Department of Built Environment

Sustainability of buildings - New perspectives on material-related environmental impacts of buildings

Antti Ruuska

Aalto University

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Antti Ruuska

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Abstract

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Abstract

The human influence and impact of GHG emissions on climate system are globally acknowledged. Limiting global temperature rise requires significant emission savings by all countries across all sectors, building sector being one of the most prominent ones.
Buildings consume natural resources and cause environmental pressure over their life cycles. The design stage decisions influence all the environmental impacts of the building life cycle, but they are a less researched topic. Also material-related impacts, or embodied energy and emissions of building materials, have been given only limited attention in past research, despite their increasing importance due to the development towards more energy efficient, and zero energy buildings. In spite of the seemingly great importance of material efficiency (or material savings), of buildings, it is not evident, which are the most important environmental impacts of building materials. This dissertation creates new knowledge on aforementioned topics.

Keywords Sustainability, environmental impacts, GHG-emissions, material efficiency, embodied carbon, design process, construction, buildings, building materials

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Tiivistelmä
Ihmiskunnan vaikutus ilmastoon on kansainvälisesti tunnustettu ilmiö. Ilmakehän lämpötilan nousun rajoittaminen vaatii huomattavia päästövähennyksiä. Tarvittavien päästövähennysten laajuus edellyttää vähennyksiä kaikilla sektoreilla, rakennussektorin ollessa yksi merkittävimmistä. Rakennukset kuluttavat luonnonvaroja ja aiheuttavat ympäristökuormitusta elinkaarensa aikana. Suunnitteluvaiheen päätökset vaikuttavat kaikkiin elinkaarenaikaisiin ympäristövaikutuksiin, mutta aihe on saanut vain vähän huomioita aiemmassa tutkimuksessa. Myös materiaaleihin liittyvät ympäristövaikutukset, kuten valmistuksen aikainen energiankulutus ja kasvihuonekaasupäästöt ovat saaneet osakseen vain vähän huomiota. Tämä siitä huolimatta, että näiden merkitys nykyaikaisissa, energiatehokkaissa rakennuksissa on merkittävä. Vaikka materiaalitehokkuudella (materiaalisäästöillä) on näennäisen suuri vaikutus rakennusten ympäristövaikutuksiin, ei ole selvää, mitkä ovat materiaalitehokkuuden oleelliset ympäristövaikutukset. Tämä väitöskirjatyö tuottaa osaltaan uutta tutkimustietoa näistä aiheista.

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Preface

I'm writing this preface in the library of the Aalto University. It is only now that I realize in that I'm actually about to reach the highest degree within the Finnish educational system: a doctoral degree! I'm feeling very thankful for being given the opportunity to take this journey. For me, this has been a massive individual undertaking that has required a lot of time and work. However, this would not have been possible without the support from a large group of people, whom I'd like to thank in the following.

Firstly, I want to thank Tarja Häkkinen, who has been the advisor for this thesis, and the co-author for all of the publications of this dissertation. Thank you for your time and effort that you've put into this work! Special thanks also go to my other co-authors, Nusrat Jung and Matti Kuittinen. Thank you both! Professor Seppo Junnila also deserves my sincere thanks for his role as the supervising professor. Thank you for your invaluable support and guidance during the process!

I also want to express my gratitude towards my preliminary examiners Alice Moncaster and Alexander Passer for their deep and insightful feedback on my dissertation. Thank you for your thorough and constructive feedback during the pre-examination process!

Finally, I'd like to thank all of my colleagues, and my family, mom, dad and friends for making this happen. Be it at the office, in a restaurant, on the bike or at home, it's all been part of the journey and I wouldn't change a thing. Thanks, it's been awesome!

I want to conclude this preface with a quote from my 1.5-year old son, Voitto. To me, it captures the magical moment of suddenly realizing that something wonderful has just happened and that you were able to witness a miracle come true. As such, it perfectly describes my current feelings, and it goes like this:

"O-ho!".

Saara and Voitto, you fill my life with love and happiness every day. I love you!

Espoo
Early 2018
Antti Ruuska

List of Publications

This dissertation consists of a summary report and the following original publications which are referred to in the text as Publications I to III. The publications are reproduced with kind permission from the publishers.

List of publications I to III:

I Ruuska, A. Häkkinen, T. The significance of various factors for GHG emissions of buildings. International Journal of Sustainable Engineering 2015, 8, 4-5. doi:10.1080/19397038.2014.934931

II Ruuska, A.; Häkkinen, T. Material Efficiency of Building Construction. Buildings 2014, 4, 266-294. doi: 10.3390/buildings4030266

III Häkkinen, T, Kuittinen, M., Ruuska A. Jung, N. Reducing embodied carbon during the design process of buildings. Journal of Building Engineering 2015, 4, 1-13. http://dx.doi.org/10.1016/j.jobe.2015.06.005

Author’s contributions to the publications

The author’s contributions to the original publications of this dissertation are summarized here.

Authors contributions to the publications I - III

I The significance of various factors for GHG emissions of buildings
The author of this this dissertation was the principal author of this publication and responsible for data collection and analysis.

II Material Efficiency of Building Construction
The author of this this dissertation was the principal author of this publication and responsible for data collection and analysis.

III Reducing embodied carbon during the design process of buildings
The author of this dissertation was responsible for the building case study data collection and analysis. In addition to this, the author was responsible for the synthesis of the case study and interview results.

It is acknowledged here that the author of this dissertation did not work in isolation when writing the three publications. Doctor Tarja Häkkinen had a significant role as the co-author of Publications I and II, especially through contribution on the theoretical part of the publications. She also had a large role in initiation of the publications and in drawing conclusions.
Doctor Häkkinen was the main author of Publication III and had a leading role in initiating the publication. Doctor Matti Kuittinen contributed to Publication III especially by formulating a framework that presents the main objectives for each stage of the design process from viewpoint of low-carbon design. Furthermore, he drafted templates for semi-structured interviews and conducted part of the interviews. Doctoral candidate Nusrat Jung had an important role in research design and in research methodology formulation. She also contributed to literature review and conducted part of the interviews. Furthermore, she had a significant role in the review process through her role as the corresponding author.

Contents

Abbreviations and notation

ADP	Abiotic depletion potential
ADP-elements	ADP for mineral-based natural resources
ADP-fossil	ADP for fossil-energy resources
AP	Acidification potential of land and water
ARK12	Finnish descriptions for architectural design tasks
CF	Carbon footprint
CML	University of Leiden, Institute of Environmental Sciences
CML-IA	CML Database for LCA Characterization factors
CO_2eq	Carbon dioxide (equivalent)
COP21	Paris Climate Conference
EP	Eutrophication potential
EU	European Union
GHG(s)	Greenhouse gas(es)
GJ	Gigajoule
GWP	Global warming potential
IEA	International Energy Agency
ILCD	The International Reference Life Cycle Data System
IO	Input-Output
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
MJ	Megajoule
Non-CO_2 GHGs	Other greenhouse gases than CO_2
ODP	Depletion potential of stratospheric ozone layer
POCP	Formation potential of tropospheric ozone photochemical oxidants
RIBA PoW	Royal Institute of British Architects Plan of Work
Sb eq	Antimony equivalent

1. Background

The right to an adequate standard of living and *the access to housing* [1] are considered universal human rights. Buildings help to fulfil the *basic needs* of the people by providing them and their families a shelter to live in [2]. At the same time, they consume natural resources and cause environmental pressure during their construction, operation, maintenance, renovations and demolition.

According to a well-known definition for sustainable development [3]:

> *"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."*

This definition, originally included in the *Bruntland report* [3], links the fulfilment of people's basic needs to the requirement that environment's ability to meet the present and future needs are not compromised while fulfilling those needs. In accordance to this, the premise of this dissertation is that the present and future need for buildings and housing should be met sustainably.
This dissertation aims to bring new perspectives on sustainable building by focusing on the environmental aspects of buildings' sustainability, as defined in European Standards EN 15978 and EN 15804 [4], [5]. As such, the *social* and *economic aspects* of sustainability (defined in the European Standard EN 15643-1 [6]), are outside the scope of this dissertation. More specifically, this dissertation focuses on the material-related environmental impacts of buildings.

1.1 Global sustainability issues

According to estimates by the United Nations, the global population is expected to near ten billion by 2050, compared to today's 7.4 billion [7], [8]. The current consumption rates suggest that more than two planets would be needed to cover the resource need of 2050 [9]. Due to world's dependency on fossil-fuels (over 90% of the global primary energy use is based on fossil-fuels [10]), consumption of resources and energy are commonly associated with greenhouse gas (GHG) emissions. According to the Intergovernmental Panel on Climate Change (IPCC), the

GHG emissions from fossil fuel combustion and industrial processes are responsible for some 65% of the global GHG emissions [11].

The current scientific consensus, as presented by the IPCC, is that the human influence on climate system is clear, and that the anthropogenic GHG emissions, together with other anthropogenic drivers, are extremely likely[1] the dominant cause of the observed warming since the mid-20th century [11]. However, the link between GHG emissions and climate change has long been [12], and continues to be, a debated topic especially in the politics and in the media.

On a high political level, the climate change and the need for GHG emission reductions were acknowledged by the 2015 United Nations Climate Change Conference, *or COP21,* by all participating 195 countries [13]. The level of ambition and commitment varies by country, but for example, the European Union has committed to reduce its GHG emissions by 80 to 95% from 1990 level, by 2050 [14]. The vast scale of targeted emission savings calls for emission reduction actions across all sectors, the building sector being one of the most prominent ones.

1.2 Environmental impact of the building sector

The building sector has a major global environmental impact, as it accounts for some 32% of the final energy use and 19% of the energy-related GHG emissions [15]. For example, the production of cement, an important component for many building materials, is estimated to be responsible for some 5% of global CO_2-emissions [16], [17]. In the European Union, buildings account for more than half of the extracted materials, for 42% of total energy consumption and 35% of all GHG emissions [9], [18], [19].

Respectively, the building sector also has significant saving potentials. It is estimated that with a combination of technological solutions, design practices and behavioural changes, large reductions in the energy use of buildings (50-90% in new buildings and 50-75% in the existing stock) could be achieved [15]. For example, in Europe, the building sector is seen as one of the key sectors for GHG savings [14] with the largest potential for energy-efficiency improvements [20].

[1] Other anthropogenic drivers include cooling effects of aerosols and the effect of land use change. The expression e*xtremely likely* refers to IPCCs terminology, and translates to quantitative likelihood, or probability of 95-100% for a specific well-defined outcome.

However, in order to choose the right actions to achieve these potential savings, a thorough understanding of the relevant environmental impacts of buildings is needed.

2. Literature review

The following Figure 1 illustrates the life cycle of a building. A *building project* starts with the design stage, which largely defines the structures, materials, spaces and the building systems. The *life cycle* of a building then starts with the *product stage*, as raw materials are acquired, transported and processed into building materials. After this, the building materials are transported to a building site, and the building is constructed during the *construction process.* The *use stage* begins as the building is taken into use and it starts its operation. Over time, the building consumes energy during its use, and renovations (maintenance, repair, replacements and refurbishments) take place. Finally, at the *end of life*, the building is de-constructed and waste is transported to processing and final disposal. After the *end of life,* there might be specific benefits or loads for a building through *reuse, recovery and recycling* of materials. The following Figure 1 shows the building life cycle, as understood in this dissertation.

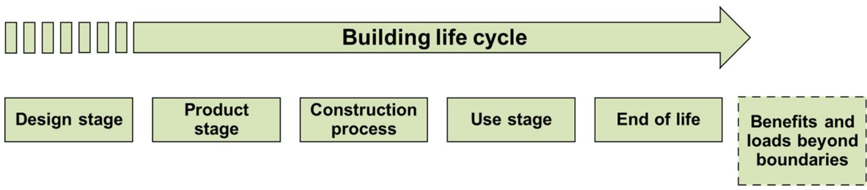

Figure 1, the life cycle of a building, as understood in this dissertation. The naming of life cycle stages is adopted from EN 15978 [4], with the exception of the design stage that has been added before the product stage.

Buildings use material and energy resources and cause environmental burdens throughout their life cycles. There is a multitude of existing norms, guidelines and standards to support the assessment of environmental impacts of buildings through life cycle assessment (LCA) methodology. On international level, the *ISO/TC 59/SC 17*[2] *- Sustainability in buildings and civil engineering works*, has prepared a catalogue of standards for sustainability in buildings, such as the ISO 21930 for environmental product declarations (EPDs). In Europe, the *CEN/350 TC*[3] *- Sustainability*

[2] ISO/TC 59/ SC 17 is a subcommittee of the technical committee 59 of the International Organization for Standardization, ISO
[3] CEN/ 350 TC is a technical committee of the European committee for standardization, CEN

of construction works, is responsible of the development of standards for sustainability of buildings and building products, such as the EN 15978 and EN 15804 [4], [5]. Furthermore, there are national-level product category rules (PCRs) for calculation of construction product EPDs, for example, the Finnish PCR by Building Information Foundation RTS [21]. Despite of all the standardization and guidelines relating to building sustainability, there seems to be a lack of consensus on how these should be applied in practice, as argued in a recent critical review of industry practices [22].

