole life cycle of a building in any country that also accounts for future construction of buildings up to 2050, and provides a breakdown of this target into individual life cycle stages. The proposed approach was subsequently applied to a detached house in New Zealand, which is the most common type of residential building in the country, representing almost 80% of residential buildings [19].

2. Methods

2.1. Overview of the top-down approach

The procedure for calculating the climate target for a building was:

- Determine the maximum acceptable amount of GHG emissions that can be emitted while respecting the chosen global climate target during a chosen time period (referred to as the global carbon budget).
- Assign a share of the global carbon budget to a country based on population projections.
- Assign a share of the country's carbon budget to the country's construction sector based on the relative contribution of the sector to the country's total climate impacts in a reference year (or period).
- Calculate the climate target for different building categories by assigning the construction sector carbon budget to the different building types based on the LCA climate impact of each type of building and the projected number of those buildings, both pre-existing and built in the chosen time period. Note that this means that, for example, buildings constructed in 2030 will only include 20 years of utilisation if the chosen time period extends to 2050.

The following sub-sections describe the proposed top-down approach in detail, illustrated for a case study of the New Zealand detached house (see Figure 1). In this study, the term 'detached house building sector' refers to the total number of detached houses in New Zealand.

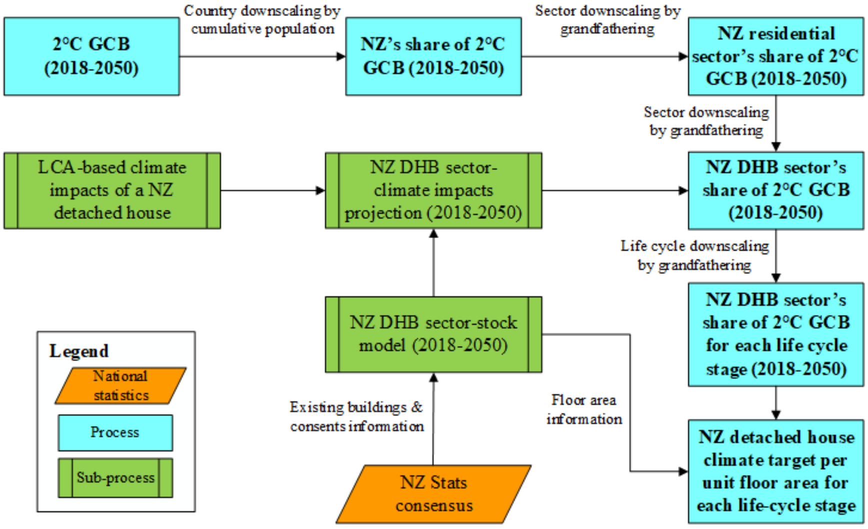

Figure 1. Proposed top-down approach to set a GHG emissions target for New Zealand (NZ) detached house. GCB= global carbon budget; and DHB= detached house building.

2.2. Global climate target and carbon budget

In this study, 2°C was chosen as the global climate target i.e. the maximum amount of GHG emissions that can be emitted and still limit average global warming to below 2°C above pre-industrial levels. The chosen global climate target was subsequently translated into a global carbon budget of 1110 $GtCO_2eq$ for the period of 2018-2050 ($CB_{Glo,2018\text{-}2050}$), using the approach proposed by Rogelj et al. [20]. The year 2018 was chosen as the starting point due to the accessibility of good quality data developed as part of BRANZ's New Zealand whole-building whole-of-life framework research [21]; data were modelled up to 2050, the year chosen for the target year of many on-going climate change negotiations, including the New Zealand Zero Carbon Act [22].

2.3. Carbon budget of New Zealand

To assign a share of the 2°C global carbon budget to New Zealand, the so-called sharing principle of *cumulative impacts per capita* was applied. The principle focuses on achieving equality in terms of the cumulative climate impacts of different populations [23]. This means that, if the people of New Zealand emit more GHG emissions today than the global average per capita, future people of New Zealand should be restricted to emit a smaller proportion of GHG emissions in future based on the global carbon budget. And people in less-developed regions who may emit less GHG emissions today than the global average per capita, will be entitled to emit a higher proportion of GHG emissions in future based on the global carbon budget. The cumulative carbon budget available for New Zealand for 2018-2050 was calculated as follows:

$$CB_{NZ,2018\text{-}2050} = \frac{POP_{NZ,2018\text{-}2050}}{POP_{Glo,2018\text{-}2050}} \times CB_{Glo,2018\text{-}2050} \quad (1)$$

where:

$CB_{NZ,2018\text{-}2050}$ - the share of the global carbon budget available for New Zealand for 2018-2050
$POP_{NZ,2018\text{-}2050}$ - the cumulative population of New Zealand for 2018-2050
$POP_{Glo,2018\text{-}2050}$ - the cumulative population of the world for 2018-2050
$CB_{Glo,2018\text{-}2050}$ - the global carbon budget for 2018-2050.

2.4. Carbon budget of New Zealand detached house building sector

The *grandfathering* sharing principle was used to assign a share of New Zealand's carbon budget to the New Zealand detached house building sector (as previously applied in [3, 8]). The grandfathering principle assigns a carbon budget share to the chosen sector based on its relative contribution to New Zealand's climate impacts in a reference year (or period), as represented in Equation 2. Ideally, this year should have been 2017, which is the year prior to the period under analysis. However, due to data limitations, the year 2012 was selected and it was assumed that the relative contribution of the detached house building sector to New Zealand's consumption-based climate impacts remained unchanged during the period 2012-2050.

$$CB_{NZ,DHB,2018\text{-}2050} = \frac{GHG_{NZ,DHB,2012}}{GHG_{NZ,2012}} \times CB_{NZ,2018\text{-}2050} \quad (2)$$

where:

$CB_{NZ,DHB,2018\text{-}2050}$ - the share of the global carbon budget available for the New Zealand detached house building sector for 2018-2050
$GHG_{NZ,DHB,2012}$ - the GHG emissions of the New Zealand detached house building sector in 2012
$GHG_{NZ,2012}$ - the consumption-based GHG emissions of New Zealand in 2012
$CB_{NZ,2018\text{-}2050}$ - the share of the global carbon budget available for New Zealand for 2018-2050.

2.5. Stock model of New Zealand detached house building sector

In order to estimate the climate impacts of the New Zealand detached house building sector, a stock model developed by BRANZ was used, which was based on several assumptions including socio-economic growth in different regions of New Zealand, net floor area of a (future) detached house and demolition rate [R Jaques, personal communication, Dec 21, 2018].The model consisted of two components: one projected the growth in the number and net floor area of detached houses up to 2050 and the other estimated the associated climate impacts. Firstly, the total number and the net floor area of detached houses that existed at the end of 2017 were modelled. Next, the number and net floor area of detached houses for 2018-2050 were projected based on the long-term trend in building consents, considering the anticipated changes in building regulations [R Jaques, personal communication, Dec 21, 2018]. Finally, using the climate impacts of a typical New Zealand detached house [D Dowdell, personal communication, Jan 11, 2019], the LCA climate impacts of the complete detached house building sector (both existing and future detached houses) for 2018-2050 were estimated.

2.6. *Climate target of New Zealand detached house*

The carbon budget share of the detached house building sector for 2018-2050 ($CB_{NZ,DHB,2018\text{-}2050}$) was shared between the existing and future stock using the grandfathering principle (see Section 2.4). Similarly, using the same principle, $CB_{NZ,DHB,2018\text{-}2050}$ was shared between different life cycle stages. Then, for each life cycle stage, the associated total floor area of the detached house building sector was calculated. By dividing the available carbon budget for each life cycle stage by the associated total floor area of the sector, climate targets per unit floor area for individual life cycle stages were determined. Finally, to determine the climate target for the whole detached house: (i) the climate targets per unit floor area for product life cycle stages, construction process life cycle stages and end-of-life stages were multiplied by the projected floor area of a detached house; (ii) the climate targets per unit floor area per annum for maintenance and replacement, total operational energy use, and operational water use stages were multiplied by the floor area and the time period of utilisation; (iii) and then, the two values were summed.

3. Results and Discussion

3.1. *Climate target of New Zealand detached house*

Using the proposed top-down approach, the climate target for the whole life cycle of the New Zealand detached house over a 90-year lifetime was calculated as 71 tCO_2eq. This was equivalent to a climate target of 292 $kgCO_2eq/(c.a)$ when normalized, given the average household size in New Zealand is 2.7 [24]. A breakdown of the climate target in terms of individual life cycle stages is presented in Table 1. The largest share of the climate target was assigned to total operational energy use (42%) followed by operational water use (22%), product life cycle stages (15%), maintenance and replacement (13%), end-of-life stages (7%) and construction process life cycle stages (2%). These results, which have a relatively higher proportion of the carbon target assigned to the use phase compared with a conventional LCA study of a building, can be explained by the sharing principle (i.e. grandfathering) applied to assign a share of the New Zealand detached house building sector's carbon budget to individual life cycle stages. This principle assigned a carbon budget share based on the GHG emissions contribution of each life cycle stage to the GHG emissions of the New Zealand detached house building sector during 2018-2050. Thus, the percent-wise GHG emissions contributions of different life cycle stages to the New Zealand detached house building sector were comparable to the percent-wise shares of the climate target of the detached house, as represented in Table 1.

3.2. *Comparison with other studies*

Direct comparisons between the climate targets of this study and previous work [3, 4, 8] were not possible due to the significant differences in the top-down approaches and underlying assumptions. To understand the uncertainties associated with the choice of top-down approach for setting climate targets, both with and without consideration of future building projections, the approaches available in the literature were applied in the context of a New Zealand detached house without accounting for the growth in the detached house building sector (see Section 1 for the details of the approaches). As observed from Figure 2, when the approach of Zimmermann et al. [4] (i.e. based on the final consumption expenditure principle) was applied to New Zealand detached house, the climate target of the detached house reduced to 260 $kgCO_2eq/(c{\cdot}a)$. This was due to the low household expenditure share of New Zealand (26%, [25]) compared with the household expenditure share of Switzerland for housing (37%, [4]). Similarly, when the approach of Hollberg et al. [3] was applied (i.e. based on the grandfathering principle), the climate target of the New Zealand detached house was further reduced to 57 $kgCO_2eq/(c{\cdot}a)$. This significant reduction was due to the low contribution of the New Zealand detached house building sector to the national GHG emissions (approximately 6%, according to this study) compared with the Swiss residential sector (36%, [3]). Furthermore, according to the top-down approach developed by Brejnrod et al. [8] (i.e. based on the final consumption expenditure principle), the climate target of New Zealand detached house was 256 $kgCO_2eq/(c{\cdot}a)$. This was because the share of household expenditure of New Zealand (26%, [25]) was more than twice the share of household expenditure of Denmark for housing (11%, [8]).

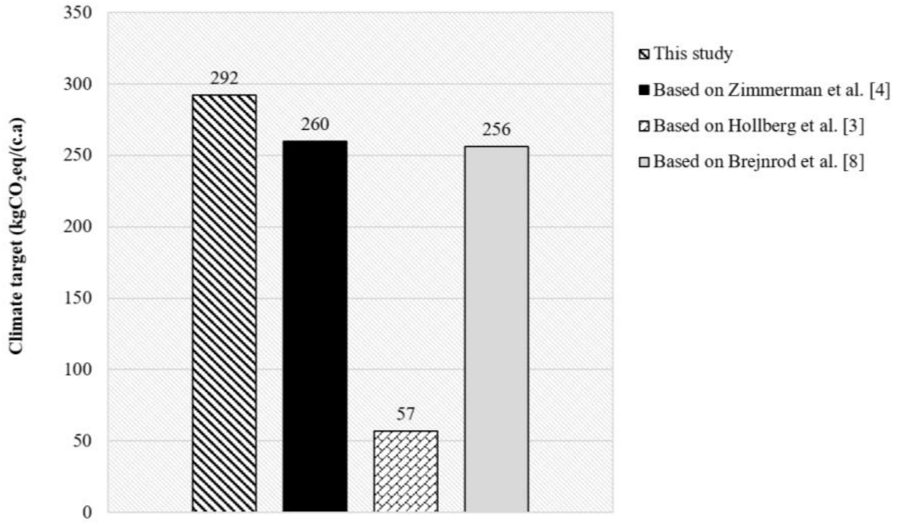

Figure 2. Comparison of climate targets of the New Zealand detached house calculated using the top-down approaches available in the literature.