This dissertation divides the life cycle energy use of buildings into embodied energy and operational energy. These are defined in the past research as follows ([23]–[26]):

- The embodied energy entails the energy consumption for building materials and components over the life cycle of a building, including production, renovation, refurbishment and demolition of buildings
- The operational energy consists of the energy consumed for maintaining indoor environment through operation of heating, ventilation and air conditioning systems (HVAC), hot water and for appliances and lighting.

Energy consumption is also closely linked to carbon dioxide emissions, as described earlier. Recently, an International Energy Agency (IEA) project, *IEA Annex 57,* has suggested defining embodied energy and embodied carbon as follows [27]:

- Embodied energy (EE) is the total amount of non-renewable primary energy required for all processes related to the creation of a building, its maintenance and end-of-life, from other sources than the operation
- Embodied GHG emissions (EG), are the cumulative quantity of greenhouse gases, which are produced during creation of the building, its maintenance and end-of-life, from other sources than the operation.

The embodied energy can be seen as an integral part of the cumulative primary energy demand, and embodied GHG emissions as a part of the total GWP, or carbon footprint, of a building [28]. This dissertation uses a term *material-related impacts*, when referring to the embodied energy, embodied GHG emissions and re-

source consumption of a building. For the use stage energy and resource consumption, and the related GHG emissions, this dissertation uses the term *operations-related impacts*.
The following Figure 2 further illustrates how this dissertation understands *the material-related* and *operations-related impacts*. The figure shows the different life cycle stages of a building, together with the sources of material-related and operations-related environmental impacts[4]. It is also noted here that this dissertation focuses on the environmental impacts of the design stage that come through decision-making about the structures, materials, spaces and building systems, not on the environmental impacts of the design work itself.

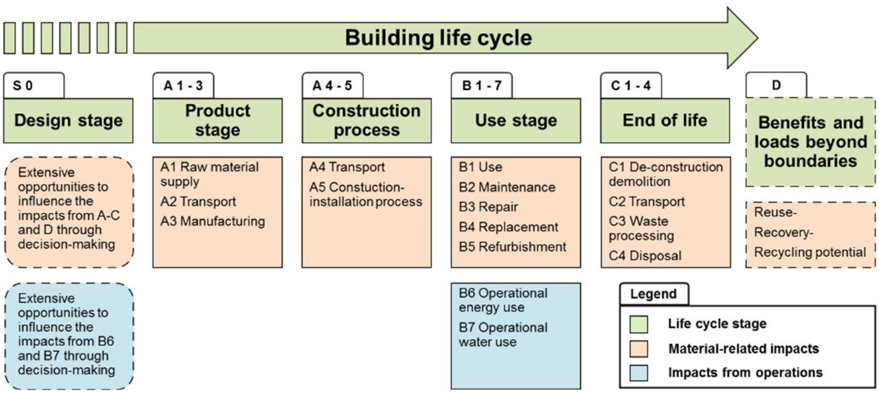

Figure 2, the sources of material-related and operations-related environmental impacts over the life cycle of a building, as understood in this dissertation. The naming of the life cycle stages and the sources of environmental impacts is adopted from EN 15978 [4]. Contrary to the standard, the design stage is included in the life cycle.

2.1 Life cycle impacts of design stage decisions

The design stage of a building project offers extensive opportunities to influence the environmental impacts of a building through decision-making on building systems,

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[4] The phrase ‘sources of environmental impacts’ refers to the EN 15978 life cycle ‘modules’. For example, for the product stage, the environmental impacts come from the ‘modules’ of raw material supply, transportation and manufacturing. However, using the phrase *sources of environmental impacts* is more descriptive for the purpose of this dissertation than using the term *module*.

structures and materials. It seems that ideally, sustainability requirements should be taken into consideration from the early stages of design, where they could complement functional and technical requirements [29]. However, this does not seem to be the case today, and for example embodied energy and embodied carbon are not commonly considered in the design and construction of buildings [29], [30]. One explanation for this may be the designers' lack of knowledge about the importance of decisions contributing towards a building's impact [31]. Also, there appears to be a lack of decision support tools that could support the architects and designers to find optimal design solutions for the multiple dimensions of sustainability [32]. In a recent research, Zuo et al. (2017) argue that in order for life cycle assessment (LCA) tools to become more widely adopted in the construction industry, they should be easier to use and applicable to the early stages of design [33]. Similarly, Anand et al. (2017) claim that LCA-based decision-making is still mostly limited to research, and not utilized by building practitioners, due to lack of LCA capabilities in common building related tools [34]. This dissertation sees that informed decision-making during design stage is crucial for lowering environmental impacts of buildings. Furthermore, it sees that it is important to identify, at which stage of design the decisions contributing to material-related GHG emissions are made, and what is the importance of such decisions.

2.2 Lifetime energy use and related emissions of buildings

Research on the lifetime energy use and emissions of buildings has traditionally focused on operational energy and related emissions, and paid less attention to embodied energy and emissions [24], [35]–[39]. Past research and reviews on the topic have suggested that up to 85 to 95% of lifetime energy consumption [25], [38], [40]–[43] could be from operational energy use for conventional buildings.

The research on low energy buildings[5] shows that the embodied energy may form over half of a buildings lifetime total energy consumption [44]–[47] . The increase in the relative share of embodied emissions can be explained through both, lower operational energy demand [48], and through the use of more energy-intensive mate-

[5] Low-energy buildings are understood here broadly as buildings with a low operational energy consumption

rials in building shell and in building systems [26]. The ongoing development towards zero energy buildings[6] further highlight the importance of embodied energy and emissions, as the embodied energy may dominate their life cycle energy use (with a share of 74% to 100% of life cycle totals) [49]. The multitude of definitions for ZEBs is extensively discussed by Marszal et al. (2011) [50], and for the European NZEBs, in Agostino et al. (2016) [51].

The time scale of emissions also highlights the importance of embodied energy and embodied carbon. Whereas the operational emissions take place over several decades, the majority of material-related emissions are emitted over a relatively short period of time. Karimpour et al. (2014) discuss the term *time value of carbon* for the building sector and highlight the importance of considering the life cycle energy use of buildings in the context of greenhouse gas emission reduction targets, which are time dependent [52]. It can also be argued that if embodied energy and GHGs are not taken into account properly, greenhouse gas reduction goals might be compromised in short and medium term [53], [54]. The emission savings of today may also be more valuable than savings in the future. For example, the concept of social cost of carbon, or SCC[7] illustrates this issue. As Nordhaus (2017) states, the SCC of carbon was 31$ per ton (in 2010 US$) in 2015, and it is estimated to grow by 3% annually until 2050 [55]. Also, other reasons for higher value of present day GHG savings are suggested, such as the physical carbon discount rates [56].

The building sector also has a great energy and greenhouse gas savings potential. In general, the greenhouse gas emissions from buildings can be reduced by lowering the operational energy consumption, or the embodied energy of buildings, by switching to low-carbon fuels, and by controlling the non-CO_2 GHG emissions [57]. Thus far, a lot of attention has been directed to reduce the operational energy use, and minimum requirements commonly exist in legislation for new buildings [58]. Whereas the importance of operational energy is now commonly acknowledged,

[6] The definitions for zero energy buildings (ZEBs), near zero energy buildings (NZEBs) or NET-ZEBs (net zero energy/emission buildings) are not discussed here in depth. In short, this dissertation understands ZEBs and / or NZEBs broadly as buildings that try to achieve a zero, or near zero energy (or environmental) balance through a combination of low energy consumption, on-site/off-site renewable energy production, and interaction with the utility grid, over a certain time period. As for NET-ZEB, this dissertation understands them as described above, but with a specified balancing period of one year.

[7] SCC is understood as the change in the discounted value of economic welfare from an additional unit of carbon dioxide equivalent emissions. Thus far, regulations using SCC in economic analysis have distributed over $1 trillion of benefits in the US.[55]

embodied energy and life cycle analyses are still consistently left out from legislation and certification proposals [59], [60]. The embodied energy considerations are also commonly absent in energy assessment and rating methods [48] and embodied energy and carbon are typically not considered when designing and constructing new buildings [30].

2.3 Material efficiency of buildings

As disclosed in the *background* section, consumption of resources always comes with some measurable impacts. *Resource efficiency* can be defined as ways to reduce such harmful impacts over the life cycle of products [9], [61]–[63]. *Material efficiency,* in contrast, is a part of resource efficiency that focuses on reducing the material consumption in material processing and manufacturing processes. For buildings, material efficiency can be improved with several ways, most of which need to be considered early in the design stage. These include: use of lightweight structures, minimisation of material loss, improved durability and longer service life, use of secondary materials and use stage flexibility [64], [65]. In spite of the seemingly great importance of material efficiency (or material savings) on the environment, it is not clear, which are the most significant environmental impacts it has in the context of building materials. This issue can be studied from the viewpoint of scarcity and criticality of resources.

Essentially, scarcity of a resource means that the demand of a resource is, or will soon be, greater than its supply, whereas criticality means that a scarce resource is also essential for the society [66]. These generalizations are used here, as the exact definitions for both critical and scarce resources are still open research questions [67].

The global raw material deposits for traditional building materials, such as aggregates, are practically inexhaustible. However, their supply may be very constrained on a local, regional, or country-level, as shown, for example, for Singapore [68]. Oil and minerals are also common raw materials for building materials, and many countries are dependent on their imports [69]. For oil and minerals, there seems to be an understanding that easy and cheap resources are becoming scarcer. The peak oil is a relatively well accepted concept, even though its timing remains a debated topic [70], [71]. A similar concept, *peak minerals*, has been introduced for mineral raw materials, to describe the impacts of falling resource quality and accessibility, and the reduction in their quantity and availability [72].

It seems that the development towards zero-energy buildings may increase the use of scarce or critical natural resources in the structures, technical systems, and renewable energy systems of buildings. For example, rare earths and critical natural resources are often needed in the production of photovoltaic cells, batteries, and energy-efficient lighting [73]. Also, large scale deployment of renewable technologies, such as photovoltaic cells and wind turbines may increase the global demand of scarce metals [74].

As of today, it remains unclear whether the rare earths, scarce metals, or traditional raw materials are more important for material efficiency of buildings. As Frenzel et al. (2017) argue, the existing assessments of raw material scarcity may be flawed, and traditional materials, such as those needed for steel making, and for the power infrastructure may be defined critical in future assessments [75].

2.4 Resource depletion and abiotic depletion potential (ADP)

From the environmental standpoint, resource depletion refers to the geological, or natural stocks of resources, and it means that a resource's presence is reduced on Earth [66]. The concept of abiotic depletion potential (ADP), introduced in 1995 by Guinée and Heijungs [76], and developed into the *baseline method* in the Dutch LCA handbook in 2002 [77], reflects this problem by taking the decrease of the resource itself as the key problem [78]. The baseline method uses the *ultimate reserves*, which refer to the quantity of a resource that is ultimately available on Earth, in its ADP calculation. The characterization factors for ADP are expressed in Antimony equivalent kilograms (Sb eq kg), and they are available in a database by Oers et al. (2002) [78]. The database has since been updated and maintained by the CML [79] as an online database.

In 2011, the European Commission Joint Research Centre published the ILCD handbook (2011) which gives recommendations for the life cycle impact assessment in Europe [80]. The handbook recommends using the CML characterization factors for the ADP calculation, but instead of the ultimate reserves, it recommends using the *reserve base* figures. The reserve base figures reflect the size of the reserves that have a reasonable potential to become economically and technically exploitable, considering future development [77]. The same approach has been since adopted to the European Product Environmental Footprint (PEF) method [81].

Most recently, the European standards [4], [5] have also adopted ADP calculation within their scope. Interestingly, the standards do not follow the European recommendations, but build on the earlier ADP work. Most important differences between the recommendations of ILCD and PEF, and the standards, are that the ADP calculation of the standards use the *ultimate reserves* for ADP-elements calculation and the lower heat value (MJ/kg) for the ADP-fossil calculation. Drielsma et al. (2016) and Oers and Guinée (2016) offer a thorough review on the history and the ongoing debate of ADP calculation [66], [82]. These differences have also implications on this dissertation, an issue which is further discussed in Section 6.1.4.