4. Conclusion

This study introduces a new top-down approach for setting a climate target for the whole life cycle of a building and a breakdown in terms of individual life cycle stages. This approach, for the first time, includes a stock model that accounts for the projected growth in the number (and size) of buildings and associated climate impacts in a country up to 2050. The proposed approach was applied to a detached house in New Zealand to define a climate target. The study has highlighted the importance of accounting for the temporal aspect when setting climate targets for future buildings, which includes the selection of time period and the projected number of future buildings. On the other hand, it should also be noted that the approach and climate targets are associated with a large amount of uncertainty. For example, when assigning a share of the New Zealand carbon budget to the detached house building sector, the grandfathering principle was applied but other sharing principles could be used instead (such as the final consumption expenditure principle). Likewise, to estimate the climate impacts of the New Zealand detached house building sector, the stock model developed by BRANZ was used [R Jaques, personal communication, Dec 21, 2018] which was based on several assumptions including socio-economic growth in different regions of New Zealand, building regulations, net floor area of a (future) detached house and demolition rate. These assumptions, of course, are also associated with a significant amount of uncertainty. Further research is, therefore, necessary to quantify the uncertainty associated with these aspects. However, overall, the proposed approach and climate target provide an approach that can potentially support designers and other interested stakeholders (including architects, civil engineers, scientists and investors) in aligning their building designs with global climate targets such as the 2°C climate target.

Table 1. Results of the application of the top-down approach to New Zealand detached house.

Life cycle stage [a]	LCA impacts- detached house over a 90-year lifetime [b] (ktCO₂eq)	LCA impacts- detached house building sector (2018-2050) ($MtCO_2eq$)			Carbon budget - detached house building sector (2018-2050) ($MtCO_2eq$)	Net floor area- detached house building sector (2018-2050) ($10^6 \times m^2$)	Climate target per unit floor area ($kgCO_2eq/m^2$)	Climate target- detached house over a 90-year lifetime [e] (tCO_2eq)
		Existing	Future	Total				
Product life cycle stages	33	-	18	18 (18%)	5	109	50	10 (15%)
Construction process life cycle stages	5	-	3	3 (3%)	0.9	109	8	2 (2%)
Maintenance & replacement	29	10	3	13 (13%)	4	8,272 [c]	0.5 [d]	9 (13%)
Total operational energy use	71	35	8	42 (43%)	13	8,272 [c]	1.6 [d]	30 (42%)
Operational water use	38	18	4	22 (22%)	7	8,272 [c]	0.8 [d]	15 (22%)
End-of-life stages	15	-	0.6	0.6 (1%)	0.2	8	23	5 (7%)
Whole life cycle	**191** [f]	**-**	**-**	**98** [f]	**31** [f]	**-**	**-**	**71** [f]

[a] The LCA was conducted following the EN 15978:2011 standard [26].
[b] The LCA climate impacts were from [D Dowdell, personal communication, Jan 11, 2019].
[c] Since the net floor area of this life cycle stage is a function of area and time the unit is square meter annum ($m^2 \cdot a$).
[d] The unit is $kgCO_2eq/(m^2 \cdot a)$.
[e] The projected average floor area of a (future) detached house is 207 m^2.
[f] Column totals may not add up due to rounding.

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Analysing the impact of retrofitting and new construction through probabilistic life cycle assessment. A method applied to the environmental-economic payoff value of an intervention case in the Albanian building sector.

Jorgji O[1], Di Bari R[1], Lenz K[2], Gantner J[2], Horn R[1]

[1]Institute for Acoustics and Building Physics, University of Stuttgart, Stuttgart, DE
[2]Fraunhofer IBP Institute for Building Physics, Stuttgart, DE

olivia.jorgji@iabp.uni-stuttgart.de

Abstract. The EU building stock is relatively old with 40% of it built before 1960. In Albania the building sector accounts for 26, 9% of final energy consumption, offering high energy saving potentials due to the great number of old residential buildings. Intervention is not always possible and, in order to achieve significant environmental savings, the national action plans cannot rely only on the physical improvement of existing buildings. This paper proposes a probabilistic LCA and LCC evaluation model using MC simulation, for the prediction of intervention options in existing buildings. The potential environmental and economic impacts of three intervention options: standard, ambitious retrofitting and new construction during the whole life cycle of a building are analysed. A framework is defined, with the purpose of estimating the value of a building in a specific time during its life cycle. Comparing the generated values of potential environmental impacts and associating them with the changes on the buildings value enables the process of deciding upon the most desirable and/or agreed combination. The results of the SLED Study 2015 on Albanian building typology are used, while the new construction model is defined according to German EnEV2014 requirements. The GWP values from the LCA/ LCC assessment of the intervention scenarios, done through the SBS tool of Fraunhofer IBP, are used to create a prediction model for future alternative solutions especially in early planning phase. Decision-making through this model can encourage a sustainability strategy for energy efficiency improvement in the building sector of Albania.

1. Introduction

In the EU building sector, the replacement rate of old buildings by new build is around 1% a year, while the renovation rate goes up to 1-2% per year. Considering that more than 90% of the existing building stock in the EU was built before 1990, the renovation of old buildings holds major significance in employing energy efficiency strategies [1].

As the obligation to accomplish CO_2 emissions reduction by 2050 becomes more urgent, the responsibility of acting upon this goal cannot be directed only towards EU countries, rather it requires a joint pursuit in global scale. That is why non EU countries, as part of the Energy Community Treaty, have to be actively engaged and, as growing economies, their contribution on European energy efficiency improvement cannot be neglected. With regard to this, several studies have been carried out in non EU area in order to investigate current trends and encourage new politics and more attention to environmental issues. Among them, in Balkan region, SLED Study (Support for Low-Emission Development in South Eastern Europe) reported for instance that the energy costs will be 47% lower in comparison to the costs of the BAU (business-as-usual) intervention scenario, if the ambitious retrofit is applied in 2030 [2].

Even if meaningful, the results provided by SLED study do not consider the environmental impact of the buildings during their whole life cycle, including renovations work because of building parts obsolescence, and neither do they consider the difference of the GWP values between different intervention scenarios. This is actually a methodological issue, which is largely debated within the sustainability assessment of products use phase and leads to new approaches which can derive more results and can be better related to external factors as well. Standard LCA and LCC methodologies, which are widely applied for the assessment of products environmental and economic sustainability, could represent the basis for a comparison study, but considering the complexity of the building sector and the different factors that are known to affect such decisions during a building's lifespan [3], the necessity arises for a more complex processing of the environmental-economic results. For this purpose, some statistical instruments such as Monte Carlo Simulation have been recently introduced into "probabilistic approaches", which can integrate parameters associated to specific economic and environmental boundaries and can provide results within the whole building's lifespan in a more comprehensive form.

In this paper the environmental impact of different intervention scenarios for the building sector in a non-EU country is analyzed in order to generate relevant results for a non EU economic and environmental reality including a comparison between a static standard approach and a more dynamic probabilistic one.

2. LCA – LCC analyses for renovation measures: state of art

With the increasing attention to the existing building stock, new measures supported by new techniques and innovative materials lead to a richer terminology: classical terms, recovery and rehabilitation, have been recently accompanied by new words, such as retrofit and refurbishment. Such measures have overlying meanings, which very often leads to lack of clarity. In fact, while refurbishment process is a general improvement of the building by cleaning, decoration and re-equipping and includes energy efficient and sustainable activities, a retrofit measure is more specifically a provision of a component of feature not fitted during manufacture or addition of something that the building did not have when first constructed. The term derives in fact from the crasis of "retroactive" and "refit" (reassemble, repair). It conveys an addition of elements (surfaces, volumes, etc.) which were not provided during the object production, in order to extend its service life [4]. Among the variety of solutions, an aware choice has to be carried out in order to provide an indication about the pay-off time of the selected measure [5]. Nevertheless, the need for a change into more energy efficient systems has exposed the necessity of a more accurate investigation of such solutions in order to ensure a significant global enhancement of performance with awareness of the environmental impacts. In conclusion, the economic analysis cannot be anymore solely the instrument for decision-making, but it should be accompanied by an environmental assessment of the considered measures.

Life Cycle Assessment (LCA) is a standardized methodology which has been applied for decades in the building sector, especially as basis for the building certification labelling systems. LCA considers the entire life cycle of a product from raw material extraction and acquisition through energy and material production and manufacturing, to use phase and end-of-life treatment and final disposal. Through such a systematic overview and perspective, the shifting of a potential environmental burden between life cycle stages or individual processes can be identified and possibly avoided. For such reasons, LCA results can be included in the decision process by considering natural science, framework and principles according to the international standards ISO 14040 and ISO 14044 [6].

The consideration of retrofitting and further measures on existing buildings can be seen as new challenge by LCA point of view. In fact, the selection of refurbishment technologies and the success of a retrofit project cannot be indicated with complete certainty due to aspects and factors related to humans' behavior and choices [7]. For these reasons, quite recently LCA investigations focused on uncertainties associated to this methodology. Such uncertainties are due to insufficient and incomplete information (e.g. lack of data on construction materials, geometry of the building, etc.), inaccuracies of models and available software unpredictability of future events (e.g. change of use, service life duration, unexpected seismic events, etc.) and, considering the wide building lifespan (50 years) can be relevant for the final evaluation. With the regard to the building carbon embodied emissions can be distinguished [8]:

- uncertainty about the current embodied carbon of construction materials, components and whole buildings;
- uncertainty about the future embodied carbon of construction materials and components, including technological innovation;
- uncertainty about future events in the service life of built assets, including length of component life, component replacement or substitution, changes of use, end of life;
- Uncertainty about system boundaries and methods of measurement.

With regard to handling of uncertainties, many applications in literature are carried out with probabilistic approaches by using statistical instruments such as Monte Carlo Simulation (MCS). The basic idea of such approach is using randomness to solve problems that might be deterministic in principle and is the most useful when it is difficult or impossible to use other probabilistic approaches. In the field of LCA, MC Simulation performs risk analysis by building models of possible results by substituting a range of values – a probability distribution – for any factor that has inherent uncertainty [9].

3. **Method**

Taking into account that there are several possibilities of interventions able to render satisfying results with regards to energy efficiency and environmental improvement in the building sector, the involved actors face the existence of different decision strategies during a building's life cycle (50years) [8]. The decision making process considers:

- the possibility of allowing the building to continue its life cycle in its existing state until it has reached its end of life
- the possibility of refurbishment/ retrofit and further local and global intervention during its life cycle, which can extend the nominal building service life as well
- the possibility of rebuilding, with demolition of existing building, in a given moment in time during the building's life cycle, in order to build a new

3.1. Economic issues in the final decisions

Decisions about existing building interventions are influenced by several factors associated to technical aspects, such as available technologies, material and engineering/ architects knowledge, as well as economical and financial limitations (i.e. -long payback periods, willingness of building owners to pay for retrofits with missing public financial instruments) [10]. On the other hand, the environmental evaluation of different intervention options, if accompanied by an economic analysis which facilitates the comparison among alternative refurbishment measures, can provide an indication of whether the alternatives are energy efficient and cost- effective.

As depicted here the economic factor is at the moment probably the most important one: especially for developing economies, such as non EU countries. For this reason, even if the main objective of this study is linked to the environmental assessment of retrofit/refurbishment measures, economical matters cannot be neglected in the decision making part of the methods.

3.2. Probabilistic LCA with MC Simulation: determined framework

In this paper a probabilistic LCA with application of MC Simulation has been carried out. For the assessment of the total GWP (kg CO_2-eq/ m² year) of an existing building subjected to renovation works, the LCA analysis considers a cradle to grave system boundary (A1-A3, B4-B6, C+D phases). The study takes into account a 50 years period for the building's life cycle, with 2018 as start of investigation.

The GWP values extracted from the environmental assessment of the building represent the data input. The reference building has been analyzed and probability values have been established by considering previous studies for each intervention alternative (existing, refurbishment, rebuild) [11]. The real age of the existing building type is assumed to be 40 years; hence, the start intervention probability on year 2018 is calculated to be 33, 7 %. Decision about an intervention option is fixed in a 5 year period, where a random value Rv (x) impacts the behavior of the rest of the parameters. The first decision in the system regards only two possibilities: *0 - no intervention*, the building is assumed to continue the rest of its life cycle in its existing state; *1- intervention*, it is determined that the building is suitable for a change, but the specific intervention method is not yet defined. The generated random value is then compared with the given intervention probability functions. If the probability of intervention in a given moment in time *(t=x)* exceeds the random value *(Rv)*, then an intervention occurs; otherwise the building will not be subjected to any renovation work (See 3.1).

$$R_v=\begin{cases} \geq P(I) \text{ No intervention Dec=0} \\ < P(I) \text{ Renovation measure Dec =1} \end{cases} \quad (3.1)$$

Where: *P(I)* – probability of intervention in a specific point in time

The next decision regards the type of intervention. The economic data are used as input values in this phase, where the decision for refurbishment *(Intrv. 1)* or rebuild *(Intrv. 2)* depends on the relation between the respective costs (3.2):

$$C_{t+p}=\begin{cases} \geq 75\%{*}C(Reb)\rightarrow \text{Rebuilding Dec = Intrv.2} \\ < 75\%{*}C(Reb)\rightarrow \text{Refurbishment Dec=Intrv.1} \end{cases} \quad (3.2)$$

Where: *Ct+p*- total costs of refurbishment; *C(Reb)* – costs of rebuild

The total GWP after a study of 50 years is calculated by adding contribution due to production, use phase (due to total energy demand) and end-of-life of the building system. Since whatever intervention enhances the global energy performance of the buildings, the energy demand depends on the achieved quality of the building (3.3).

$$GWP_{tot}=\sum_{y=1}^{50} GWP_{prod,\,y}+GWP_{use,\,y}+GWP_{EoL} \quad (3.3)$$

With regards to the GWP due to retrofit and rebuilding interventions, as suggested by previous works [12], the environmental impacts are adapted through a decarbonisation rate. Such value expresses the potential development of technologies and processes in order to reach better environmental quality, as required by international agreements (i.e. Paris COP31) (3.4).

$$GWP_{prod,\,y}= GWP_{prod,\,y-1}\cdot(1-c_r) \quad (3.4)$$

Costs are analogously discounted by considering a price increase rate and a discount rate as defined below (3.5).

$$C_y= C_{y-1}\cdot\frac{(1-p_i)}{(1-d_r)} \quad (3.5)$$

The total time frame in which a series of decisions takes place: a 50 year period is considered for the building's life cycle. The sum of GWP values is calculated for the intervention strategy that takes place during the life cycle of the building. The distribution of most likely GWP values in the MC simulation is measured by the standard deviation with larger values indicating higher probability of occurrence.

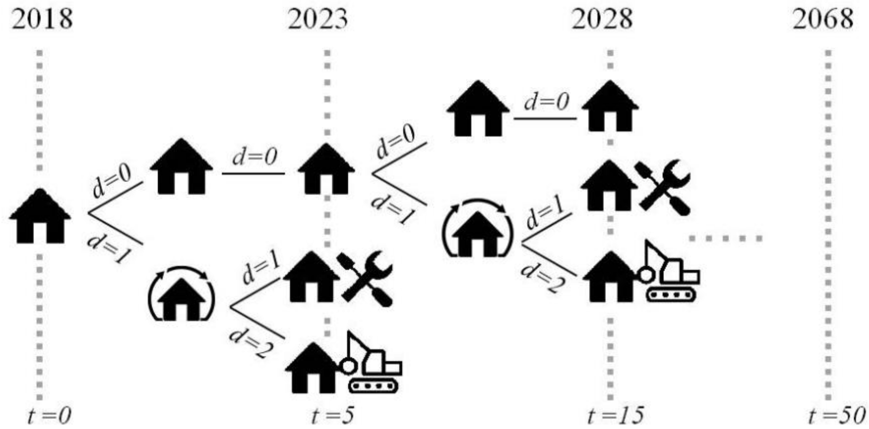

Figure 1. Time-based decision process

4. Case study

The provided model analyses three intervention alternatives for the building stock. The evaluation model is applied in one building type taken as a case study from the Albanian building stock typology system, to show preliminary results, but it is considered relevant for the whole building sector.

This requires first of all a mapping of the Albanian existing building stock: a good overview has been provided by the CENSUS 2011 study, used to establish a building classification which consists of 20 building types based on use type, construction periods, size of buildings and number of floors. According to the INSTAT'11 statistical data, the greatest part of the building stock has been constructed during 1991-2000 with 21% of the whole building stock [13] and surveys carried out in 2009 about the comfort conditions on the Albanian households, ascertained that approx. 85% of them are in bad conditions [14].

Hence, the energy improvement of the building sector in Albania represents a necessity and at the same time a great challenge due to the high amount of required investments and the shortage of public funding. In addition to that, private investments are restricted by further economic obstacles, such as insufficiently funded EE (energy efficiency) units, depressed energy pricing and norm-based billing for heating, data incompliance, unreliable municipalities and homeowner associations, etc. [15].

Regarding climate characteristics and considering the Albanian zoning, 48% of the building stock belongs in Climate Zone B (hilly Mediterranean area) [14] [16]. The most common energy source was wood (57, 5%), followed by LPG (20, 8%) and electricity (15, 4%), while solar heating and other energy sources are irrelevant. Altogether, according to AKBN (The National Agency of Natural Resources) in 2008 electricity covered most of the energy demand (65%), followed by LPG (18%) and fuel wood (15%) [17].

In a second phase, retrofit solution have been investigated: based on the typology system for the Albanian building stock proposed on the SLED Study of the Regional Environmental Centre for Central and Eastern Europe (REC) in 2015, only the "ambitious retrofit" (improvement 2) option proposed is analyzed. The alternative of "standard retrofit" (improvement 1) in fact considers only changes in the envelope of the building but does not include energy use systems. The intervention case of "rebuild" assumes the substitution of an existing building type after demolishing it, with a new building that has same geometry, and energy standard compliant to EnEV2014 requirements.

As a case study the building type, B1 from the typology system is selected. This type is assumed to be the representative for the group of buildings that share same building function, material construction, building period and similar surface area. The B1 type represents detached houses built in the period 1961-1980.

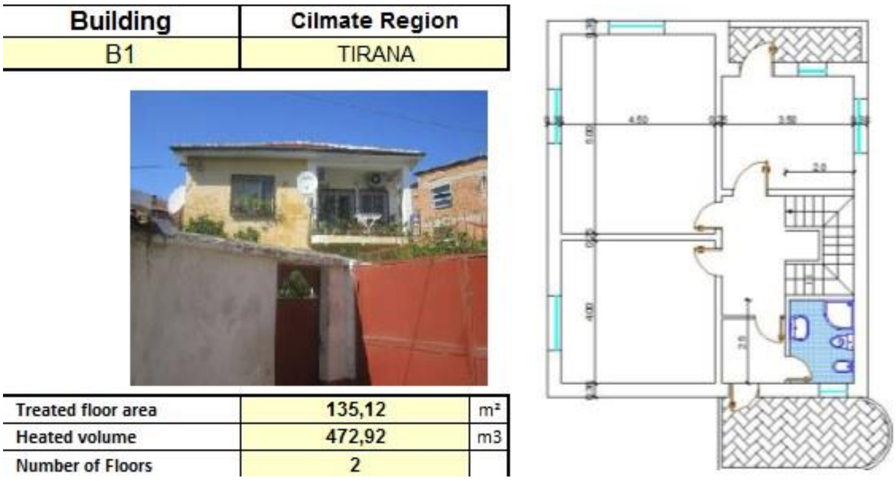

Figure 2. Geometry data on B1 type of building [2] [14]

The building's construction characteristics are shown below (Table 1)

Table 1. Information applied for the life cycle assessment of the building

Building type B1	1961-1980	Type	Features	Figures
General information	Detached house			
	Construction elements	Exterior wall	Solid red brick	208,4 m²
		Roof/Ceiling	Roof with red tiles	67,6 m²
		Floor slab	Concrete floor	67,6 m²
		Window	Single glazed, wooden frame	17,3 m², 4,92 W/m²K
		Exterior door	Wooden door	7,2 m², 3,0 W/m²K
	Energy supply system	National net of electricity supply (Hydropower energy generation) Multi-split AC Pellet boiler		
	Energy demand			275,32 kWh/m²a
	Envelope surface		**368,0 m²**	
	User surface area		**135,12m²**	

GWP results are then calculated for the existing building model with the SBS Building Sustainability Tool in compliance with the LCA methodology for the ambitious retrofit (Refurbishment), as well as the "Rebuild" case [18]. Characteristics of the refurbishment measures and rebuild construction defined according to EnEV standards are shown in Table 2 and LCA/ LCC results of the life cycle and costs analysis for the three cases of intervention are reported in Table 3 [19]:

Table 2 Differences in construction of two intervention options taken into analysis

Construction	Refurbishment measures	Rebuild characteristics
Exterior wall	Red brick, Polyst. EPS 10cm, U-Value=0.29 W/(m²·K)]	Limestone, EPS, Plaster, U-Value=0.24 W/(m²·K)]

Roof/Ceiling	Roof with red tiles, Polyst. EPS 12cm, U-Value=0.27 W/(m^2·K)]	Plasterboard, Therm. insulation EPS, Wood constr., MDF-plates, Roof tiles, U-Value=0.176 W/(m^2·K)] cement, Insulation EPS, PVC-P, reinforced concrete, mineral-wool, gips, U-Value=0.14 W/(m^2·K)]
Floor slab	Concrete floor, Polyst. EPS 5cm, U-Value=0.54 W/(m^2·K)]	=
Window	Triple thermal insulation glass, 90% Plastic frame, U-Value =0.65 W/(m^2·K)]	
Exterior door	Plastic door, U-Value =0.75 W/(m^2·K)]	=
Energy supply system	Electricity (Hydropower) Pellet boiler 25% energy Low temperature gas system 10% energy Multisplit-clima unit 65% energy	Energy supply based on electricity based systems Electricity from Hydropower 100%
Energy demand	9.410,5 kWh/y. En. for electricity 27.785,9 kWh/y. heat energy demand	16.079,3 kWh/year

Table 3 GWP and costs results. Life Cycle Assessment and Life Cycle Costing

Building type B1	**A1-A3**		**B6**		**C1-C4**	**C3+D**
	(kg CO_2-eq./m^2)	**(€/m^2)**	**(kg CO_2-eq./m^2)**	**(€/m^2)**	**(kg CO_2-eq./m^2)**	**(€/m^2)**
Existing state	-	-	1737,85	-	39,9	120,00
Standard retrofit	15,9		794,6	-	72,4	
Ambitious retrofit	29,25		436,96		95,5	
Refurbishment		175,00		-		-
New building/ Rebuild	242	257,38	35,25		-	-

For the economic analysis the information about investment costs on refurbishment are obtained from SLED Study, while for rebuild are obtained from the Albanian National Housing Authority [20]. According to OBC-Transeuropa, a trustworthy discount rate of 5.7% is applied to all the costs and price increase rate of 1, 5 % considered [21]. Discount rate does not consider any risk prices, in order to obtain a conservative estimation and price increase rate due to the Albanian inflation rate.