3. Conceptual framework, research questions and scope of publications

Buildings add to the environmental pressure of the planet in multiple ways, but the building sector is also one of the most prominent ones, for example, for energy, resource and greenhouse gas emission savings. Environmental impacts of buildings can be reduced with different means. However, there is only a limited understanding about the material-related environmental impacts of buildings and the role of the design stage on these emissions.

Thereby, the central research question, is formulated as follows:

> “What is the quantity and the relative importance of material-related environmental impacts over the life cycle of a building, and what is the role of the design stage in determining these impacts?”.

It is understood that the central research question cannot be answered exhaustively. Therefore, the focus of this dissertation is on the global warming potential (GWP) and on the consumption of material and energy resources (ADP-elements and ADP-fossil). This dissertation also assesses the less-researched topic of life cycle impacts of the design phase.
This dissertation consists of three publications. In practice, each of the publications answers a separate, more focused research question, which together allow to answer the central research question. The conceptual framework in Section 3.1 illustrates how the publications relate to the larger context of life cycle environmental impacts of buildings, and the research questions are listed in Section 3.2.

3.1 Conceptual framework

As discussed earlier, the life cycle impacts of buildings are largely set at the design stage. After buildings are constructed and taken into use, they add to the existing building stock, and the operational stage begins. During their lifetime, buildings are part of the building stock, and their properties may be altered through renovations. Finally, at the end of life, buildings are demolished and removed from the building stock.

The following Figure 3 shows how the publications of this dissertation relate to the larger context of life cycle environmental impacts of buildings. The environmental impacts of energy use, GHG emissions and resource use are divided between material-related and operations-related impacts. Publication I covers the life cycle from the product stage to the end of life (for both material-related and operations-related sources) and focuses on the greenhouse gas emissions. Publication II covers the same life cycle stages, but focuses on the lifetime resource use (again, for both material-related and operations-related sources). Finally, Publication III focuses on the GHG impacts of the design stage decisions (from material-related sources only).

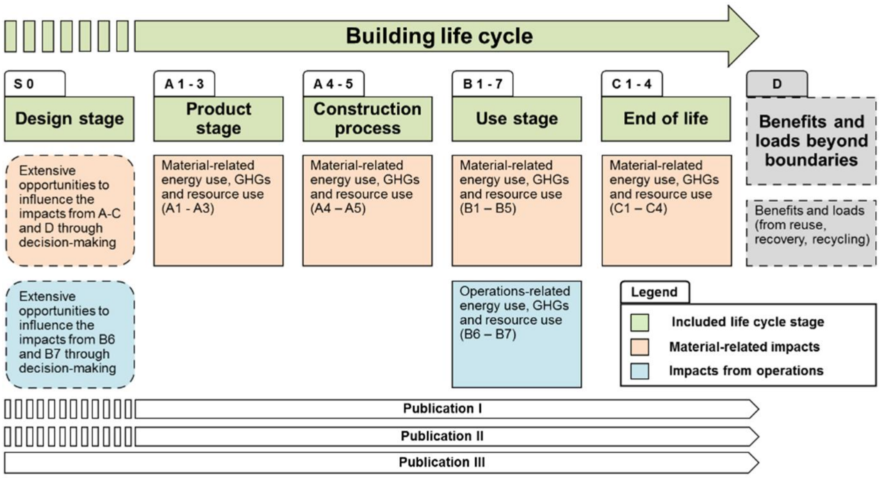

Figure 3. The conceptual framework of this dissertation, illustrating how the Publications I - III relate to the larger context of material-related and operations-related impacts over the life cycle of a building.

3.2 Research questions

As discussed in the preceding sections, this research aims to answer one central question, which is:

> "What is the quantity and the relative importance of material-related environmental impacts over the life cycle of a building, and what is the role of the design stage in determining these impacts?".

This dissertation divides the main question into three more specific research questions (RQs), numbered from one to three. The research goal is to answer these research questions through Publications I to III. The following subsections present the RQs, together with the reasoning behind their selection.

3.2.1 Significance of material-related GHG emissions

As shown in the literature review, past research on the energy use and emissions of buildings has mainly focused on operations, largely neglecting the material-related impacts. However, the development towards low and zero-energy buildings calls for more focus on the material-related environmental impacts. In order to focus the GHG savings actions better, more information about the life cycle GHG emissions of buildings is needed.

Publication I addresses this topic through a life cycle assessment of a case building. It aims to answer one specific research question, which is:

> RQ1: "What is the quantity and the relative importance of material-related greenhouse gas emissions of a building, when considering the whole life cycle of a building, and what are the most important parameters impacting the calculation results?".

3.2.2 Environmental impacts of material efficiency

As pointed out in the literature review, it is not evident, what are the most significant environmental impacts, regarding the material efficiency of buildings.

Publication II focuses on this issue by assessing the abiotic depletion potential (ADP minerals and ADP fossil) for a case building. It aims to answer the following research question:

> RQ2: "What is the quantity and the relative importance of material-related abiotic depletion potential of a building, when considering the whole life cycle of a building?"

3.2.3 Environmental impacts of the design stage

The design stage largely defines the environmental impacts of buildings through the decisions concerning building systems, structures and due to material selection. Despite the great potential to influence the life cycle impacts, for example, embodied energy and carbon are not common considerations during the design stage.

Publication III focuses on this topic through a case study. It aims to answer the following research question:

> RQ3: “At which stage of design the decisions contributing to material-related GHG emissions are made, and what is the quantified impact of these decisions?”

4. Research methods

As explained in the preceding section, this dissertation aims to create new knowledge on the broader, central research question, by answering three more focused research questions (RQs). The research design of this dissertation is in line with this broader aim.

The starting point for the research design and method selection of this dissertation is three-fold. Firstly, it is understood that the research methods of each publication need to fit the purpose of answering their specific RQs. Secondly, this dissertation sees that in order to answer the broader research question, each of the publications need to share a similar research approach and utilize comparable methods for consistency. Finally, this dissertation sees that the research design needs to link the individual publications with each other, in order ensure coherence across publications and to enable common conclusions. The research design and methods are presented in more detail in the following subsections.

4.1 Research design and methods

This dissertation and its three publications utilize a mixed method, or mixed strategy approach that is described in detail, for example, by Denscombe (2008) [83]. The selected method offers a pragmatic research approach, which uses both quantitative and qualitative research methods to answer a pre-defined set of research questions. In short, the approach allows to: answer different research questions, enhance the validity of findings through triangulation, produce a more complete picture of the topic of the research, explain the findings, and utilize the findings better for a holistic picture of the phenomenon under investigation [84], [85].

Each of the three publications share a similar research approach and comparable methods, but apply them from the viewpoint of their corresponding research questions. The key design element of this research is that it links all the individual publications together by utilizing the same real-world building for each of their case studies. The methodological similarities of Publications I to III can be summarized as follows, as each of them:

1. Utilizes a literature review to identify state-of the art and current scientific debate about their specific topic

2. Contains an empirical building case study, which investigates a specific phenomenon in depth and within its real-life context

3. Looks into specific environmental aspects and potential environmental impacts throughout a building's lifetime by using the life cycle assessment (LCA) methodology.

The following table lists the specific research methods utilized in the publications of this dissertation. The methods are further described in the following subsections. As this dissertation utilizes a narrative literature review, as opposed to *a systematic literature review* [53], literature review is not listed here as a research method.

Table 1, Research methods utilized in the publications of this dissertation.

Publication	Research Method		
	Case Study (Quantitative and Qualitative)	Life Cycle Assessment (Quantitative)	Parametric calculation (Quantitative)
Publication I	x	x	x
Publication II	x	x	
Publication III	x	x	

4.2 Case study approach

A case study is an empirical study, which investigates a contemporary phenomenon, the case, in depth and within its real-life context [86]. It is a valuable method, as it allows to contribute towards scientific development through generalization of findings of individual cases, although this is not without debate [87]. For building research, drawing general conclusions from individual cases, and from review articles, is not a straightforward task, due to differences in methodological factors and characteristics between the individual cases [23],[88]. Nevertheless, the case study approach is utilized broadly in the field of this dissertation, as indicated by a number of review-articles based on individual cases [25], [40], [41], [45] and the large quantity of cases reviewed in them (206 cases in [41], for example).

The case study method is utilized in this dissertation, in line with Woodside (2010), [89] for: description, explanation, prediction and control of cases. In practical terms, the method is utilized in Publications I to III to: *describe* a specific case building in detail and *explain* the specific factors impacting the results, to *predict* results for similar cases, and to offer new information to *control* environmental impacts of similar buildings in the future. This dissertation acknowledges the difficulties of drawing conclusions between cases due to differences in methodological factors and characteristics, and utilizes the same case building for each of the individual publications to overcome these issues. The use of a single case building has its own limitations, which are further discussed in Section 6.2.2.

4.3 Life cycle assessment (LCA)

The life cycle assessment (LCA) methodology addresses the environmental aspects and potential environmental impacts (e.g. the use of resources and environmental consequences) throughout a product's life from acquisition of raw materials through production, use, end-of-life treatment, recycling and final disposal (i.e. from cradle to grave). The general principles for assessment of products and services have been agreed in standardization (ISO 14040 and ISO 14044) [90], [91] and more recently in building-specific standards [4], [5]. LCA is widely accepted as one of the best tools for environmental assessment of a variety of products and processes [92].

This research utilizes *attributional LCA,* as opposed to *consequential LCA.* Attributional LCA focuses on describing the environmentally physical flows to and from a life cycle and its subsystems [93], as opposed to consequential LCA, which is designed to generate information about the consequences of decisions [94]. The topic of consequential LCA is continued in section 6.1.2.

More specifically, this dissertation uses process-based LCA, as it's generally recognized as more accurate, although more labour and time consuming than, for example, input-output (IO) analysis [95], [96]. However, the selected method also has embedded limitations [91], [92], [95], [96], which need to be understood when utilizing the method and analysing the results. The process-based LCA is, for example, associated with underestimation of the impacts, as the number of processes and the order of upstream processes are limited [95], and sufficient boundaries may be difficult to cover due to the complexity of upstream processes [96]. For basic building materials, for example, the incompleteness factor, often referred to as truncation error [90] has been estimated to range from 10% [96], to up to 60% for residential buildings [92]. Hybrid LCA, which combines IO models with process-based LCA is widely considered as a more accurate means for LCA [97]. However, for example Yang, Heijungs and Brandão (2017) argue that hybrid LCA does not necessarily improve the accuracy of process-based LCA, as highly aggregated IO models could result in larger relative error than the truncation error resulting from incomplete process model [97]. The process-based LCA is selected for this dissertation as it is deemed to offer the best possible accuracy for building-level LCA, despite of its limitations

This dissertation uses *streamlined LCA*, as it only focuses only on specific environmental impacts and issues [98] (GWP and ADP). LCA is commonly utilized in building research to assess the impacts from life cycle energy use and the GHG emissions of buildings, as shown through review articles on the topic [26], [40], [42], [99]–[103]. However, despite being emphasized in standards for buildings [4], [5], research on ADP is not widely available.

It should also be noted, that even though standardized LCA approaches exist, the modelling choices, such as system boundary definitions, database choices and replacement scenarios have a significant impact on the LCA results, as argued by Häfliger et al. (2017) [104].

The following subsections present the critical LCA choices of this dissertation, and Appendix 1 gives more detailed information on the LCA boundaries and scenarios. The standard EN 15978 is used here as a reference, and the LCA choices are explained with regard to the standard.

4.3.1 General information on the object of assessment and functional equivalent

The object of assessment for the LCA is a multi-storey residential building, including all of its structures, foundations and external works within the site, following the EN 15978. The standard uses the term *functional equivalent* to represent the required technical characteristics and functionalities of a building for the basis of comparison[4].[8] The functional equivalent for this dissertation is defined as follows:

- **Building type:** residential building
- **relevant technical and functional requirements:**
    - Finnish building regulations
    - Six storeys and a basement floor with civil-shelter spaces
    - 28 apartments
    - floor area of 2460m²
    - net floor area of 2080m²;
    - gross area of 3060m².
- **pattern of use:** according to standard use as in regulations
- **required service life:** 50 years.

4.3.2 Description of the case building and alternative scenarios

The case building utilized in this dissertation represents typical residential construction in Finland, as it is a standard design by a well-established contractor with a high production volume. The case building fulfils the requirements for functional equivalency.