4.1 Results

The Monte Carlo simulation is modelled in a first screening to identify the range of results generated through 200 runs. In the first instance maximal, minimal and average values are obtained. The GWP results are afterwards divided in 7 ranges and for each of them the probability of occurrence has been determined. The distribution of such probabilities shows that most of intervention scenarios for a 50 year time frame fall in the range of 1300-1600 kg CO_2-eq. / m^2 year.

GWP (kg CO2-E./m² year)	
MAX	4448,29
MIN	1052,57
Avarage	1398,97
Standard deviation	256,34

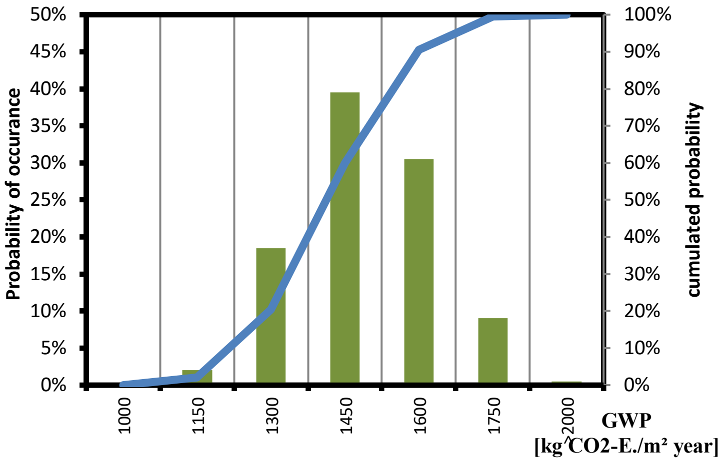

Figure 3. Graph showing cumulative probability distribution for the GWP value of three intervention scenarios for the Building type B1

In a second instance a significant mean value of 1495 kg CO2-eq. / m²year has been established. Here the mean value is the one which reaches a cumulative probability of 80%, namely 20% probability of exceedance. The total number of refurbishment interventions in one simulation run is 547, while for the rebuild intervention it counts 66 times. According to the results, in a costs-based simulation of possible scenarios, refurbishment is most preferred than rebuild. This justifies the high values of GWP which come from the impact due to the use phase of a refurbished building.

5. Discussion and outlook

This paper proposes a probabilistic LCA approach for intervention cases in the Albanian building stock and illustrates the effectiveness through a building type case study undergoing three scenarios of intervention.

The results of this research show how different LCA approaches determine different final decisions. In fact, from the perspective of a static LCA, a rebuilding for the analyzed case study may be advantageous: the emissions during the use phase are in fact strongly reduced, thanks to the low yearly energy demand. On the contrary, the results of the probabilistic LCA, show that the refurbishment solution has been preferred the most: this is due to the included economic factors, which dictate strongly the final decision.

It is necessary to underline that refurbishment interventions alone are not advantageous in the long term: in fact, while they can improve the energy performance of the building, further issues, e.g. structural vulnerabilities, may not be solved. As shown in the case study of this paper, the building has almost exhausted its nominal service life and therefore a global integrated intervention may be required, rebuild included. On the other hand, the rebuild process requires a long time, high investments and the demolition of the previous construction produces huge quantities of waste destined to landfill [22]: in this sense, a rebuilding is not the optimal solution for both environmental and economic points of view. Hence, innovative technology options for eco-efficient buildings have been investigated: those can restart the service life of the building and improve the whole structural and energy performance. With awareness of the material choice, a good recycling rate can be guaranteed and total costs may be limited [23].

With regard to the LCA methodology, a static LCA approach would not reflect the likewise way of making a decision. On the other hand, this is possible by carrying out a probabilistic analysis: even if it represents a more complex procedure, it can handle the uncertainties due to variations or intervention during its operating phase. As further advantage of the probabilistic LCA with MC simulation, the methodology can be easily modified, depending on the economic and environmental conditions, and can take into account the remaining value of a newly constructed building after the 50 years of considered lifetime, which in this case is not included.

Acknowledgement
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Towards conceptual understanding for the adoption of building environmental sustainability assessment methods in the UAE built environment

Shibeika A, Abdel Raheem T, Hittini B

Architectural Engineering Department, United Arab Emirates University, Al Ain, Abu Dhabi, UAE

a.shibeika@uaeu.ac.ae

Abstract. The UAE is witnessing increased interest for sustainable development which poses challenges on the development processes for the large amount of built environment projects taking place in this emerging economy. While, great attention has been given to the development of tools and methods to measure and assess the performance of buildings to meet specific environmental sustainability targets, however, less is known about the effect of these assessment methods on the built environment development process itself. This paper addresses this gap through the investigation of the adoption of building environmental sustainability assessment methods for development projects in the UAE. Currently, there are two assessment methods in the UAE; Pearl Building Rating (PBR) and Al Sa'fat systems. Background study revealed that both systems: are developed in parallel to the development of building codes, adopt performance-based approach for assessment methods, and their adoption for development projects is basically mandatory. This paper draws from diffusion of innovations theory and growing literature in the adoption of similar assessment methods in projects, with the objective of proposing a conceptual framework that conceptualizes PBR and Al Sa'fat methods as innovations and the development projects as the social system for adoption, while focusing on the adoption process dynamics rather than the decision to adopt or not. The proposed framework captures specific conceptual themes, providing the foundation for further empirical investigation. As such, this paper contributes to the growing literature on the adoption of global energy assessment tools and specifically addresses the UAE's sustainable development policy and regulation.

1. Introduction

Sustainable development is important for emerging economies such as the UAE, which has been witnessing rapid development in buildings and infrastructure for the last 30 years or so, propelled by an oil-rich economy. As the country aspires to couple economic development with social and environmental development [1], and to confirm its commitment to the sustainable development goals (SDGs) set out by the United Nations for 2030 [2], numerous federal and local policies and strategies has started to converge to enable the realization of sustainable development goals. Examples of these are: UAE Vision 2020, the UAE Centennial 2071, and the UAE Energy Strategy 2050. This sustainability discourse which is increasingly emerging and diffusing from policy into practice has great effect on construction work and firms specially that construction and building sector contributed 8.40% of the UAE GDP in 2017 [3]. Hence, the broad focus of this research is the sustainable development for the UAE built environment.

A lot of attention has been given to the development of tools and methods to measure and assess the performance of buildings to meet specific environmental sustainability targets. While, assessment methods have been considered as *market transformation tool,* which not only provide objective evaluation of environmental performance but also enable green design guidance and encourage communication within sustainable project teams [4], less is known about the effect of these assessment methods on the built environment development process itself. A growing literature has started to address this gap and found that while these methods provide opportunities for innovation, it also has the potential to stifle innovation by prescribing specific solutions and promoting a tick-boxing approach to meet required regulations instead of adopting sustainable design and construction practices [5] [6]. Drawing on Diffusion of Innovations (DOI) theory, this paper contributes to this growing literature by proposing a conceptual framework for understanding of the adoption of Building Environmental Sustainability Assessment Methods by the UAE built environment projects, this framework serves as the foundation for further empirical investigation of the UAE construction industry.

The paper is organised as follows: The following section introduces the UAE context for environmental sustainability of the built environment. That is then followed by conceptual framework for understanding the adoption of assessment methods by development projects based on the analysis of relevant literature in light of DOI theory. Finally, the paper concludes with a discussion of the planned empirical investigation through case studies of UAE sustainable projects as the next step for this research.

2. The UAE context for environmental sustainability of the built environment

The UAE has started to adopt a pro-active approach towards sustainable development of the built environment from the mid-nineties. In 1996, the Environmental Agency-Abu Dhabi (EAD) was established with the aim to protect biodiversity; provide cleaner environment and sustainable development; and decrease energy and water use, waste and carbon footprint. The focus of EAD is on 6 themes, which are: air and climate change, water, marine, energy, biodiversity and waste [7]. In 2006, the Emirates Green Building Council (EmiratesGBC) was established, also, work has started on Masdar city, which is a carbon-neutral, zero-waste city in Abu Dhabi. Masdar city sheds the light on Abu Dhabi as a technology developer instead of being an importer [8]. The UAE places attention on increasing sustainability literacy through launching pioneer projects such as Masdar, as well as setting clear guidance for performance and methods for assessment of buildings, this could be attributed to its nature as a wealthy emerging economy opposite to other developed countries which focus on subsidising energy cost or providing tax reduction for sustainable products and services.

The use of assessment methods to promote sustainable practices for the built environment has started in the UAE through the adoption of two adaptations for the main two international assessment methods of LEED and BREEAM in 2007 and 2008, respectively. To meet the specific requirements of the UAE environmental resources, both methods gave special attention to the issue of water, hence, Emirates LEED has three more total scoring points compared to LEED for giving a higher weight to water conservation according to the region's climate. This increased emphasis on water conservation is exemplified in the fact that UAE buildings could not be certified unless potable water is reduced by 20% regardless of the points achieved in any other category. Similarly, the weight of the water category in Gulf BREEAM was increased to 30% compared to 6% in BREEAM [9]. This reflect the country's awareness and sensitivity to the adoption of assessment methods that address its specific climatic condition and available resources, which is in line with what has already been established in the literature proving the difficulty in having a set of pre-designed environmental criteria that is prepared for worldwide use without further adjustments [10].

Currently, there are two building environmental assessment methods in the UAE. First, there is Abu Dhabi's Pearl Building Rating (PBR) system which was launched in 2010, PBR systems is based on Estidama program which is a framework for sustainable built environment launched in 2009. Similar to other sustainability frameworks, it addresses the three main pillars of sustainability: environment, economy and society, this is in addition to a fourth pillar "culture" which is unique to Estidama to reflect the local climate and culture of the UAE. Unlike BEEAM and LEED which reference existing national codes and planning guides, PBR system is being developed in parallel to the building codes. PBR assessment method is set to assess the performance of buildings, communities, and villas, establishing separate ratings across the design and construction phases of development projects. The system addresses seven categories - integrated development process, natural systems, liveable communities, building and villas, precious water, resourceful energy, stewarding materials and innovating practice - where there are both mandatory and optional credits. To achieve a 1 Pearl rating, which is mandatory for all new projects, all the mandatory credit requirements must be met. Government funded buildings must achieve a minimum of 2 Pearl rating. To achieve a higher Pearl rating (2-5 Pearls), all the mandatory credit requirements must be met along with a minimum number of credit points.

Second, there is Al Sa'fat building rating system launched in the Emirate of Dubai in 2016, which is a reestablishment of the Dubai Green Building Regulations of 2010. The rating system focuses on building performance, and evaluates all buildings types - residential, commercial, industrial and other facilities- at four stages; planning, design, construction and operation, and is split into four classifications: platinum, gold, silver and bronze. All new buildings are required to achieve bronze rating. It's worth noting that Al Sa'fat in its new form is at the early stages of adoption compared to PBR which hasn't changed since 2010.

This review of building environmental sustainability assessment methods in the UAE shows that both PBR and Al Sa'fat systems are developed in parallel to the development of building codes for each emirate, they both also adopt a performance-based approach for diffusing environmental sustainability practices, as such, they have the potential to improve performance leading to systemic technological change, however, this will only be achieved if these new innovations are adopted following a progressive approach which promotes information sharing and integration among the different parts of the development projects [11]. This raises questions around the processes, people and technology associated with this progressive approach, hence, the aim of this research is to investigate the adoption process of available local UAE assessment methods for development projects.

3. Conceptual framework

3.1 Diffusion of innovations lens and process approach for understanding

Diffusion of innovations theory examines how new ideas move through a particular social system. Diffusion is defined to be *"the process in which an innovation is communicated through certain channels over time among the members of a social system"* [12]. While, innovation is classically seen as both a process to generate new ideas and a new product or service resulting from this generation process [13] [14], innovation adoption is more concerned with the behavior of the adopting unit towards the innovation. In other words, how decisions are made to either adopt or reject the innovation. However, in the case of this research, and as presented above, the adoption of PBR and Al Sa'fat assessment systems in the UAE is basically mandatory for all buildings with opportunities for voluntary adoption for higher ratings, therefore, the focus of this research is on the dynamics of the adoption process rather than the decision itself. The goal of this paper is to develop a framework which will provide the conceptual foundation for further empirical investigation to achieve the research aim.

3.2 Assessment methods as innovation

Classic diffusion of innovations theory claims that there are certain attributes of the innovation that influence adopters' behaviour towards the innovation and subsequently influence the decision and rate of adoption [12]. On one hand, there are attributes which are inherent in the innovation, such as the innovation complexity and trialability. While, Ding argues that the inflexibility, complexity and lack of consideration of a weighting system are still major obstacles to the acceptance of environmental building assessment methods [10], differences between PBR and Al Sa'fat and to other well-known systems such as BREEAM and LEED might lead to different adoption patterns and behavior by projects teams calling for further analysis of the structural characteristics and components of both assessment methods.

On the other hand, there are other attributes which are linked to the adopters and their envisaged use of the innovation (competitive advantage, compatibility and observability). Along this line, construction innovation is found to influence and be influenced by the interdisciplinary and interorganisational nature of development projects [15] [16]. Furthermore, the adoption of BREAAM in projects is found to be influenced by the level of experience of the tool specifically and sustainable design in general among the project team participants, as well as the degree of the assessor's involvement in the project [17]. This argument calls for further investigation of the assessment methods in relation to the development projects to capture project characteristics which influence the assessment process, and the alignment of PBR and Al Sa'fat methods with the development process itself.

3.3 Construction projects as the social system for diffusion

Innovations diffuse into social systems which are defined as "*a set of interrelated units that are engaged in joint problem solving to accomplish a common goal*" [12]. This social system is comprised of two main structures: formal and informal, each represents information that reduces uncertainty and gives regularity and stability to human behavior in the system. Rogers defined structure as "*the patterned arrangements of the units in a system"* [12], and highlighted the ability of the system's norms to facilitate or impede the diffusion of innovation. While, built environment development projects are considered as the social system for innovations such as building environmental sustainability assessment methods, the growing literature highlighted some of the components and dynamics associated with assessment methods in projects. For example; Schweber and Haroglu's investigation of the adoption of BREEAM in eight UK projects highlighted the impact of the assessment process on standard project practices [18], revealed factors influenced the fit of the assessment method to design processes [17], and captured significant design changes in order to meet the rating requirements [19]. Similarly, Thomson and El-Haram presented the findings of four case studies of BREEAM adoption over 15 years period and highlighted four elements associated with the assessment process in projects, these are: sustainability leadership, alignment of assessment method with project management, project culture which promote engagement, and efficient knowledge flow [6].

While, delivery methods such as Design-Build-Operate-Maintain, which integrates the designers, contractors and operation and the maintenance managers under one contract to the owner were suggested as useful methods to integrate sustainability practices in projects [20]. Other scholars have also investigated relevant issues such as the importance of the integration of the project supply chain [21] and stakeholder engagement [22] into the assessment process in order to achieve environmental sustainability goals. Linked to this is the importance of adopting and promoting effective knowledge management and learning mechanisms to ensure knowledge brokering [23], and dynamic flow of sustainability knowledge through codification and personalization [6]. Furthermore, besides sustainability leadership and the involvement of sustainability assessors, sustainability literacy and project team dynamics and communication have received considerable attention as enablers for successful adoption of assessment methods. [16] [24] [6]

The above discussion provides useful points of departure which are summarized in Table 1 below, these will provide conceptual foundations for the empirical investigation of the adoption of assessment methods in the UAE development projects which will be presented in the following final section of the paper.

Table 1. Conceptual themes for empirical investigation.

PBR and Al Sa'fat assessment methods as innovation	1. Structural elements for PBR and Al Sa'fat systems, and their effect on the assessment process. 2. Project characteristics which influence the assessment process and the alignment of PBR and Al Sa'fat methods with the development process	
Development projects as the social system for adoption	Formal structure	Informal structure
	3. Project delivery method and (supply chain management, stakeholder engagement). 4. People issues: leadership, assessors' involvement, sustainability literacy, and culture of engagement. 5. Knowledge management and learning mechanisms for sustainable practices.	

4. Conclusion and future research

The aim was to propose a conceptual framework for understanding the adoption of building environmental assessment methods in development projects in the UAE. This aim was founded on the need to address the emerging discourse for sustainable development of the built environment through policy and implementation of local assessment methods in the UAE. Guided by diffusion of innovations theory, literature review of relevant studies considered the conceptualization of the two current assessment methods in the UAE - PBR and Al Sa'fat – as innovation. The adoption process of this innovation is likely to be influenced by its structural elements and how that effect project work. Furthermore, structures and dynamics of development projects also impact the adoption process; these are focused around issues related to project delivery methods, people, and knowledge management. This conceptual framework is useful because it provides the foundation for further understanding and the starting point for the empirical investigation of the research aim which is set to investigate the adoption process for local assessment methods in development projects in the UAE employing case study approach.

This paper contributes to the growing literature concerned with the effect of assessment methods in the development process by providing focus for environmental sustainability of the built environment in emerging economies, with substantial similarities between the UAE's local assessment methods and those developed by other countries, the core concepts and adoption themes could be generalized for various contexts, hence the proposed framework's applicability in terms of conceptualizing development projects as the social system for the diffusion of rating systems. However, the uniqueness of the UAE's context remains evident due to its climatic, social, cultural, and economic conditions. The paper also contributes to the rising discourse in sustainable development in the UAE and beyond through policy and regulations and has the potential to provide directions for projects and regulation development.

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SPECIAL FORA

Transition Towards a Net Zero Carbon Built Environment

SBE19 Graz

SUSTAINABLE BUILT ENVIRONMENT D-A-CH CONFERENCE 2019
Graz, 11–14 September 2019

SPECIAL FORUM

Level(s)[1] *and its place in the tool box for sustainable construction*

Andreas Rietz, Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR), Germany

12 Sept 2019, 11.30am -01.00pm | Rechbauerstraße 12, 8010 Graz

SUBJECT

Systems for describing, assessing and certifying the contribution of individual buildings to sustainable development are important tools for motivating building owners and assisting architects in the design process. So far, they are used in Europe for only a limited number of objects. Potential users fear a high nancial expenditure for the collection of additional data and detailed documentation combined with additional costs for the certification process itself. Thus, the question arises for an additional entry point into the topic through the scope and type of sustainability assessment. Level(s) is a voluntary reporting framework for describing and documenting relevant building features with respect to their sustainability related characteristics.The Special Forum will discuss the role of Level(s) in the overall system of instruments and tools to promote sustainable design, construction and operation, and how interdependencies with other approaches can be shaped.

As part of the Special Forum, four presentations and a detailed discussion with all participants with interactive elements are planned:

Presentation 1	Overview of the Level(s) framework/Results of test applications Josefina Lindblom Ph.D., DG Environment, European Commission
Presentation 2	Level(s) in Austria – 2 case studies Martin Röck & Alexander Passer, TU Graz
Presentation 3	Results of Level(s) testing process in Denmark Harpa Birgisdottir & Kai Kanafani, Danish Building Research Institute
Presentation 4	Demand for building related information to support appraisal and green finance – (how) can Level(s) help? Ursula Hartenberger, Head of Sustainability, RICS
Presentation 5	Job sharing between Level(s) and Sustainability Assessment Systems Andreas Rietz, Head of Division Sustainable Building, BBSR
Moderation	Thomas Lützkendorf, KIT

QUESTIONS AND RESULTS

During the discussion with the participants the following questions will be discussed, among others:

(1) How can obstacles be overcome in the context of a broad application of design process accompanying sustainability assessment systems?;
(2) What new approaches and indicators does Level(s) offer?;
(3) What are the experiences with Level(s) in practical application?;
(4) How can a division of labor between Level(s) and other instruments and tools designed to support sustainable planning, construction and operation?

The results of an interactive opinion-forming and the overall discussion are summarized and made available to the participants of the Special Session, the organizers of the SBE19 Graz and the European Commission.

[1] http://ec.europa.eu/environment/eussd/pdf/factsheet_DEF.pdf

Contact: Graz University of Technology, Austria | Institute of Technology and Testing of Building Materials | Working Group Sustainable Construction
Waagner-Biro-Straße 100, 8020 Graz | SBE19 Graz Secretariat: sbe19@tugraz.at | > **sbe19.tugraz.at**

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Federal Institute for Research on Building, Urban Affairs and Spatial Development within the Federal Office for Building and Regional Planning

SBE19 Graz

SUSTAINABLE BUILT ENVIRONMENT D-A-CH CONFERENCE 2019
Graz, 11–14 September 2019

SPECIAL FORUM

„Die 3 Schwestern in der Seestadt Aspern Bauplatz D22“ – Paradebeispiel für nachhaltiges Wohnen

Natürlicher Baustoff Ziegel als ideale Voraussetzung für wohngesundes Bauen und Wohnen

Wienerberger Österreich GmbH
12.09.2019, 11.30-12.45 Uhr | Rechbauerstraße 12, 8010 Graz

Überblick - Vorstellung des Bauprojekts „Die Drei Schwestern“ in der Seestadt Aspern

In der Seestadt Aspern wurde auf dem 5.200 m² großen Baufeld D22 nach den Plänen der Kirsch ZT GmbH gestalteten Architektur die Wohnhausanlage „Die Drei Schwestern“ von der Wohnbauvereinigung für Privatangestellte (WBV-GPA) errichtet. Im Zuge der Planung der Gebäudehülle der drei mehrgeschossigen Baukörper (Bauteil A-NNA, B-ELLA, C-LARA) entschieden sich die Verantwortlichen gezielt für den Wienerberger „Porotherm 50 W.i. Plan“ Ziegel. Aufgrund der durchgängig in mineralischer und einschaliger Bauweise als Niedrigstenergiehaus errichteten Baukörper, wurde ein wesentlicher Beitrag zum Verzicht auf erdölbasierten Vollwärmeschutz geleistet. Das Gebäude erreichte bei der ÖGNB Gebäudezertifizierung 769 von 1000 Punkten und wurde mit klimaaktiv GOLD ausgezeichnet.

Im Zuge des Special Forums sollen die hohen ökologischen, ökonomischen und soziokulturellen Qualitätsansprüche der Planung diskutiert werden. Aspekte der Nachhaltigkeit spiegeln sich beispielsweise in der ökologischen Materialauswahl, Langlebigkeit, Wertbeständigkeit, etc. wider.