The building consists mainly of concrete-element structures. It has a basement floor and a civil defence shelter[9], as mandated in Finnish Rescue Act and Decree [105]. The floor slabs, roof structures, lift shafts, and internal and external walls are all made of concrete elements. The foundations and the base-floor slab are in situ concrete, along with some of the structures of the civil-defence shelter. The building has an energy class ‘A’, according to the Finnish regulation [106], [107]. This dissertation also considers two other functionally equivalent scenarios to the case building. Both of these scenarios and the case building are described in more detail in Appendix 1, in Publication I, and in the appendix of Publication I.

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[8] EN 15978 standard uses *functional equivalent* as the basis for assessment, as opposed to *functional unit*, that is used in ISO 14040, ISO 14044, and in EN 15804.
[9] The construction of civil defence is mandatory for permanently occupied new buildings with a floor area of over 1200 square meters in Finland. The owner of a building has a duty to build civil defence shelters to protect the occupants from the effects of weapons, collapsing buildings, ionising radiation and toxic substances (Finnish *Rescue Act and Decree, Chapter 11)*

4.3.3 Statement of boundaries and scenarios

The system boundary includes the life cycle of the building, as illustrated in Figure 3, and the object of assessment is the building and its site. The assessment covers the processes and operations that take place within the system boundary (Modules A-C, see Figure 2). The system boundaries are discussed in more detail for each of the life cycle stages and their modules in Appendix 1.

4.3.4 Indicators of assessment and expression of results

This dissertation assesses and reports the results for material-related and operations-related environmental impacts over the life cycle of the building, as illustrated in Figure 3. The indicator selection is based on the research questions of this dissertation. The selected indicators include the global warming potential (GWP) and the abiotic resource depletion potential (ADP-elements and ADP-fossil). The data sources for GWP and ADP are shown in Appendix 1.

This dissertation does not address the environmental impacts on stratospheric ozone layer (ODP), acidification potential (AP), eutrophication potential (EP), and formulation potential of tropospheric ozone photochemical oxidants (POCP). This issue is further discussed in Section 6.2.1.

4.4 Parametric calculation approach

Publication I utilizes a *parametric calculation approach*, where the LCA sensitivity analysis (scenario analysis and factorial design [108], [109]) is in central role. The approach allows to assess the impact of selected LCA calculation parameters, which are: alternative production methods and materials, site conditions and location, energy performance of the building, and the role of emission profiles for energy. This calculation approach should not be confused with *parametric LCA approach*, which utilizes a simplified parametric model for the LCA calculation [110].

The parametric calculation approach of Publication I also supports the sensitivity analysis of the whole of this dissertation, as the same case building is utilized for all Publications I to III. The sensitivity analysis conducted as part of discussions and conclusions of section 6.

5. Summary of publications

This section summarizes Publications I – III and their key findings, in relation to the research questions.

5.1 Greenhouse gas emissions of building materials

The specific focus of Publication I was on the quantity of material-related GHG emissions of buildings and on the relative importance of such emissions, in comparison with the total life cycle GHG emissions. Publication I also aimed to create an improved understanding of the significance of different parameters on the total GHG emissions of buildings.

Publication I aimed to answer RQ1:

> “What is the quantity and the relative importance of material-related greenhouse gas emissions of a building, when considering the whole life cycle of a building, and what are the most important parameters impacting the calculation results?”.

The following sections present the key results of Publication I, in relation to RQ1.

5.1.1 Material-related GHG emissions

The results of Publication I found that the building frame is the most significant contributor to the material-related GHG emissions. The role of renovations was found to be the second biggest contributor to the GHG emissions, ahead of groundwork, supplementing structures and construction and renovation work.

Publication I also suggests that the material-related emissions may vary greatly, depending on the selections of materials and structural systems. The results indicate that a similar building could be produced with widely varying GHG impacts. The emissions for the baseline case (1666 tonnes, or 0.54 t/m²) were 1.9 times those of the lower scenario (891 tonnes), and the emissions of the higher scenario (2336 tonnes) were 1.4 times those of the baseline[10]. Finally, the results indicate that soil stabilization, solar-energy and air conditioning installations may add significantly to the material-related emissions. Especially the soil stabilization was found to embody significant GHG impacts in the high scenario, adding almost 1100 tonnes to the totals. It is highlighted there that these items embody high uncertainty, the impacts of which are critically reflected in Section 6. The calculation results are shown in Table 2 that presents the emissions for different building items and the estimated range of variation for each of them from low to high. Further information about the calculations can be found from Appendix 1, and the appendix of Publication I.

Table 2, The embodied GHG emissions for different building items and the estimated range of variation from low to high for each of the items.

Item	**GHG emissions for base-case (tonnes of CO_2-equ)**	**Range of variation for the emissions from low to high (tonnes of CO_2-equ)**
Groundwork and substructures	265	52–545
Soil stabilization	0	0–1080*
Building Frame	582	308–731
Supplementing structures	264	157–313
Building systems	31	23–38
Solar energy and AC installations	0	0–264*
Renovations	281	211–354
Construction, renovation and demolition work	243	140–355
Total	1666	891–2336

* not included in *Total*

[10] The scenarios are named minimum and maximum in Publication I, but the naming is changed here to low and high scenarios. The reasoning for this is explained in Appendix 1.

5.1.2 Relative importance of material-related GHG emissions

Publication I also assessed the lifetime GHG emissions for the case building (with energy class 'A' and a 50-year life cycle) including emissions from material-related sources and from operations. The results show that the building materials are a significant source of GHG emissions. For the baseline, the material-related GHG emissions accounted for 37% of the life cycle total emissions, with a range of variation from 24 to 45% from low to high scenario. More information about the baseline and high and low scenarios is available in Appendix 1. The following Figure 4 illustrates the results.

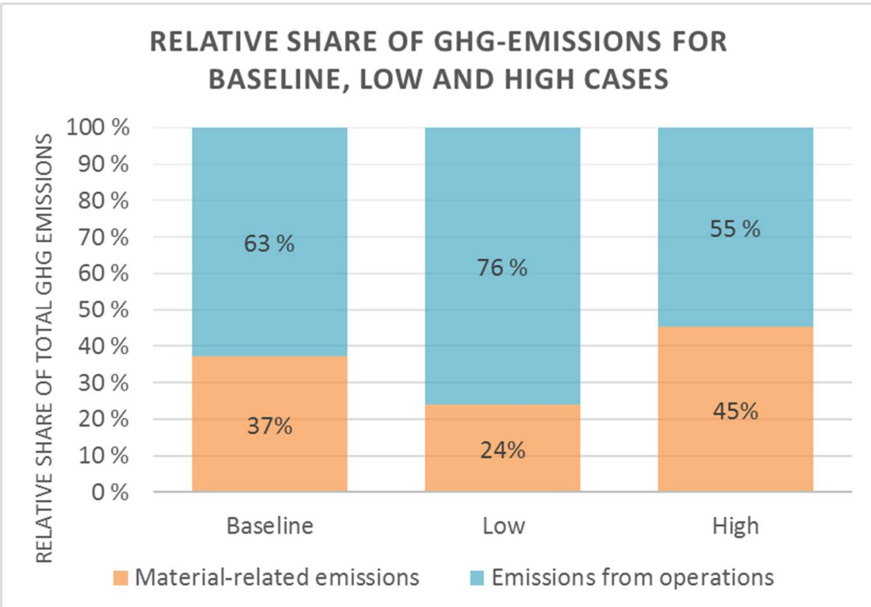

Figure 4, Relative share of GHG emissions from material-related sources and from operations. The results are for the base-case and the low and high scenarios with energy category 'A' structures and a 50-year life cycle. Original figure: Publication I, Figure 3.

5.1.3 Energy performance and lifetime GHG emissions

Publication I also assessed the material-related emissions and the emissions from operations for a passive-level and a near-zero energy scenario. The total life cycle emissions were the lowest for the near-zero-level case and the second lowest for the passive-level case. More information about the calculation scenarios is given in Appendix 1 (specifically under 'Module B6').

The results show that the importance of material-related emissions increases with increased energy-efficiency. As Figure 5 illustrates, the relative importance of building materials increases to 42% of lifetime totals with the passive-level structures, and to 54% with the near-zero-energy structures.

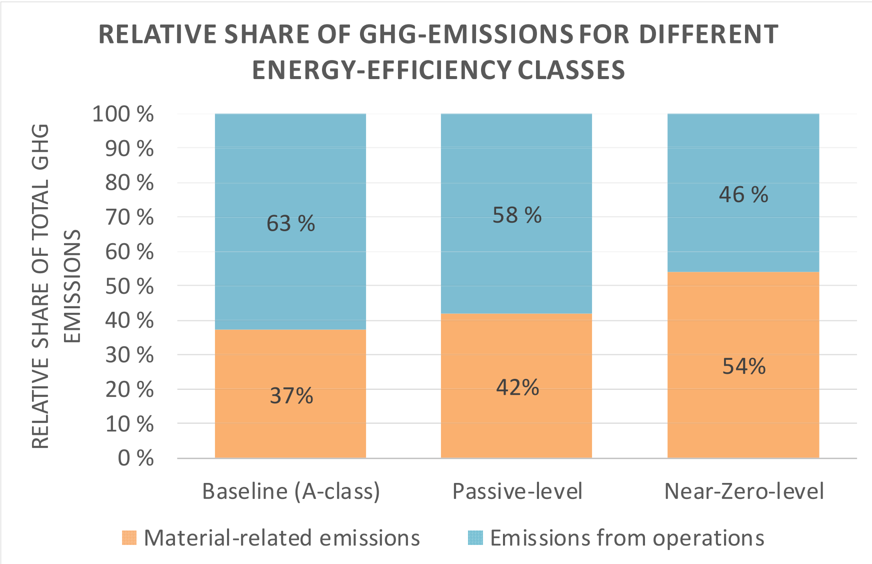

Figure 5, Relative share of the GHG emissions from material-related sources and from operations for different energy efficiency classes. The figure shows the results for the base-case with energy category 'A', and for the passive level and the near-zero-energy structures. Original figure: Publication I, Figure 5.

5.1.4 Emission profile for energy

The role of emission profile for energy was analysed by calculating the life cycle emissions using present-day (2010) emission profiles. The result shows that when the present-day (higher emission) profiles are used, and the future development is not accounted for, the role of material-related emissions becomes less significant. This can be seen from Figure 6, which shows that the material-related emissions contribute to 28 - 41% with present-day profiles, as opposed to 37 - 54% that was shown in Figure 5.

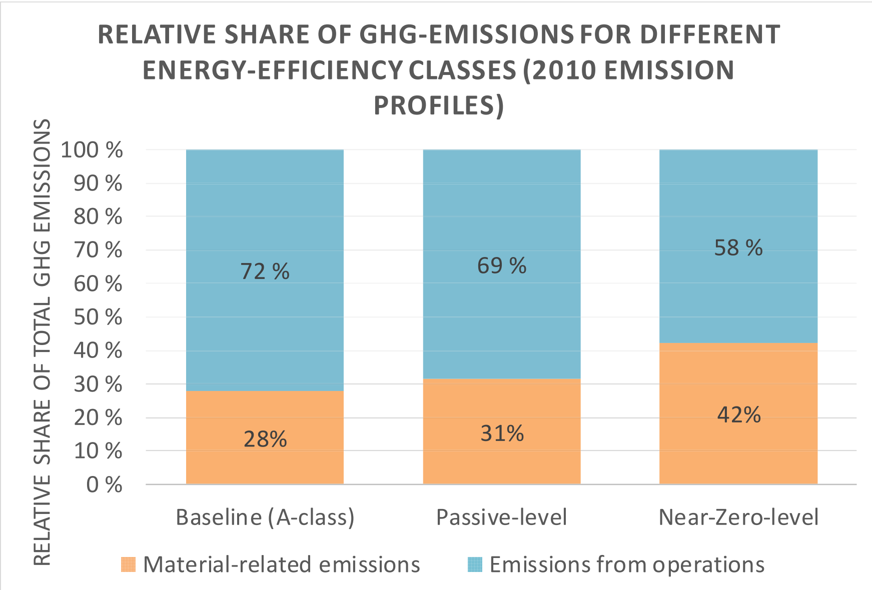

Figure 6, Relative share of GHG emissions from material-related sources and from operations for different energy-efficiency classes and with 2010 emission profiles. The figure shows the results for the base-case with energy category 'A', for the passive level and the near-zero-energy structures. Original figure: Publication I, Figure 6.

5.2 Environmental impacts of material efficiency

As pointed out in the literature review, it is not evident, what are the most significant environmental impacts, regarding the material efficiency of buildings. It was also suggested in the background section that the development towards zero-energy buildings may increase the use of scarce natural resources. The existing standards suggest calculating the ADP for resource depletion, but only limited results are available in the literature. Publication II focuses on these issues and answers the following research question:

> RQ2: “What is the quantity and the relative importance of material-related abiotic depletion potential of a building, when considering the whole life cycle of a building?”