Geplanter Aufbau der moderierten Diskussion

Neben einer interaktiven Diskussion sind folgende Impulsvorträge geplant:

- **Vorstellung des Gebäudes durch den Bauträger und Architekt**
  Ing. Franz Pranckl MSc (GPA-PlanungsgesmbH)
  Prok. Ing. Herbert Wolf (HAZET)

- **Erläuterung der beiden Nachhaltigkeitszertifizierungen von ÖGNB und klimaaktiv**
  DI^{in} Franziska Trebut (ÖGUT)
  Robert Lechner (Ökologie-Institut)

- **Informationen über das verwendete Baumaterial**
  Mario Kubista (Wienerberger Österreich GmbH)

- **Round-Table mit Publikumsfragen**

Die Moderation wird von Fachjournalistin Mag. Sabine Müller-Hofstetter geführt.

Contact: Graz University of Technology, Austria | Institute of Technology and Testing of Building Materials | Working Group Sustainable Construction
Waagner-Biro-Straße 100, 8020 Graz | SBE19 Graz Secretariat: sbe19@tugraz.at | > **sbe19.tugraz.at**

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SBE19 Graz

SUSTAINABLE BUILT ENVIRONMENT D-A-CH CONFERENCE 2019
Graz, 11–14 September 2019

ETH zürich | BOKU Universität für Bodenkultur Wien | KIT Karlsruher Institut für Technologie | TU Graz

SPECIAL FORUM

CONDEREFF European project regarding construction & demolition waste

Improve environment and resource efficiency and enhance reuse

Land Steiermark - A14 Abfallwirtschaft und Nachhaltigkeit
12 Sept 2019, 11.30am-01.00pm | Rechbauerstraße 12, 8010 Graz

SUBJECT

In 2015, 10 million tons of construction and demolition waste have been generated in Austria. To foster a move towards circular economy and minimize this high amount, Styria is part of the EU project CONDEREFF. CONDEREFF is an interregional cooperation project, which brings together 8 partners from 7 countries to accelerate their policy work on improving resource efficiency at territorial level.

Furthermore, Styria has developed a guideline for the deconstruction of buildings to enhance the amount of recycled materials. The country aims to increase the volume of reused construction materials.

PRESENTATION

Four presentations are planned, focusing on:

Presentation 1 – CONDEREFF: interregional cooperation project (Construction & demolition waste management policies for improved resource efficiency)

Presentation 2 – Guideline for construction and demolition waste: implementation of reuse

Presentation 3 – Reuse in Styria: state of the art

Presentation 4 – Implementation of recycling in planning phase

DISCUSSION AND INTERACTIVE PARTICIPATION

During the discussion with the participants, following questions will be discussed:

- How to handle the separation duty, hazardous waste, appearing during demolition work, how to carry out the examination of contaminants and undesired substances and how to develop the recovery concept
- Practical problems occurring on-site
- Problem end of waste status and the transfer of construction materials to second parties
- Recycled construction materials/ recycling aggregate production, use and awareness raising activities
- How to implement reuse in public procedures and in regulatory framework
- How to implement reuse already in the planning phase
- Improvement of the construction and demolition waste management policy

Contact: Graz University of Technology, Austria | Institute of Technology and Testing of Building Materials | Working Group Sustainable Construction
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SUSTAINABLE BUILT ENVIRONMENT D-A-CH CONFERENCE 2019
Graz, 11–14 September 2019

TU Graz | ETH zürich | BOKU Universität für Bodenkultur Wien | KIT Karlsruher Institut für Technologie

SPECIAL FORUM

Implementing BWR 7 „Sustainable Use of Natural Resources“ in Europe

Peter Maydl, Prof.em. Graz University of Technology, Consulting Engineer “Sustainable Engineering”
12 Sept 2019, 02.15pm-03.45pm | Rechbauerstraße 12, 8010 Graz

SUBJECT

In 2013, Construction Products Regulation (CPR) has come into force including the new Basic Work Requirement (BWR) 7 “Sustainable use of natural resources”. Although CPR is well established and BWR 7 is in this context a legal demand, it is not yet common practice to take it into account in most of the member states. One of the reasons may be the current wording, which sometimes lacks in clear definitions (e.g. “environmentally compatible raw materials”). In 2020 CPR will be modified by the EC. This is a good opportunity to create a better wording, to ask for more clarity in the case of targets, assessment rules and ways for communication.

Therefore, it is interesting how member states handle these questions and how they are prepared for. This Special Forum shall give the opportunity to all participants to discuss the present situation and future possibilities, exchange experiences from different member states, experts and involved parties and to develop some suggestions for a more precise concept and wording.

OPENING STATEMENTS / IMPULSE-LECTURES

- Presentation by Manfred Fuchs, DG GROW, European Commission: What European Commissions intends with BWR 7
- Oscar Nieto, Construction Products Europe: Environmental information in CE marking – What can we expect?
- Thomas Lützkendorf, Peter Maydl and Alexander Passer: Handling BWR 7 in practice: obstacles, opportunities and proposals for a new wording within a next generation of CPR
- Robert Jansche, Provincial Government of Styria, OIB – Austrian Institute of Construction Engineering: Implementing BWR 7 from the perspective of a national legislative body

DISCUSSION WITH THE POSSIBILITY OF INTERACTIVE PARTICIPATION

During discussion there will be time to

- analyse EC´s intentions and expectations in terms of implementing BWR 7 in the context of the new CPR
- share experiences made in the member states so far
- discuss proposals for an amended BWR 7
- assess the need for action
- develop recommendations for a change of the current BWR 7

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Graz, 11–14 September 2019

SPECIAL FORUM

The role of background databases in the environmental assessments of buildings: what is the way forward?

ecoinvent Association

12 Sept 2019, 02.15pm-03.45pm | Rechbauerstraße 12, 8010 Graz

SUBJECT

The availability of accurate and up to date life cycle inventory (LCI) data is key to support environmental decision making in the construction sector. However, as the data needs of life cycle assessment (LCA) practitioners, including those working in Environmental Product Declaration (EPD), continuously evolve, the role and structure of background LCI databases must also develop to ensure that the needs of users are met. The ecoinvent Association is organising this forum to provide information on and discuss the role of background databases in environmental decision making and EPD creation.

As part of the special forum, the following presentations and discussion will take place:

- Welcome
  Gregor Wernet, ecoinvent Association
- The new impact categories in the amended standard EN15804 and their relevance for the construction sector
  presentation by Karen Allacker, Professor, KU Leuven
- The role of the background database in the framework of the amended EN15804
  presentation by Dimitra Ioannidou, ecoinvent Association
- Software development and the amended EN15804
  presentation by Marisa Vieira, PRé Sustainability, developer of the LCA software SimaPro®
- Presentation of a more policy related perspective on the new standard and on the EPD development in Austria
  presentation by Hanna Schreiber, Environment Agency
- Discussion on the experience with the use of background data in EPDs
  Lars G. F. Tellnes, research scientist, Ostfold Research
  Hildegund Figl, IBO-Österreichisches Institut für Bauen und Ökologie GmbH
- General discussion with participants on the role of background databases related to EPDs.

QUESTIONS TO BE DISCUSSED

The participants are invited to provide their insights and experiences with using background datasets for Environmental Product Declarations or Product Environmental Footprints. Among others, the following questions will be addressed:

- What are the expectations of users in a background database, especially with respect to EPDs?
- What should be the role of a background database in supporting efforts to harmonise different methodological approaches, choices and assumptions used in EPDs and LCA?

ORGANIZER

The ecoinvent association is an internationally active not-for-profit organization devoted to supporting high quality environmental assessments. Its activities currently include publishing and maintaining the ecoinvent database and further leading, or participating in initiatives with the aim of promoting good practice in the creation and use of life cycle inventories around the world.

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SPECIAL FORUM

Certified Sustainability: Should the VinylPlus® Product Label be Integrated in Existing Sustainability Label Schemes for Buildings?

Heinz G. Schratt, PlasticsEurope Austria, industry spokesperson for all plastics, representative of VinylPlus®
12 Sept 2019, 02.15pm-05.45pm | Rechbauerstraße 12, 8010 Graz

SUBJECT

Sustainability and PVC may go together well—admittedly not all PVC, and not all applications. Hence, it is the goal of industry to provide a tool for the specifier to discriminate between PVC that fits and supports a sustainable built environment. The PVC value chain demonstrates the thinking and the science behind their new VinylPlus® Product Label and invites participants to discuss the potential of that very label, which is being applied to qualified window frames from May 2018.

Long service time of all construction elements and, consequently, of the entire building is in the core of sustainability. The most common materials in B&C undoubtedly provide such longevity: concrete, steel, glass… but so do certain plastics, particularly PVC, in pipes, window frames, roofing and waterproofing membranes, flooring, and coated fabrics (“textile architecture”).

However, not all PVC is created equal. Process technology and/or formulations (additives) of PVC may vary. It is this state of uncertainty that led many environmentalists to putting PVC, also known as Vinyl, under general suspicion and to discourage the use of PVC. Nevertheless, in the right applications, using PVC might substantially contribute to sustainability.

TOPICS TO BE DISCUSSED

Formal presentations

- The four system conditions of TNS – The Natural Step
  A scientific basis for a sustainable development | *Richard Blume, Senior Consultant, TNS*
- Documentation of „Responsible Sourcing“ as a central requirement for sustainability assessment | *Vincent Stone, Technical & Environmental Affairs Senior Manager, VinylPlus®*
- Presentation of the VinylPlus® Product Label | *Heinz G. Schratt, Secretary General PlasticsEurope Austria*

Audience discussion / panel discussion

- Open questions
- Pros and cons of the VinylPlus® Product Label
- A fundamental paradigm shift inside the PVC industry versus a “marketing smokescreen”?
- Status quo: Does the label make life easier for the sustainability schemes and/or their auditors?
- Should the VinylPlus® Product Label be integrated in existing or future sustainability label schemes for buildings?
- Other topics from the participants
- Conclusions

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Graz, 11–14 September 2019

TU Graz | ETH zürich | BOKU Universität für Bodenkultur Wien | KIT Karlsruher Institut für Technologie

SPECIAL FORUM

EPD thought through to the end?

Proposals how to deal with the modules C and D in Environmental Product Declarations (EPD)

12 Sept 2019, 04.15pm-05.45pm | Rechbauerstraße 12, 8010 Graz

SUBJECT

A pre-requisite to achieving circular economy as contribution to resource efficiency and environmental relieve is the provision of appropriate information. The amended EN 15804+A2 requires the calculation of environmental impacts during modules C (End-of-Life) and D (recycling potential).

Questions resulting from such requirements will be discussed in this forum. We will show the results of a project funded by the German federal EPA, which essentially describes the involvement of the waste management industry (recycling, recovery, incineration) with the calculation of the environmental performance of construction products.

QUESTIONS TO BE DISCUSSED

- How to deal with Modules C, considering different possibilities of dismantling, recovery processes and national waste management regulations within Europe?
- Companies dealing with waste management or recycling have the relevant experience and access to data needed for the quantification of modules C and D. How can this knowledge be applied in EPD?
- How to model the Lifecycle (focusing on EoL) of complex products, e.g. windows or thermal insulation composite systems (ETICS)?
- Is it possible to include the product category rules for the calculation of the EoL stage in product standards?

IMPULSE-LECTURES

- Who is afraid of module C? New approaches and solutions for EoL in EPD
- Why do the waste industries not participate in developing product category rules for EoL scenarios in EPD?
- Traps to be considered when developing recycling routes.

Possibility of interactive participation in the discussion for all participants

Technical equipment for everybody's participation is provided

Umwelt Bundesamt | KIT Karlsruhe Institute of Technology | thinkstep | TU Graz

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SUSTAINABLE BUILT ENVIRONMENT D-A-CH CONFERENCE 2019
Graz, 11–14 September 2019

SPECIAL FORUM

Beton als Baustoff - wieviel ist uns Nachhaltigkeit wert?

Bewertung, Kosten und Mehrwert von Stahlbeton für Infrastrukturbauleistungen

Dr. Joachim Juhart, TU Graz, Institut für Materialprüfung und Baustofftechnologie

13.09.2019, 09.30-13.00 Uhr | Rechbauerstraße 12, 8010 Graz

INHALT

Beton bzw. Stahlbeton ist aufgrund seiner hervorragenden Eigenschaften der für Infrastrukturbauwerke weltweit meist verwendete Baustoff. Diesen Baustoff nachhaltig herzustellen – also ressourceneffizient, umweltfreundlich, dauerhaft und wiederverwertbar – ist ein erstrebenswertes Ziel in Zeiten des Klimawandels.

Folgende Themen und Fragen werden in dem Workshop diskutiert:

- Wie wird Nachhaltigkeit speziell in Bezug auf Betonbauwerke spezifiziert?
- Wie können Nachhaltigkeitskriterien der Baustoffe Beton und Betonstahl in Ausschreibung und Vergabe von Bauleistungen berücksichtigt werden?
- Kostet nachhaltiger Beton mehr als Standardbeton oder ist er sogar günstiger?
- Welchen Mehrwert in Bezug auf Umweltfreundlichkeit, Ressourcenschonung etc. bringt nachhaltiger Stahlbeton für die Gesellschaft? In welcher Maßeinheit wird dieser Mehrwert gemessen?
- Wie sind Umweltauswirkungen und die Lebensdauer von Stahlbeton zu monetarisieren?

MODERIERTE DISKUSSION UND INTERAKTIVE TEILNAHME

Impulsvorträge im Rahmen des Forums:

- **Definition von „nachhaltigem Stahlbeton"**
  Umweltwirkungen, Dauerhaftigkeit und Kreislauffähigkeit von Beton; Ökozemente, Ökobetone, Lebensdauer und Performance [J. Juhart, TU Graz]
- **Ökobilanz von Betonstahl - eine Einordnung der Ergebnisse in Österreich**
  [A. Passer, TU Graz]
- **Die Schweizer „Ökobilanzdaten im Baubereich" – Grundlage zur effizienten Umweltbeurteilung von Bauwerken und Baustoffen**
  Datengrundlagen (Ecoinvent etc.) und Bewertung am Beispiel Schweiz
  [R. Frischknecht, treeze Ltd- Life Cycle Assessment]
- **Environmental Cost Indicator: its application in tendering in the Netherlands (MKI („Milieukostenindex") – Ausschreibungspraxis in den Niederlanden)**
  Kosten für Umweltauswirkungen von Umweltindikatoren von Beton [U. Hofstra, SGS Intron]
- **Weiße Wanne plus – ein Standard für nachhaltiges Bauen mit Stahlbeton in Österreich?**
  Bewertung, Kosten und Performance bezüglich Nachhaltigkeitskriterien am Beispiel Weiße Wanne
  [ÖBB bzw. ASFINAG, A. Hüngsberg / M. Kleiser]

ASFINAG | ÖBB INFRA | VÖB Verband Österreichischer Beton- und Fertigteilwerke | Das Land Steiermark A16 Verkehr und Landeshochbau | MARIENHÜTTE

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SPECIAL FORUM

Workshop Plastics in Sustainable Building & Living: Protection of Health and the Environment

13 Sept 2019, 09.30am-01.00pm | Rechbauerstraße 12, 8010 Graz

SUBJECT

International Sustainable Chemistry Collaborative Centre (ISC3) is a new international organisation founded by the German environmental ministry with its Headquarters in Bonn. It is aiming at sustainable solutions for chemicals. Among other topics the ISC3 has a workstream Plastics in Sustainable Building & Living. The centre has installed an expert group to prepare a transparent report that will show the innovative fields in the construction sector and provide guidelines for industry, politics and consumers, on how to drive construction products towards sustainability in sense of SDGs. ISC3 is in dialogue with stakeholders from academia, industry, NGOs and international organisations. The fundamental questions in workstream are: How to drive construction products towards sustainability in sense of SDGs? And, what are the most relevant innovative areas and potentials for Sustainable Chemistry in the field of Building, Living and Plastics? The current workshop is devoted to the topic Protection of Human Health and the Environment aiming at Polymers in Building and Living area.

The Goals of the workstream are:

- to transform chemical products in building and living towards Sustainability
- to give impulses for the research and entrepreneurship
- to investigate the innovative fields and set the agenda for the near future
- to show the potentials for the Sustainable Chemistry regarding SDGs

The following questions will be discussed at the workshop:

- Where do plastic materials provide benefits for affordable housing in times of rapid urbanisation without compromising health and the environment?
- Which plastics might be substituted for health and environmental reasons?
- What are alternative solutions for plastic products?
- What properties and special features of plastic products contribute to sustainability?
- How can construction plastics be reused and/or recycled at the end of their lifecycle?
- What plastics are subject for concerns regarding waste and emissions throughout the life-cycle?

At the workshop the following presentations are planned:

Welcome and Introduction:

- Introduction of ISC3 – C.Cinquemani, Director Science & Innovation
- Workstream Plastics in Sustainable Building & Living, O.Ditkovskiy, Workstream Manager
- Preliminary Study Plastics in Construction, Prof. Dr. H. Friege, Leuphana University

Session 1 TBC:

- Presentation: LEVELS Framework – EU Commission, DG Environment (TBC)
- Presentation: Application of Building Physics for Climate Change Mitigation, Czech Technical University (TBC)
- Presentation: Plastics & Environment, President of Think Beyond Plastics (TBC)
- Presentation: Plastics in Building, Plastics Europe (TBC)

Session 2:

- Discussion on the leading questions in a round table with all participants

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Graz, 11–14 September 2019

SPECIAL FORUM

Was leistet grüne Infrastruktur in stark verdichteten Städten und wie lässt sie sich weiter ausbauen?

Handlungsspielräume zur Erhaltung lebenswerter und kooperativ genutzter Städte

green.LAB Graz Projektkonsortium

13 Sept 2019, 12.00am-03.00pm | Waagner-Biro-Straße 99, 8020 Graz

INHALT – VORSTELLUNG green.LAB GRAZ

Green.LAB Graz ist ein aktuell stattfindendes angewandtes Forschungsprojekt im Smart City Stadtteil in der Waagner-Biro in Graz. Das green.LAB Graz verfolgt das Ziel, Erkenntnisse über grüne Infrastruktur als eine zentrale Klimawandelanpassungsmaßnahme in Städten zu gewinnen und zu vermitteln.

Grüne Infrastruktur kennen lernen, erleben sowie selbst umsetzen und mitgestalten findet innerhalb drei verschiedener Schwerpunkte und Herangehensweisen statt:

- innovative Zwischennutzungen von Brachflächen unter Bezugnahme auf das Thema grüne Infrastruktur und Klimawandelanpassung als strategisches Instrument einer nachhaltigen Stadtteilentwicklung praxisnah und kooperativ umzusetzen
- ein innovatives Demogebäude zu errichten als Weiterentwicklung der „Urban Boxes“ in Richtung transportabler modularer Holzbau in Kombination mit Bauwerksbegrünung, Biodiversität, Stadtteilgarten, Regenwassermanagement, effizienter Energieversorgung und Einsatz erneuerbarer Energiequellen
- Spezifizierung eines technischen Monitoring-Systems inkl. Messgrößen sowie Maßnahmen zur Auswertung des „social impacts“

GEPLANTE INHALTE DER IMPULSVORTRÄGE

- Aufzeigen der Problemstellung und des Bedarfs für das Vorhaben Modulare Bausysteme mit integrierter Begrünung als Elemente nachhaltiger Stadtentwicklung
- Warum macht grüne Infrastruktur für verdichtete Städte und Stadtteile Sinn? Welche Kriterien und Maßnahmen können zur Auswertung des „social impacts“ herangezogen werden?
- Aufzeigen von Zwischennutzung von Brachflächen in Kooperation mit lokalen Initiativen als strategisches Element für eine nachhaltige Stadtentwicklung. Der Frage nachgehen, inwieweit Möglichkeiten der Replizierbarkeit von Zwischennutzungen bestehen.
- Welche Fördermöglichkeiten bestehen für die Umsetzung grüner Infrastruktur in Graz?
- Vorstellung der begrünten Uniqua-Fassade in der Annenstraße in Graz

MODERIERTE DISKUSSION UND TEILNAHME DURCH DAS PUBLIKUM

Begehung des Projektgebiets Smart City und vorstellen der Aktivitäten des green.LAB Graz, Erfahrungsaustausch mit AkteurInnen im Bereich Stadt- und Bauwerksbegrünung und Motivation der TeilnehmerInnen / BesucherInnen zur Umsetzung von Begrünungsmaßnahmen, Bewusstseinsbildung über Kosten und Nutzen von Grünflächen, Vernetzung

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SUSTAINABLE BUILT ENVIRONMENT D-A-CH CONFERENCE 2019
Graz, 11–14 September 2019

SPECIAL FORUM

Holzbau im urbanen Raum – eine Chance für Städte?

Holzcluster Steiermark

13.09.2019, 13.30 - 15.45 Uhr | Rechbauerstraße 12, 8010 Graz

Stadt gemeinsam entwickeln

Vortragende: Mag. Barbara Hammerl / StadtLABOR GmbH

Die Zukunft der Städte stellt uns vor große Herausforderungen und offenbart gleichzeitig enorme Potentiale für die Stadtentwicklung. Entlang bestehender Infrastrukturen wird, wie beispielsweise in Graz, verdichtet und eine Stadt der kurzen Wege entsteht. Welche Aspekte der nachhaltigen Stadtteilentwicklung werden dabei berücksichtigt? Wie verändert sich das Mobilitätsverhalten der Menschen? Welche Bedeutung bekommt die Gemeinschaft? Wie kann kooperative Planung gelingen?

Urbaner Holzbau – Holzbau 2.0

Vortragende: Univ. Prof. Tom Kaden / Technische Universität Graz

Nur wenige Referenz- und Leuchtturmprojekte wurden bislang im mehrgeschossigen Wohnbau bzw. im Nichtwohnbau (z. B. Büro- und Verwaltungs- oder Industriegebäude) in Holz errichtet. Dies obwohl die technischen und wirtschaftlichen Vorteile des Baustoffs auf der Hand liegen, wenn es darum geht, den wachsenden Bedarf an bezahlbarem Wohnraum in den Städten zu decken. Kurze Bauzeiten, ein geringes Gewicht bei hoher Tragfähigkeit und Flexibilität bei der Aufstockung von Gebäuden oder der Wohnraumerweiterung sind Pluspunkte gerade bei der Nachverdichtung im urbanen Raum.

leanWOOD – Optimierte Planungsprozesse für Gebäude in vorgefertigter Holzbauweise

Vortragende: DI (FH) Sandra Schuster / Technische Universität München

Der moderne Holzbau zeichnet sich durch die Produktion von Bauelementen in der Werkstatt mit hohem Vorfertigungsgrad aus. Die Vorfertigung ist eine Prämisse der Wirtschaftlichkeit sowie der Qualitätssteigerung, erfordert aber eine vertiefte Planung, die die Fertigung der Bauelemente, deren Transportlogistik und die Montage berücksichtigt. Die übliche Projektorganisation mit den separierten Einzelschritten Planung, Ausschreibung, Produktion und Montage stellt für den vorgefertigten Holzbau eine große Erschwernis dar.
Im Rahmen des Forschungsprojekts leanWOOD wurden vor dem Hintergrund innovativer Planungsprozesse und Kooperationsmodelle Organisations- und Prozessmodellen für den vorgefertigten Holzbau entwickelt. »lean« zielt dabei auf die »schlanke« Abwicklung von Prozessen und die effiziente wie effektive Koordination der Akteure.