The following sections present the key results of Publication II, in relation to RQ2.

5.2.1 Depletion of abiotic material resources

The case study of Publication II aimed to create new knowledge on the quantity and the relative importance of different building materials in terms of their abiotic depletion potential (ADP-elements). The results show that basic building materials have only a minor effect on the results when assessed in terms of ADP-elements. The results are dominated by the ADP of aluminium and copper that account for under 1% of the total weight of the building. The results also indicate that the ADP of advanced building systems and solar panels may be far greater than that of the basic building materials.

The following Table 3 shows that the total need of building materials over a 50-year life cycle for the case building is 4960 t, or 1.62 t/m². It also shows that the production of building materials requires a total of 7320 t of abiotic inputs, or 2.39 t/m². Furthermore, the table shows that the building-level abiotic depletion potential, over the lifetime of the building, is 1.05 kg of Antimony equivalents, or 0.34 g/m². The results for advanced building systems and solar panels (not included in Table 3) suggest an ADP-elements of 180 to 180 000 kg (Sb eq), for the case building, which is significantly higher than that of the basic building materials.

Table 3, Total mass of materials (t), total abiotic material inputs (t) and total ADP of materials (kg Sb eq) for the case study. Original tables: Publication II, Table 1 and Table 3.

Material	Total mass of materials (t)	Total abiotic material inputs (t)	Total ADP of materials (kg Sb eq)
Aluminium	29	142	0.46
Concrete	3549	5016	0.04
Copper	4	26	0.49
Fossil materials	90	256	0.00
Gravel	629	1202	-
Other minerals	337	254	0.00
Steel	83	291	0.05
Wood	42	5	0.00
Wood boards	200	129	0.00
Soil Stabilization	1420	3500	0.53*
Total	4960	7319	1.05

*Not included in totals

5.2.2 Depletion of fossil energy resources

The case study of Publication II also aimed to create new knowledge on the importance of different building materials in terms of their depletion potential for fossil energy resources (ADP-fossil). It also assessed the importance of material-related fossil energy depletion in relation to the fossil energy depletion from the operational energy use. The results for material-related ADP-fossil are shown in the following Table 4.

Table 4, Total mass of materials (t), total fossil energy inputs (t) and total ADP of fossil energy (GJ) for the case study. Original Table: Publication II, Tables 2 and 3. Construction work value from Publication II, section 5.5.

Material Specification	**Total mass of materials (t)**	**Fossil energy inputs per material ton (GJ/t)**	**Total ADP-fossil (GJ)**
Aluminium	29	37.0	1090
Concrete	3549	0.8	2720
Copper	4	17.5	75
Fossil materials	90	85.6	7700
Gravel	629	0.1	40
Other minerals	337	3.7	1260
Steel	83	15.7	1300
Wood	42	0.6	30
Wood boards	200	8.7	1730
Soil stabilization	1420*	-	6400*
Total	4960	-	15900

***Not included in total**

The results show that the fossil materials are the biggest contributor towards depletion of abiotic energy resources, followed by concrete. Publication II also showed an ADP of 2400 GJ for the material transportations and construction work, giving a total of 18300 GJ for the material-related ADP-fossil.

The following Table 5 summarizes the total material-related emissions for the building (including the ADP-fossil of Table 4 and the ADP-fossil of transportation and construction work), and the ADP-fossil from operations. Table 5 shows that the material-related ADP for the case building is 18300 GJ (5.9 GJ/m²), and that the operations-related ADP is 38700 GJ (12.6 GJ/m²). The results also show that the share of material-related fossil-energy consumption accounts for some 30% of the life cycle totals.

Table 5, Total mass of materials (t), and total ADP of material-related sources (GJ) for the case study. Original table: Publication II, Table 2. Construction work value from Publication II, Section 5.5.

	Total mass of materials (t)	**Total ADP of materials (GJ)**
Material-related sources	4960	18300
Operational energy	-	38700
Total	4960	57000

5.3 Environmental impacts of the design phase

Publication III aimed to identify, at which stage of design the decisions contributing to the material-related GHG emissions are made, and what is the importance of such decisions, in terms of the GHG emissions.

Publication III aimed to answer RQ3:

> RQ3: "At which stage of design the decisions contributing to material-related GHG emissions are made, and what is the quantified impact of these decisions?"

5.3.1 GHG emissions over the design process

Publication III suggests that in order to design buildings with low greenhouse gas emissions, or with low *carbon footprint* (CF)[11], planning for low-carbon solutions must start early in the design stage, and the planning should proceed gradually and in a systematic way. Publication III finds that during the design process, the carbon footprint calculations change their purpose from *setting target values* in the early stages to calculating *specific values* at the latter stages. This is due to two factors.

[11] The term carbon footprint, or *CF* is used in Publication III as a synonym for material-related greenhouse gas emissions of a building, over the whole life cycle of a building. The calculation follows the system boundaries that are described in more detail in Appendix 1.

Firstly, the coverage of the CF calculations gets better as more design options are locked in. Secondly, the accuracy of calculations improves as general-level CF data of the early phases of design can be replaced with more specific product data in the later phases.

5.3.2 GHG emission impact of different design phases

Publication III shows the relative share of the total material-related GHG emissions for each component of the case building. In addition to this, it ties the results together with the design phase, in which the main decisions are made regarding these components. Effectively, the results indicate how large a share of the total material-related GHG emissions is locked in in each of the design phases.

Table 6, The relative share of the total GHG emissions for different building components, together with the design stage at which the decisions are made relating to these components.

Source of GHG emissions	Relative share of total GHG emissions[a*]	Design phase (by RIBA PoW and ARK12)[b]
Yard structures, foundations, piling, excavations and backfills, bottom floor slab	16%	Strategic definition and preparation
Building frame	35%	Concept and developed design
Supplementing structures	16%	Concept and developed design
Construction, renovation and demolition work	14%	Concept and developed design
Building systems	2%	Technical design
Renovation and refurbishment	17%	Technical design

a based on results obtained through the case study
b based on interviews
*total GHG emissions for the case building 1670 t (CO_2 eq)

The results of Table 6, show that the *strategic definition and preparation* locks in some 15% of the total material-related emissions, the *concept and developed design* some 65% of them and the *technical design* the remaining 20%. The results are further discussed in Section 6.

6. Discussion and conclusions

This dissertation had one central research question, which was formulated as follows:

> "What is the quantity and the relative importance of material-related environmental impacts over the life cycle of a building, and what is the role of the design stage in determining these impacts?"

This dissertation focused on selected material-related impacts of buildings, by addressing the global warming potential (GWP) and the consumption of material and energy resources (ADP-elements and ADP-fossil). It also assessed the less-researched topic of the life cycle impacts of the design phase. Each of the publications of this dissertation created new knowledge on the central research question from their individual viewpoints by answering their separate, more focused research questions. The following subsections critically discuss the research methods, and the results of GHG and ADP calculations. They also give suggestions about generalization of the findings.

6.1 LCA system boundary

The selected LCA calculation method, system boundaries and scenarios have a great impact on the results of this dissertation. A recent research by Säynäjoki et al. (2017) finds that the methodological and other choices by the LCA practitioner cause the majority of the variance in building LCA results. The authors also highlight the importance of the documentation of LCA choices of individual cases to enable well-informed policy-making [111]. Whereas Appendix 1 of this dissertation gives detailed information about the LCA boundaries and scenarios, this section critically reflects the impacts of the LCA choices on the results. This section uses the naming of the modules of the EN 15978, and assesses the differences between the approach of this dissertation, and that of the standard.

The system boundary of this dissertation deviates from the standard, for Modules A1-A3, as it also includes the impacts of domestic appliances and some of the non-building related furniture, fixtures and fittings. The impact of this deviation on the initial embodied GHG emissions is at the level of 1% of the total material-related emissions, based on data of appendix of Publication I. This selection of the boundary has also implications on Modules B3 to B5, through the life cycle renovations of these items. Concerning the results of GHG emissions from renovations, the system boundary selection increases the emissions from these modules by approximately a third[12], as compared to the standard. As a result of these LCA choices, the material-related impacts of the base-case of Publication I are some 7% larger than with the EN 15978 system boundary. The impact of the system boundary differences on ADP calculation results are not assessed here in detail, but they are estimated to be of a similar scale.

Module B6 also deviates from the standard, due to the Finnish regulation that sets requirements not only for the building integrated technical systems, but also for non-building related appliances. Therefore, the system boundary of B6 also includes the non-building related appliances (e.g. plug-in appliances, refrigerators and washing machines). This choice increases the operational energy consumption and GHG emissions. Effectively, the system boundary choice doubles the life cycle electricity consumption, as compared to the standard. The impact of this system boundary choice can be seen from the figures of Appendix 1, Table 3. The figures of the table show that halving the electricity consumption would decrease the building level operational energy consumption by 20%, and the GHG emissions from operations by 12%[13].

One notable exclusion was made for Module 7, as compared to the standard, as the pre- and post-treatment of water was not included in the assessment. A simple assessment, using publicly available per capita emissions for the Helsinki capital region for pre- and post-treatment of water[14], suggests that the total emissions for the case building would be at the level of 200 tonnes for the 50-year life-cycle. When comparing this to the emissions from the operational energy use of the base-case, 2820 tonnes, it seems that the inclusion of pre- and post treatment of water could add some 7% to the total operational emissions. The result suggests that water-savings have a potential for meaningful GHG emission savings over the building life

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[12] See appendix of Publication 1 for more details. The wood chip board in Tables 4 and 6 is from furniture, that is not included in the standard's boundaries

[13] The difference between these figures is explained by the lower GHG emission factor for electricity, than for the district heat.

[14] Pre-treatment and supply of water: 0.8kg (CO_2e) /inhabitant (per year), post-treatment of water 74kg (CO_2e)/ inhabitant (per year), number of inhabitants 53 (see appendix of Publication I), life cycle 50 years

cycle. However, for further conclusions and deeper analysis, more research would be needed.
For the end of life, only the demolition energy was accounted for. This means that the transportation (C2), collection of waste fractions and processing of waste for reuse, recycling and energy recovery (C3), and waste disposal (C4) at the end of life were left outside the scope of this dissertation. Effectively, this system boundary selection means that the demolished building materials would be left at the building site at the end of life, an unrealistic assumption. The reason for this choice was that also the Module D was excluded from the system boundaries, as recommended by the standard. The author sees that as no scenarios were prepared, for example, for energy use or recycling of building materials after the end of life (Module D), it was not reasonable to include Modules C2-C4 that are dependent on these scenarios. The author sees that the impact of this system boundary choice is minimal for this dissertation. However, inclusion of Module D could have larger implications on the results, depending on the scenarios.

6.1.1 Relative importance of material-related GHG emissions

The results of this dissertation show that the material-related GHG emissions account for a significant share of a building's lifetime GHG emissions. As shown in Publication I, the material-related GHG emissions were 37% of the life cycle total emissions for the base-case. For the near-zero energy case of Publication I, the material-related emissions were 54%. The results are in line with past research that shows that embodied energy may be responsible for over 50% of the lifetime total emissions [44], [45], [47], and could rise to 74% to 100% for zero-energy buildings [49]. As of today, the design and assessment of zero energy buildings still largely focus on the operational phase, and ignore the embodied environmental impacts over the building life cycle [29]. A way forward could be a methodological framework that would take the life cycle energy balance into account, such as the one proposed by Cellura et al. (2014) [112]. The past research also suggests that information about embodied impacts of key building components can guide designers towards significantly lower GHG impacts [113]. Furthermore, it is suggested that identifying which impacts are most important to consider, and which ones can be considered in early design with limited information, is vital [33]. This is where the value of this dissertation lies in. Effectively, the results can help to increase the awareness about the embodied emissions, and to direct the focus towards the key items for emission

reductions. However, the author sees that the GHG emission targets need to be included in the owner's goals for a specific project, or else the savings potentials will remain theoretic considerations.
The results of this dissertation suggest that the most significant design decisions affecting GHG emissions are made early on in the design process and that planning for low-carbon solutions should proceed gradually and systematically. From the viewpoint of lowering the material-related GHGs of future buildings, it is important to understand, how these embodied GHGs are divided between the structures and what kind of savings potentials the utilization of alternative choices possess.

6.1.2 GHG savings potential

The results of Publication I showed total material-related GHG emissions of 1666 tonnes (or 0.54 t/m²) for the case building. This result falls within the broad range of variation (from 0.03 to 2.00 t/m²) of past LCAs in the field, as shown in a recent review [111]. This section critically discusses the results and GHG savings potentials for different building components.
The structures of the case building were based on the actual design of the building, and the material quantities were extracted from the original building information model. The quantities that were included in the original model are considered high quality data with low uncertainty. On the other hand, the structures that were not included in the model, are based on estimates, and therefore embody more uncertainty.
The following Table 7 (based on Publication I Table 8), compares the material-related GHG emissions of the base-case to the low emission case and illustrates the potential GHG savings between the two cases as savings percentages. The table suggests that groundwork and substructures possess a great savings potential (80% for the case building). Effectively, what this figure indicates is that the site selection may have a crucial role in GHG emissions, as good quality sites can lead to significantly lower GHG emissions than poor-quality sites. At the same time, it implies that when building on poor quality sites, the GHG emissions from groundwork and substructures should be high on the agenda for designers and owners, when aiming for GHG reductions.
For the building frame, the case study of Publication I showed that alternative structural systems can produce functionally equivalent buildings with significantly different GHG emissions. As the supplementing structures (balconies, etc.) go largely

hand in hand with the building frame, the same conclusions apply to them. In the case of Publication I, the comparison was made between concrete and timber structures. It is highlighted here that the results show no preference for one material over another. Moreover, the main result is that very different level of emissions can be achieved through design choices related to the building frame. For example, the emissions of the case building could also be lowered by using lower emission concrete mixes. It is also emphasized here that decisions that would result in larger-scale changes in the way that buildings are constructed in society, would also have consequences outside the life cycle of a single building. Effectively, accounting for these consequences would require modelling of causal relationships originating from the decisions, meaning consequential LCA could be needed (see for example [94] for consequential LCA). These themes offer valuable research topics for the future.

The relative importance of building systems on building level is very low, leading to low GHG savings potential. Based on the results, it seems that the focus of GHG reductions should be on the energy-efficiency of these systems, not on their embodied energy. However, the situation is not that clear for advanced building systems, such as solar PV systems. Publication I suggests that solar PV systems could have a relatively high embodied impact, an estimated 80 tonnes for the case study. The estimate embodies a relatively high uncertainty, but some conclusions can still be drawn. Since Publication I, Nugent and Sovacool (2014) have conducted a critical meta-survey of the life cycle GHG emissions of solar PV and wind energy studies (153 in total) that offers some indicative information on the issue [114]. Their central finding is that these systems are not emission free, but for example solar PV emits 1 to 218 g of CO^2-eq/kWh (with a mean of 50 g) over their life cycle[15] through embodied emissions. When utilizing solar PV in buildings, it is important to note that the energy mix of the production country dictates the variation in emissions. This highlights the importance of the procurement process, as PV panels are not all equal in terms of their GHG emissions. In extreme cases, the emissions from PV-produced energy may even exceed the emissions of national electricity production (see for example [115] for European emission factors for electricity).

For renovations, the uncertainties are again quite high. The renovations are explained in more detail in Appendix 1 and in the appendix of Publication I. In general,

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[15] As shown in Appendix I, Publication I utilized a very similar figure, 47g (CO_2e) /kWh

it is noted here that the replacement of furniture, fittings and surfaces may contribute to a large share of GHG emissions from renovations. Therefore, selecting low-carbon alternatives for these items throughout the building life cycle seem to add up to significant savings over time. The construction, renovation and demolition work also embody relatively high uncertainty. However, the results suggests that these items cannot be omitted from the life cycle assessment, and their emissions should be minimized during the construction process stage, as they have building-level significance.

Table 7, Embodied GHG emissions for different building items for the base-case and for the lower emission case. The difference between the GHG emissions of the base-case and the lower emission case is expressed as a savings percentage (%) for the embodied GHGs, on both item and on building level.

Item	GHG emissions for the base-case (tonnes of CO_2-equ)	GHG emissions for the lower case (tonnes of CO_2-equ)	Embodied GHG savings on item level, lower scenario vs. base-case (%)	Embodied GHG savings on building level, lower scenario vs. base-case (%)
Groundwork and substructures	265	52	80%	13%
Building Frame	582	308	47%	16%
Supplementing structures	264	157	41%	6%
Building systems	31	23	26%	0%
Renovations	281	211	25%	4%
Construction, renovation and demolition work	243	140	42%	6%
Total	1666	891		47%

6.1.3 Abiotic depletion potential

The ADP-elements calculation of Publication II resulted in a total of 1.05 kg of Sb eq. Comparison of results to past research is difficult, as detailed ADP assessments of buildings are not widely available. However, a white paper by PCI, an industry association for concrete, presents LCA results for mid-rise concrete buildings in the US [116]. The white paper finds that the ADP varies between 1.66 to 2.02 (kg Sb eq) for in-situ and precast concrete buildings. A more recent research focusing on South Korea that utilizes a hybrid-LCA model, finds the material-related, or direct, ADP to be zero for their case building with concrete structures [117]. These limited examples from literature seem to indicate that the ADP of other concrete buildings is of similar scale than that of Publication II.

The result of the material-related ADP-fossil for the case building was 18,000 GJ (5.9 GJ/m²). Research on similar buildings is again limited but, for example, results of two residential buildings with concrete frame and floor area of 1200 m² in Sweden, show an embodied energy of 4.6 to 5.4 GJ/ m²[118], as summarized in [25], indicating similar levels of fossil energy consumption than in Publication II. The results also suggested that the material-related ADP-fossil was about 30% of the total lifetime ADP-fossil. The share of the material-related ADP-fossil is of the same magnitude, than the share of material-related GHGs, in comparison to the total lifetime GHGs (24 to 47%, as shown in Publication I). The result is largely explained by the close link with consumption of fossil fuels for both, ADP-fossil and GHG emissions. The correlation of these indicators is further discussed in Section 6.2.1.

6.1.4 Database choices

In a recent review article Martínez-Rocamora, Solís-Guzmán and Marrero (2016) list the main obstacles for evaluation of the environmental impacts of construction materials. These obstacles include: 1) a mismatch between the construction project location and the location in which the LCA database was made, 2) unsuitability of the data to the building project conditions and 3) lack of transparency [119]. This dissertation used VTT's ILMARI® database [120] as the source of its emission data, to overcome these obstacles. The ILMARI®-database offers Finland-specific building material LCI data, and covers the materials of the case building well. However, the database is non-transparent, as it does not offer full documentation of the processes, their sources, inventories and flow diagrams to the public. As the database is owned by the author's organization, the transparency was not a critical issue for the author. The database is presented in Appendix I, section 'ILMARI®-database (GWP calculation of materials)' on general level. In order to reproduce the results of this dissertation, the emission factors used in the dissertation are available in the appendix of Publication I.

For Publication II, two different databases were required, one for the building material LCIs, and the other for the ADP characterization factors. ELCD 3.0 database was selected as the source of the LCI data due to multiple reasons. Firstly, the representativeness and transparency of the database are good, as it contains European-level data and offers adequate documentation. Secondly, the LCI database contains the necessary data for ADP calculation, as it offers data on non-renewable material flows, non-renewable element flows and non-renewable energy resources from the ground. Finally, the database is also free to access.

It is highlighted here that even though the selected database was evaluated as the best one available, it does not mean that it was an ideal choice. For example, the selected database (as generally every other database) is limited in its materials, and it does not cover all the possible material configurations. Effectively, for Publication II this meant that 'a best fitting' process data set needed to be chosen to represent each of the materials of the building. For example, for the concrete structures, the *'Pre-cast concrete;minimum reinforcement;production mix, at plant;concrete type C20/25, without consideration of casings (en)'* of the ELCD database[121] was chosen to represent all the concrete structures of the building. The case was similar for other materials, as all the materials are grouped under broader material groups, and then modelled with the most suitable LCI from the ELCD 3.0 database. The full list of materials used in the ADP calculation, together with the ELCD database materials used for their modelling, is presented in Appendix 1, Table 2.

The ADP characterization factors were taken from the CML-IA-database [79]. The database lists characterization factors for the economic reserve, reserve base and ultimate reserve figures (in kg Sb eq), along with the lower heating values for fossil fuels (in MJ/kg). The development history of ADP, presented in Section 2.4, has a direct impact on this dissertation. Publication II was published prior to the EN 15978 [4], based on its final draft FprEN 15978 [122]. The final draft did not explicitly state which ADP factors to use, as opposed to the final standard that includes the factors in its normative Annex C. Therefore, Publication II utilized the reserve base figures, as recommended in the prevailing guidelines of the time, as opposed to the ultimate reserve figures, recommended in the EN 15978. The implications of this on the results of Publication II are discussed in the following.

As Publication II noted, the differences between the reserve base and ultimate reserve figures can be significant. For example, for copper, the reserve base figure is two times bigger than that based on the ultimate reserves. For iron, it is 30 times bigger, and for aluminium, 23,000 times bigger. What this means is that in comparison to the standard, Publication II overestimates the ADP of single elements by a factor of 2… 23,000. However, when assessing how this impacts the ADP results of this dissertation that were shown in Table 4, the difference is less dramatic. When using the ultimate reserve figures[16], the ADP of the building is 0.27 kg, as opposed to the 1.05 kg of Publication II.

Publication II also suggested an ADP of 180 … 180 000 for the solar energy systems, depending on the panel type. For these systems, the selection of the ADP characterization factor has a bigger impact. If the ultimate reserves figures are used, the results will change dramatically, to 30… 70 kg. Especially the higher estimate is very sensitive to a single material, as Indium has a dominating contribution to the ADP results. The detailed ADP data for solar cells is presented in Table 1 of Appendix 1. As stated in Appendix 1, the results on solar panels embody high uncertainty.

6.2 Generalization of findings

The findings of this dissertation are mainly based on a single case study building, and only on a few selected environmental impacts. Even though this dissertation also reviewed the recent literature on the topic, and conducted semi-structured interviews of principal designers as part of Publication III[17], this does not remove the dependency on the single case. The following sections reflect the results in this light, and discuss how representative the results are in the broader national and international context. The following also discusses how the results can be applied on a more general level.

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[16] With ultimate reserve figures, the impact shown in Table 4 for aluminium is zeroed, the impact of copper is halved, and the other values are staying at or near zero, resulting in total ADP of 0.27 kg.

[17] Semi-structured interviews of principal designers were conducted as part of Publication III. More details on the interviews are available in the publication.

6.2.1 Conclusions about other environmental indicators

This dissertation addresses only the environmental impacts of GWP and ADP (both ADP-elements and ADP-fossil). Effectively, this dissertation covers only three of the seven environmental impact indicators of the EN 15804 standard [5]. However, it seems that based on correlation of environmental indicators, some conclusions can be drawn about the other environmental indicators. In a recent publication focusing on statistical approach to identify clusters of uncorrelated indicators for existing LCIA methods, Lasvaux et al. [123], concluded that it seems possible to reduce the dimension of each LCIA to 4 - 6 principal components. Related specifically to this dissertation, the authors find that the indicators of ADP-fossil, GWP, AP and POCP correlate with each other and fall under the same principal component. The research also found that ADP-elements falls under its own component, uncorrelated with the other indicators. Effectively, this suggest that the results of this dissertation on GWP and ADP-fossil may also reflect the AP and POCP of the assessed case building. However, this dissertation offers no basis for conclusions on the EP or ODP of the building.

On the other hand, the correlation between the ADP-fossil and the GWP gives a reason to question, whether or not the calculation of these both is needed. The author sees that intuitively, it may be hard to draw conclusions between kilograms of CO_2eq emissions and MJ's of energy, and both may be needed, depending on the purpose of the LCA assessment.

6.2.2 Use of a single case building

This dissertation utilized the same case building for all of its publications, suggesting that the results are highly dependent on the properties of the case building. The use of a single case gives also a basis to question, how well the case building represents the new construction in broader terms. Whereas the sensibility and variability of the case study have already been addressed in the previous sections, the representativeness of the case building, in comparison to typical new construction, has not been analysed yet. This section critically discusses the representativeness of the selected case from material-related and operations-related viewpoints. The case building type and its main materials are first discussed in the Finnish country-level context. Second, the energy performance of the case building is critically assessed, in order to estimate if it is up-to-date with current energy regulations and typical housing production.