Moderierte Diskussion und interaktive Teilnahme

Fragestellungen der Diskussion:

- Warum hat der Holzbau eine Schlüsselfunktion in der wachsenden Urbanisierung?
- Wie kann die Leistungsfähigkeit des Holzbaus weiter verbessert und der Einsatz forciert werden?

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Transition Towards a Net Zero Carbon Built Environment

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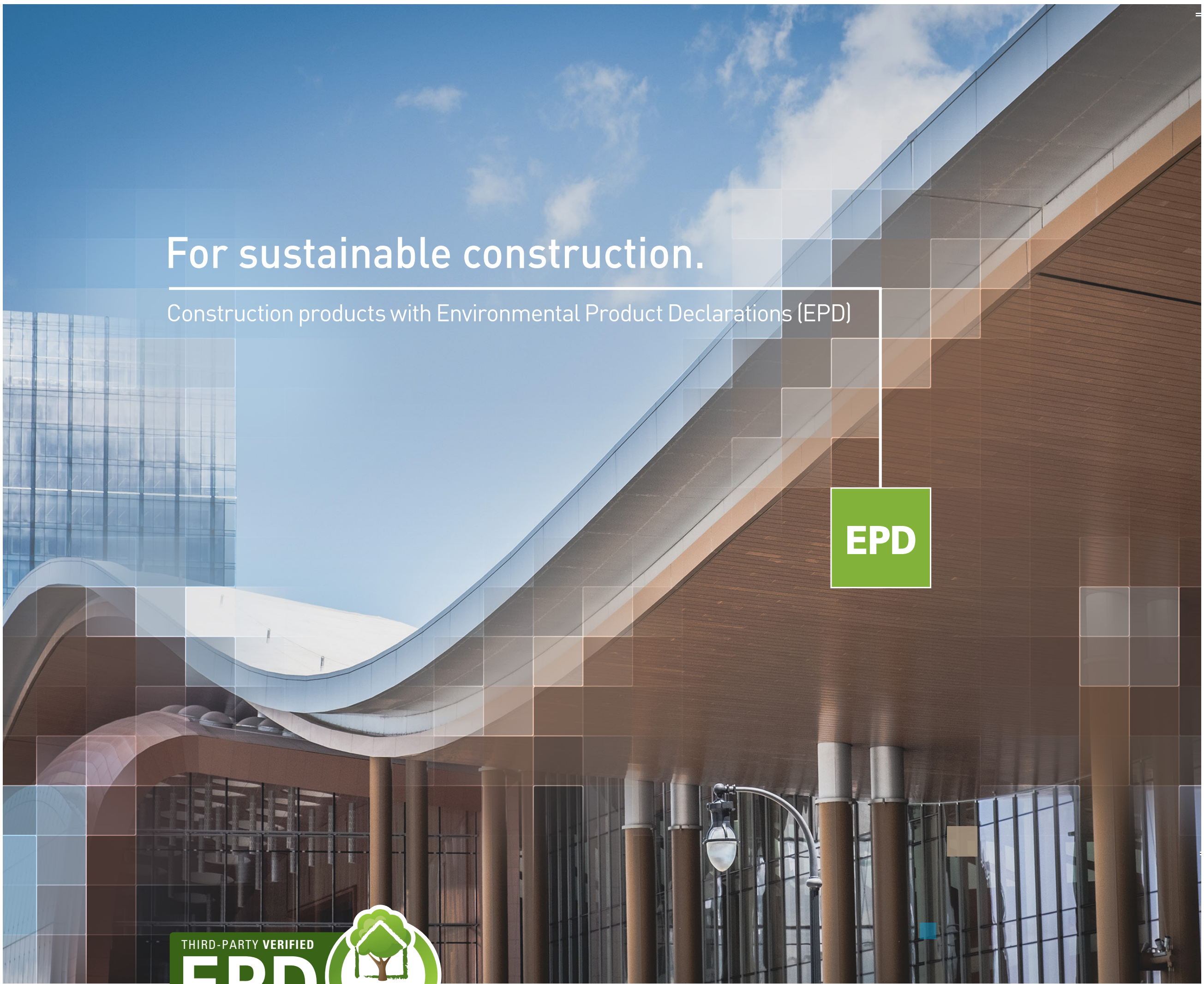
Steuerungstechnik von Beckhoff realisiert.
www.beckhoff.at/building
Die offene, PC-basierte Steuerungstechnik von Beckhoff bildet die Grundlage einer integralen Gebäudeautomation, die alle Anforderungen an eine nachhaltige und effiziente Lösung erfüllt. Eine einheitliche Hard- und Softwareplattform steuert alle Gewerke, von der nutzungsgerechten Beleuchtung über die komfortable Raumautomation bis zur hocheffizienten HLK-Regelung. Das Ergebnis: Durch die optimale Abstimmung aller Gewerke werden die Energieeinsparpotenziale über die Energieeffizienzklassen hinaus voll ausgeschöpft. Darüber hinaus reduziert die integrale Gebäudeautomation Hardware-, Software- und Betriebskosten. Für alle Gewerke stehen vordefinierte Softwarebausteine zur Verfügung, die das Engineering enorm vereinfachen. Funktionserweiterungen oder -änderungen sind jederzeit möglich.
New Automation Technology
BECKHOFF


For sustainable construction.
Construction products with Environmental Product Declarations (EPD)
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Mit zukunftsfitten Gebäuden zur #mission2030

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Das Programm Bauen und Sanieren ist ein zentraler Baustein von klima**aktiv**, der Klimaschutz-Mitmachbewegung des BMNT. klimaaktiv.at/bauen-sanieren

Die #mission2030, die Klima- und Energiestrategie der Bundesregierung, setzt klare Ziele, um den Weg in eine positive Klimazukunft zu ebnen. Der Gebäudebereich ist dabei ein zentraler Hebel zur Erreichung dieser Ziele. Daher hat das Bundesministerium für Nachhaltigkeit und Tourismus (BMNT) mit dem klima**aktiv** Gebäudestandard ein zukunftsorientiertes Gütesiegel entwickelt.

Qualität und Sicherheit

Der klima**aktiv** Gebäudestandard ist für Wohnbauten und Dienstleistungsgebäude für Neubau und Sanierung verfügbar und gibt Hilfestellung für Immobilienentwickler, Architektur- und Bauschaffende, Wohnbauträger genauso wie für alle, die ein Haus bauen, sanieren oder nutzen.

Das klimaaktiv Bewertungssystem

Energieeffizienz und erneuerbare Energien stehen im klima**aktiv** Bewertungssystem für Gebäude im Mittelpunkt, aber auch viele weitere Aspekte werden berücksichtigt. So spielen Gesundheit und Komfort, die Umweltverträglichkeit der Baustoffe und die Wirtschaft eine wichtige Rolle.

Eine Erfolgsgeschichte

Rund 800 Gebäude wurden bislang nach den Qualitätskriterien errichtet und bewertet. klima**aktiv** ist damit europaweit das erfolgreichste und gleichzeitig anspruchsvollste Gütesiegel für nachhaltiges Bauen und definiert die höchsten Anforderungen im Bereich Energieeffizienz.

Zentrale Anlaufstelle für alle Fragen zum Bauen und Sanieren nach klima**aktiv** Standard ist die ÖGUT GmbH. Das Programm wird in allen Bundesländern von Partnern unterstützt.
E-Mail: klimaaktiv@oegut.at

Mit klimaaktiv nachhaltig Bauen und Sanieren

Energieeffizienz, ökologische Qualität, Komfort und Ausführungsqualität – dafür steht klima**aktiv** Bauen und Sanieren. Ob Neubau oder Gebäudesanierung – beides stellt für BauherrInnen und ArchitektInnen eine große Herausforderung dar. Ganz speziell dann, wenn eine Sanierung höchste Ansprüche erfüllen muss. Der klima**aktiv** Gebäudestandard bietet dabei Orientierung und Unterstützung. Er ist das österreichweite Qualitätszeichen des Bundesministeriums für Nachhaltigkeit und Tourismus für nachhaltige Gebäude mit besonderem Fokus auf Klimaschutz und Energiesparen. Mit klima**aktiv** wird die Einhaltung hochwertiger Standards in folgenden Bereichen garantiert:

- **Niedriger Energieverbrauch:** Der Wärmebedarf wird gegenüber Standardbauten um rund ein Drittel reduziert.
- **Mehr Behaglichkeit:** Durch hochwertige Dämmung wird ein hohes Maß an Behaglichkeit im Sommer und im Winter erreicht.
- **Raumluftqualität und Gesundheit:** Durch das Zusammenspiel von schadstoffarmen Baustoffen mit automatischen Lüftungsanlagen werden höchste Ansprüche bei der Raumluftqualität erfüllt.
- **Ausführung und Wirtschaftlichkeit:** Hohe Qualität bei der Planung und Ausführung sind die Basis für langfristige Wirtschaftlichkeit.

Musterhaft saniert mit neuem Gesicht

Bauten aus den 1950er bis 1980er Jahren bauphysikalisch und energetisch auf Stand zu bringen ist eine herausfordernde Aufgabe. Die Fakultät für Technische Wissenschaften der Universität Innsbruck stammt aus dem Baujahr 1969 und ist nach ihrer Neugestaltung und Sanierung nun Vorbild im Bereich zukunftsorientiertes, klimaschonendes Bauen. Nicht nur was die energetische Performance angeht ist das Passivhaus beispielgebend, sondern auch im Hinblick auf die gelungene Zusammenarbeit vieler Beteiligter. Das Gebäude wurde für den Staatspreis Architektur und Nachhaltigkeit 2017 nominiert und erreicht mit 1.000 Punkten den klima**aktiv** Gold Standard.

klimaaktiv Gebäudestandard sorgt für Qualität und Sicherheit

Der klima**aktiv** Gebäudestandard ist ein idealer Leitfaden, um energieeffizientes, ökologisches und behagliches Wohnen sowie Arbeiten zu garantieren – sei es im Falle eines Neubaus oder einer qualitativ hochwertigen Sanierung. Über 800 Gebäude wurden bislang nach den Qualitätskriterien errichtet und bewertet. Damit kann klima**aktiv** die bei weitem höchste Anzahl an deklarierten Gebäuden sowohl im Neubau als auch in der Sanierung in Österreich aufweisen.

Über klimaaktiv Bauen und Sanieren

Das Programm klima**aktiv** Bauen und Sanieren ist ein zentraler Baustein der Klimaschutz-Mitmachbewegung des Bundesministeriums für Nachhaltigkeit und Tourismus, wenn es um energieeffizienten Neubau oder eine qualitativ hochwertige Sanierung geht.

Mehr Informationen zum Programm finden Sie auf **www.klimaaktiv.at/bauen-sanieren**

Alle Details zur Gebäudebewertung und den Kriterienkatalogen finden Sie auf **www.klimaaktiv.at/bauen-sanieren/gebaeudedeklaration**

Zentrale Anlaufstelle für alle Fragen zu klima**aktiv** Bauen und Sanieren ist die ÖGUT GmbH – Österreichische Gesellschaft für Umwelt und Technik.
E-Mail: **klimaaktiv@oegut.at**

Bauphysikalisch und energetisch auf Stand bringen war ein zentrales Ziel der Sanierung der Fakultät für technische Wissenschaften der Uni Innsbruck – ATP architekten ingenieure

Das Gebäude erreicht mit 1.000 Punkten den klima**aktiv** Gold Standard.

Fotos: Kurt Hörbst

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