The case study building is a standard multi-storey residential building with concrete structures, constructed by a well-established contractor with high production volume. As such, the case is estimated to represent prevailing cost-optimal methods for construction of multi-storey residential buildings in Finland with high confidence. In order to better understand the representativeness of the building on a national scale, the share of this specific building type in new construction of residential build-

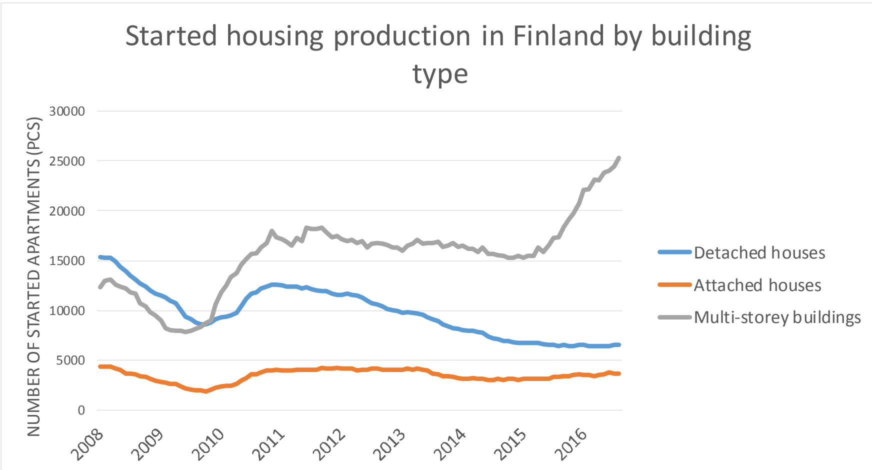

Figure 7, Started housing production in Finland by building type, number of started apartments (pcs), rolling 12-month average, data source [124].

ings in Finland is needed. The statistics show that multi-storey concrete buildings account for a large share of the Finnish housing production. Figure 7 illustrates how the housing production in Finland has increasingly focused on multi-storey buildings in recent years. Based on the official Finnish statistics [124], the share of multi-storey buildings has increased from 40% in 2008 to 70% of total in 2016, when measured with the number of started apartments. On European level, the share of people living in multi-storey residential buildings varies greatly by country, but on average some 42% of people in the EU-28 lived in this building type in 2015, according to Eurostat [125].

The selected case building has pre-cast concrete as its main building material. Multi-storey buildings may be built with different building materials and methods, but as of today, concrete is the main material in multi-storey construction in Finland. In spite of recent increase in interest towards wooden multi-storey buildings, wood is still used in less than 10% of the new multi-storey buildings [126].

Taking into account these material-related considerations, the selected case building is estimated to offer a good basis for generalization of results on country-level.

Publication I was submitted for publication already in 2013, and the selected case building represented typical housing production of that time. The energy efficiency class of the building was 'A', according to the regulations [106] of the time of its design. However, new regulations have been implemented [127] since, with renewed requirements for the calculation of energy efficiency classes. Effectively, the new regulation uses energy efficiency figures (kWh_E), in which the amount of purchased energy (kWh) is multiplied with a specific conversion factor, depending on the type of energy use. For example, for district heat, the conversion factor is 0.7, and for electricity, 1.7. Based on these factors, and on the energy consumption of the case building (shown in Appendix 1, Table 3), the 'A'-class building of Publication I ends up very close to current class 'C' building, only just falling to class 'D'. Similarly, the passive-level building qualifies as a class 'C' building, and the near-zero building as a class 'B' building, based on current regulation. The author sees that the class 'A' building of Publication I represents the current housing production in Finland quite well, as the current 'C'-class seems to be the prevailing energy efficiency class in new construction[18].

Considering both, the material-related and operations-related properties of the case building, the author sees that the case building represents the current residential housing production in Finland reasonably well. However, drawing detailed conclusions on other building types would require more research (although some information is already available, for example, for Finnish wood-based attached houses [128]). The author also points out that, generalizations to other countries need to be done with caution due to multiple reasons, as summarized for example in [129]. In general, it can be said that in countries with high-emission energy production and high operational energy consumption, the relative importance of material-related emissions is lower than in countries with low-emission energy production and low

[18] The author conducted an indicative study on the issue by assessing energy efficiency data of 20 randomly selected residential multi-storey buildings from four large contractors' housing production (five from each of the four contractors in 12 different cities in Finland). The review was based on sales brochures available online (data collected on June 1st 2017). Out of the 20 cases, one case was worse (class 'B' 2007), one was equal (class 'A' 2007), and 18 were very similar ('C' 2013) to the baseline case of Publication I.

operational energy consumption [130]. The optimal path towards GHG emission reductions for the building sector likely varies significantly from country to country. However, this dissertation sees that material-related GHG emissions are a very relevant consideration, for example for Finland, when aiming for lowering future GHG emissions.

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Appendix 1 - Statement of LCA boundaries and scenarios

This appendix complements the information presented in Publications I to III, and in the appendix of Publication I. The following presents the LCA boundaries and scenarios, in relation to the EN 15978 standard [1]. The impacts of deviations from the standard are discussed in Section 6 of the dissertation.

The product stage and the construction process stage (modules A1 to A5)

Material quantities for LCA

The material quantities of the case-building are based on a bill of quantities extracted from the building information model of the building. The full list of material quantities is available in the background information of Publication I that is appended to the dissertation (after Publication I).

The system boundary deviates from the standard EN 15978, as it also includes the materials for domestic appliances and some non-building related furniture, fixtures and fittings that are a standard part of residential buildings in Finland.

Alternative scenario -light structures

The dissertation also includes a functional equivalent for the case-building, where the original structural types of the case-building are replaced with structures from a structure library for wooden residential buildings [2]. The structures meet the prevailing Finnish building regulations for up to eight storey wooden buildings, and as such, they are estimated to provide a similar performance as the structures of the base-case over the 50-year service life.

Alternative scenario -heavy structures

The dissertation also contains another functional equivalent for the case-building. In this scenario, the case-building was converted to an ‘all concrete’ building, by replacing light external walls and light corrugated steel roof with concrete elements that match the structures that were are elsewhere in the building. Also, a heavier alternative for the hollow-core slabs of intermediate floors were used. In this alternative, thinner hollow-core slabs were utilized, but with in-situ concrete as the surface layer. The author made this selection, as this type of structure has been utilized it in the past in some cases for its time and cost benefits [3].

Minimum and maximum scenario of Publication I - high and low estimates of the dissertation

The minimum scenario in Publication I assumes very good site conditions and light structures. The naming of the scenario comes from its formulation, as it contains the low estimates for each building item, thus leading to minimum emissions for Publication I. However, as there was no intention to find an absolute minimum for emissions, the dissertation refers to the scenario as the 'low scenario'.
The maximum scenario of Publication II assumes poor site conditions and heavier structures. In practice, the high estimates of each building item were grouped together to form the maximum scenario. Similarly to the minimum scenario, the maximum scenario does not represent an absolute maximum, and therefore the dissertation refers to it as the 'high scenario'.

Estimates on the missing quantities for LCA

As stated in Publication I, the building information model of the case-building did not contain information on all the structures, and estimates needed to be prepared on the missing items. The data on yard structures, stabilization, excavation, backfilling, pilings and foundations, were not included in the BIM. In addition to this, the data did not include quantities of the building systems. This section goes through the estimates of these missing items.

Yard structures and stabilization

The emission estimates on yard structures and stabilization were based on a past research by Vares, Häkkinen and Shemeikka (2011) [4] that focused on a project with challenging site conditions, and on the expert opinion of VTT researchers[1]. The size of the yard area was based on plot density ratio of 0,7 (ratio of gross area to the total plot size). This resulted in yard area of 3400m² for the case-building. The emissions estimates for yard structures depend largely on the underlying structural layers required for the final surface, and they were estimated to be (12… 360t) in total. The stabilization scenario was based on the findings of a past research project

[1] The yard structure estimates were prepared by VTT's senior research scientist, and building LCA expert, Sirje Vares and stabilization emission estimates together with Sirje Vares and Principal Scientist, Infrastructure specialist, Mr. Jouko Törnqvist

with poor site conditions. It is emphasized here that the selection was not made to represent a typical project, but to study what is possible when building on poor quality sites. It was estimated, that on poor sites, the whole yard area needs to be stabilized with CaO-cement pillars with 1:1 mixing ratio (a common method in Finland). The usage of the stabilizing mixture is typically between 40 to 140 kg/ pile meter, of which the average of 90 kg/m was used. The total amount of stabilization piles was calculated with a 2x2 m grid and 20 m pile length, resulting in a total of 15 000 m of stabilization piles, with a weight of 1350 tonnes.

Excavations, backfilling, piling and foundations

The estimates on excavations, backfilling, and foundations were prepared as desktop work by the author, by utilizing the building footprint, base floor type and the amount of walls as the basis for work. In short, the footprint of the building (+additional 3m at each side) was used as the excavation area. The level of excavation was set at the level of -3m, to accommodate for the basement floor structures. In addition to this, the foundations under the walls of the building (total of 180m in length) were expected to require a further excavation of 2,5m in width and 1,5m in depth. The foundation type was assumed to be continuous with a cross-section of 0,4m². The backfilling amounts were calculated as the difference between the excavations and the volume of the structures that were built inside the excavated pit. For the foundations, a standard pile size of 300x300 was utilized and the piles were estimated to be 5 - 10m long, with a 2m spacing between them, under the walls of the building. These estimates embody high uncertainty. For the backfilling, it is estimated that the actual amounts could vary by 25% and for foundations by 50%. Even though these have a direct impact on the backfilling quantities, the most important uncertainty related to the backfilling is the usability of the excavated land masses for the backfilling. The range of variation was estimated to be from 100% re-usability (all backfilling done with the excavated land masses) to 0%, (all backfilling materials need to be imported to site). In addition to this, the utilization of the land masses, and amount of excavations and backfilling have a direct impact on the transportation volumes. For the piling, the range of variation was from no piling (for good sites) to excessive piling with 1.5x1.5 m grid and with a pile length of 20m.

Building systems

The building system estimates on ventilation systems [5] and on the electric system estimates [6] are based on theses focusing on similar buildings. The actual water and sewer points of the building have been used as the basis for estimates for water and sewer systems. The pipe quantities were evaluated based on these, and prevailing Finnish regulation[7]. In addition to this, manufacturer documentation has been used to convert the quantities into masses. All in all, the building systems quantities embody relatively large uncertainty, which was estimated to be some 25%.

GHGs for solar energy systems

Solar heat systems are modelled with simple calculation assumptions, based on literature, and on production estimates which are shown in more detail in section 'Near-zero scenario for B6'. The mass of the system is estimated at 50 kg/m², with unit emissions of 160 kg/m², based on literature [8]. The system also includes a hot water boiler, weighing 1000 kg. This is modelled with the profile of steel, contributing to 1.1 tonnes of GHG emissions. The heat transfer fluid of calculations is propylene-glycol (total amoung 200 kg) and its emissions are estimated to be some 1 tonne, based on [9], [10]. The total emissions of the solar heat systems equal to 26 tonnes of GHGs.

The solar PV system dimensions and energy production estimates are shown in section 'Near-zero scenario for B6'. The GHG calculations are based on simplified calculation assumptions. The energy production of panels (368m²*100kWh/m²*50a) is multiplied with a harmonized GHG median for multi-Si PV panels from literature [11], 47 g (CO_2e) / kWh equalling to a total of 80 tonnes of GHGs.

The uncertainty of the GHG estimates of solar energy systems is high due to the simplified nature of the calculations and uncertainties in both material quantities and emission factors.

GHGs for air-conditioning systems

In Finland, air-conditioning is not commonplace in new buildings. However, a simple scenario was prepared to model the possible utilization of separate air-conditioning

units in the apartments of the building. The air-conditioning equipment was assessed with a simple assumption of total weight of 70kg/apartment for the units, which totals 1.8 tonnes for the whole building. Assuming a 20-year life-cycle, the total material consumption over 50 years was 5 tonnes. Further assuming that the whole of the weight would be steel, the GHG emissions would equal to 6 tonnes of GHGs. The type of refrigerant was R410A, with amount of 0,75kg /unit and 1-2 units per apartment [12], based on manufacturer manuals. It was further assumed that half of this amount escapes to the atmosphere over the 20-year life cycle of the air conditioning units (and it is replaced upon maintenance cycles). Also, it was assumed that 25% of the refrigerant escapes at the end of life [13] Over a 50-year life-cycle, this gives a refrigerant need of 1.5 to 3 kilograms per apartment. Using a GPW of 1975 (kg CO^2e/kg) [14], the emissions per apartment equal to 3 to 6 tonnes, and for the whole building, 80 to 160 tonnes of CO^2e.
The uncertainty of these estimates is high, as the real consumption and leakage of the refrigerant is not known. Also, alternative coolants could be used. For example, for R134 the GWP is 1300 and for R-507, it is 3850 [14], potentially leading to some 50% lower or 100% higher emissions. Therefore, the results relating to air-conditioning are of indicative nature.

ADP for photovoltaic systems and lighting

Calculation of photovoltaic systems used two different scenarios, one with c-Si (Crystalline Silicone) cells and the other with CIS/CIGS (Copper Indium Selenide/Copper Indium Gallium (di) Selenide) cells. The material composition of both cell types was based on a literature source [15]. The composition for c-Si was 74% glass, 10% aluminium, 16% other components (including rare earths). The composition of the CIS/CIGS was 84% glass, 12% aluminium, 4% other components. The 'other components' were further divided into more detailed material composition with another literature source [16], after which the ADP characterization factors were assigned for each of the materials, and the ADP was calculated. For the c-Si the other components included: copper (75%), tin (16%), lead (9%) and Silver (<1%). For the CIS/CIGS these materials included: selenium (32%), indium (32%), molybdenum (14%), zinc (11%), copper (6%), gallium (2%), silver (2%) and cadmium (<1%). The ADP of c-Si was determined mostly by Silver (72% of total ADP), followed by tin (24%), copper (2%) and lead (2%). For CIS/CIGS, the results were dominated by indium (99%), with selene (1%) representing a minority share of ADP results. It is highlighted here that the calculation embodies high uncertainty and sensitivity and provides only indicative results. The ADP of solar cells is shown in detail in Table 1.

The ADP of energy efficient lighting was based on the number of lighting points in the building, and a simplified assumption that all the lighting points would be equipped with the same type of lamp (T12-type fluorescent lamp). After the material contents of a single lamp were calculated based on literature, the total amount of materials in the buildings lighting systems was calculated by multiplying the amounts of a single lamp with the total number of lamps in the building. After this, an ADP characterization factor was attached to each of the materials of the lamp, and the ADP was calculated for the lighting of the building. Section 5.4.1 of Publication II further explains the calculation.

	c-Si	*CIGS/CIS*	*ADP CF*	*ADP CF*	*c-Si*	*c-Si*	*c-Si*	*CIGS/CIS*	*CIGS/CIS*	*CIGS/CIS*
Material	Mass-%	Mass-%	(RB)	(UR)	ADP (RB)	ADP (UR)	RB/UR	ADP (RB)	ADP (UR)	RB/UR
Silver	0,7%	0,0%	8,42E+00	1,18E+00	5,50E-02	7,74E-03	7	0,00E+00	0,00E+00	
Cadmium	0,0%	0,4%	1,11E+00	1,57E-01	0,00E+00	0,00E+00		3,90E-03	5,50E-04	7
Copper	74,5%	6,4%	2,50E-03	1,37E-03	1,86E-03	1,02E-03	2	1,60E-04	8,75E-05	2
Gallium	0,0%	2,3%	6,30E-03	1,46E-07	0,00E+00	0,00E+00		1,47E-04	3,39E-09	43225
Indium	0,0%	31,6%	5,55E+02	6,89E-03	0,00E+00	0,00E+00		1,75E+02	2,18E-03	80564
Molybdenum	0,0%	13,9%	7,11E-02	1,78E-02	0,00E+00	0,00E+00		9,87E-03	2,47E-03	4
Lead	9,2%	0,0%	1,50E-02	6,34E-03	1,37E-03	5,80E-04	2	0,00E+00	0,00E+00	
Selenium	0,0%	31,9%	7,35E+00	1,94E-01	0,00E+00	0,00E+00		2,34E+00	6,18E-02	38
Tin	15,7%	2,2%	1,15E-01	1,62E-02	1,80E-02	2,55E-03	7	2,58E-03	3,64E-04	7
Zinc	0,0%	11,3%	3,65E-03	5,38E-04	0,00E+00	0,00E+00		4,13E-04	6,09E-05	7
	100,0%	100,0%			7,63E-02	1,19E-02	6	1,78E+02	6,75E-02	2633

c-Si = Crystalline Silicone cells, CIS/CIGS = Copper Indium Selenide/Copper Indium Gallium (di) Selenide cells, ADP CF=ADP characterization factor, based on CML-IA database, RB = Reserve Base, UR = Ultimate Reserve, ADP (RB) = ADP, calculated with Reserve Base, ADP (UR) = ADP calculated with Ultimate Reserves, RB/UR = ratio between the Reserve Base and Ultimate Reserve figures

Table 1, ADP of solar cells

Data sources for the product stage and the construction process stage (modules A1 to A5)

ILMARI®-database (GWP calculation of materials)

The GWP values for building materials of this dissertation are based on VTT's ILMARI® database [17]. The database contains carbon footprint information on Finnish building products, including (A1 to A3), transportation to building site and losses during construction and installation processes. The data is based on environmental declarations published by the Building Information Foundation[2], LCAs for the Finnish building material producers (prepared by VTT), and other high-quality information, such as information from the ELCD (2.0) database. In order to reproduce the findings of this dissertation, the appendix of Publication I presents all the utilized emission factors for each of the materials.

ELCD-database 3.0 (material and fossil energy inputs for ADP calculation)

The ELCD 3.0 database was used as the source of material input and fossil energy input information for ADP calculation. The following Table 2 shows which ELCD 3.0 profiles were used for modelling the materials of Publication II, together with the reference to the profile utilized.

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[2] The original database containg the environmental information has been closed down since the publication, and a new database by the Finnish Building Information foundation has been opened for EPDs. Thus far, it contains eight EPD's: three for asphalts, four for thermal insulations and one for eaves elements (situation as of 1.6.2017). Available online at: http://epd.rts.fi/en/search_for_epd_application

Material	ELCD 3.0 material name	Data source for material inputs and fossil energy inputs
Aluminium	Aluminium Extrusion profile	ELCD/EAA [18]
Concrete	Concrete Pre-cast C20/25	ELCD/PEI [19]
Copper	Copper Tube	ELCD/ECI [20]
Fossil materials	Fossil materials PP granule	ELCD/PEI [21]
Gravel	Gravel #2/32	ELCD/PEI [22]
Other minerals	Gypsum board	ELCD/EGY [23]
Steel	Steel section	ELCD/WST [24]
Wood	Pine wood timber	ELCD/PEI [25]
Wood boards	Particle board P2	ELCD/PEI [26]
Soil stabilization	50% CaO 50% CEMI	ELCD/EUL [27], CEM [28]
ELCD = ELCD 3.0 Database; EAA = European Aluminium Association; PEI = PE International; ECI = European Copper Institute; EGY = Eurogypsum; WST = World Steel; EUL = European Lime Association; CEM = Cembureau		

Table 2, Data sources for ADP material and fosasil energy inputs

CML-IA database (characterization factors for ADP calculations)

Publication II utilizes the reserve base figures of the CML-IA database for the ADP calculation, as recommended in the European guidelines ILCD and PEF. This differs significantly from the EN 15978, which recommends using the ultimate reserve figures of the same database. The implications of this are discussed in section 6.7 of the dissertation.

Finnish emission data for energy

The Finnish energy emission scenario that is used in the calculations, are based on an estimate on the electricity and district heat emissions in years 2010, 2020 and

2030, by the Finnish Ministry of Economic Affairs and Employment[3]. The remainder of the 50-year life cycle (after year 2030) is assessed with the 2030 profile. The emission scenario is based on the Finnish Climate Change and Energy Strategy, prepared by the Ministry of Employment and the Economy. The emission profiles for electricity and district heat are shown in the appendix of Publication I, in Table 11.

An alternative scenario for emission data was also utilized, where present-day (2010) emission data only was used to model the whole building life cycle energy consumption.

The use stage (modules B1 to B7)

The use stage (modules B1-B7) covers the period from completion of the construction work to the point of time when the building is demolished.

Modules B1 and B2

The module B1 is not included within the scope of this dissertation, as it is related to ecotoxicity of construction products, an impact category outside the scope of this dissertation. For module B2, no detailed maintenance scenarios were prepared, for example, for the cleaning of the internal spaces. However, the item is still indirectly included through the inclusion of energy consumption of domestic appliances in module B6.

Modules B3 to B5

For modules B3-B5, some deviations were made from the standard. Similarly to modules A1-A3, the system boundary deviates from the standard EN 15978, by including the impacts of replacements of domestic appliances and some non-building related furniture, fixtures and fittings.

The dissertation also combines the maintenance, repair, replacement and refurbishment (modules B3-B5) under a single title of *'renovations'*. Effectively, modules B3-B5 were assessed with a simple scenario for building component replacements over

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[3] Estimate received from the Ministry of Economy and Employment through communication with Bettina Lemström on 13.4.2012

life cycle. Each building component has an expected number of replacements over the 50-year life cycle. The material quantities for the replacements match the original bill of quantities for those building components. The energy consumption estimates for renovation work was 10% of the initial energy consumption at the construction stage, estimated on mass-basis (mass of renovated structures was approximately 10% of the mass of the whole building). Similarly, the demolition energy for removing the existing structures was estimated to be 10% of the demolition energy at the end of life (Module C1).
The appendix of Publication I (the table below Table 6), shows the number of life cycle renovations for each building component.

Module B6

The use stage energy consumption is based on the energy consumption figures a building with energy class 'A', set by the Finnish regulation. The approach deviates from the standard, as it also includes the building integrated technical systems and non-building related appliances (e.g. plug-in appliances, refrigerators and washing machines). This deviation from the standard approximately doubles the electricity consumption, and therefore also the GHG emissions from electricity production.
The energy consumption and the GHG emissions for the base-case (energy class 'A'), the passive-level scenario and the near-zero energy scenario are shown in the following Table 3.

	ENERGY CONSUMPTION (MWH/50A)			GHG EMISSION FACTOR (KG $CO2_E$/MWH)	EMISSIONS (TN OF $CO2_E$/50A)		
ITEM	Energy class 'A'	Passive level	Nearly zero energy		Energy class 'A'	Passive level	Nearly zero energy
HEATING OF SPACES	5050	3050	3050	203	1030	620	620
WARM WATER	5350	5350	2650	203	1090	1090	540
ELECTRICITY	7650	7650	5800	92	700	700	530
TOTAL	18050	16050	11500		2820	2410	1690

Table 3, Energy consumption and GHG emissions for different energy efficiency scenarios, over the 50-year life cycle

Passive-level scenario for B6

In the passive-level scenario, the thermal insulation of the energy class 'A' building was increased so that the space heating energy decreased to match the Finnish criteria [29] for passive houses (-40% compared to class 'A'). The change in thermal insulation was taken into account in the material quantities of the passive-level building.

Near-zero scenario for B6

In the near zero-scenario, the passive-level building was equipped with maximal solar energy utilization on the roof and on the southern façade. The produced solar energy was presumed to be fully utilized within the system boundary, thereby reducing the need for purchased energy and resulting in no export of energy.
The system calculations for maximal solar utilization scenario were based on a simple scenario, prepared by a VTT expert[4], based on his professional expertise and past projects on the topic. The key selections of the solar utilization scenario were as follows:

- maximising utilization of solar energy by production of solar heat and electricity through roof and façade installations
- maximum feasible solar heat production is 50% of the heating energy need for hot water -> reached with installation of 153m² of rooftop panels
    - the system also requires approximately 4m³ hot water storage
    - solar heat can produce annually some 17,5 kWh/m² (gross area of building) of energy
- remainder of the available rooftop area (14m²) and available surface area on the southern façade (354m²) are dedicated for solar photovoltaics installation equaling to total of 368m² of PV panels
    - annual production is estimated to be 12,0 kWh/m² (gross area of building)

Module B7

[4] Team leader, HVAC expert, Dr. Jari Shemeikka

For operational water use of module B7, only the energy required for drinking water, sanitation, domestic hot water were included. In addition to this, the energy consumption of washing machines and dishwashers were included. The energy consumption was based on consumption figures expressed in the Finnish regulation [30], [31] that contain the energy consumption of all household appliances.
One notable exclusion from the standard was made, as the pre- and post-treatment of water was no included in the assessment. The impact of this is discussed in Section 6.1 of the dissertation.

Scenarios for the end of life (Modules C1 to C4)

Module C1

Publication I used single scenario for deconstruction**.** The demolition energy was based on the mass of the case building and its components, and unit energy consumption for demolition of these components from a literature source [32]. In addition to this, the energy consumption for site functions was assumed to be 30% of the demolition energy consumption.

Module C2 - C4

Publication I did not include transport scenarios, scenarios for waste processing for reuse, recycling or energy recovery, or scenarios for disposal due to lack of data. Effectively, this means that the coverage of the LCA of the case-building ends when the building is demolished and the waste is on the ground at the building site. This issue is further discussed in section 6.

Module D

Loads and benefits from reuse, recycling and recovery beyond the system boundary were not included in the dissertation.

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