Embodied Environmental Impact from Built Environment Development – Focus on Buildings

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Dissertation submitted in partial fulfillment of a *Philosophiae Doctor* degree in Civil Engineering

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Abstract

Buildings are the key components of urban areas and society as a complex system. Traditionally, the emissions embodied in construction materials have not been considered important, in comparison with impacts from the energy use when it comes to mitigating the climate change impact of buildings. Moreover, evaluating the environmental burden of construction materials has proven problematic and the reliability of the reported impact estimates is questionable. Following the multiple case study approach, four different single-case life cycle assessment (LCA) studies were conducted in this dissertation to contribute to filling this gap.

Based on the results, the LCA approach can improve the understanding of the environmental impacts of different construction materials. Another key contribution is about the share of transport in initial embodied impacts, often not explicitly considered forming a weakly understood uncertainty factor.

Yet, the results should be interpreted cautiously. The first concern relates to the selected LCA database for the assessment that can result in very different evaluation in almost all impact categories, with climate change and fossil depletion as the only exceptions (yet with some inconsistency in them as well). The other issue is linked to the uncertainties surrounding the input data (selection of material from the database and the method) as well as the uncertainties in the sequestration capacity of a few specific materials (compressed straw, reed panels, and wooden elements). It was clear that the assessment depends heavily on those input data and sequestration capacity assumptions.

Thus, the study revealed that extensive work is still needed to improve the reliability of LCA tools in the building sector in order to provide reliable and trustworthy information for policy-making.

Útdráttur

Byggingar eru lykilþættir þéttbýlis og samfélags sem flókið kerfi. Hefð er fyrir því að losunin sem felst í byggingarefnum hafi ekki verið talin mikilvæg í samanburði við áhrif frá orkunotkun þegar kemur að því að draga úr loftslagsáhrifum bygginga. Þar að auki hefur mat á umhverfisáhrifum byggingarefna reynst vandasamt og hægt er að draga áreiðanleika matsins í efa. Með því að fylgja margvíslegri tilviksrannsóknaraðferð voru gerðar fjórar mismunandi vistferilsgreiningar (LCA) til að fylla þetta skarð.

Byggt á niðurstöðunum getur LCA nálgun bætt skilning á framlagi mismunandi hefðbundinna og annarra byggingarefna til nokkurra umhverfisáhrifaflokka. Annað lykilframlag snýst um hlutdeild flutninga í innbyggðum áhrifum, sem er oft ekki sérstaklega talin með, sem myndar lítt skilinn óvissuþátt.

Samt ætti að túlka niðurstöðurnar varlega. Fyrsta áhyggjuefnið varðar valinn LCA gagnagrunn fyrir matið sem getur leitt til mjög mismunandi mats í næstum öllum áhrifaflokkum, þar sem loftslagsbreytingar og eyðing jarðefnaeldsneytis eru einu undantekningarnar (samt með nokkru ósamræmi í þeim líka). Hitt atriðið er tengt óvissuþáttum varðandi inntaksgögnin (val á efni úr gagnagrunninum og aðferðinni) sem og óvissu í bindingargetu nokkurra tiltekinna efna (þjappað strá, reyrplötur og viður). Ljóst var að matið var mjög háð þessum inntaksgögnum og forsendum um bindingargetu.

Þannig leiddi rannsóknin í ljós að enn er þörf á mikilli vinnu til að bæta áreiðanleika LCA verkfæra í byggingargeiranum til að veita áreiðanlegar og traustvekjandi upplýsingar til stefnumótunar.

I dedicate this dissertation to my beloved family,

my husband Reza and my daughter Elena,

for their constant encouragement and unconditional love.

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Abbreviations

Abbreviation	Explanation
AP	Acidification Potential
BREEAM	Building Research Establishment Environmental Assessment Method
CEDnr	Cumulative Energy Demand-Non-renewable
CEDr	Cumulative Energy Demand-renewable
EP	Eutrophication Potential
EPBD	Energy Performance of Buildings
GHG	Greenhouse gas emissions
GWP	Global Warming Potential
HDF	High density fibreboard
HT	Human Toxicity
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LEED	Leadership in Energy and Environmental Design
NDCs	Nationally Determined Contributions
ODP	Ozone Depletion Potential
OECD	Organization for Economic Co-operation and Development
POCP	Photochemical Ozone Creation Potential
UNEP	United Nation Environment Programme

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List of Publications

This Doctoral dissertation is based on a collection of articles published in International Scientific Indexing (ISI) or Scopus journals as following:

Nargessadat Emami, Björn Marteinsson and Jukka Heinonen (2016), Environmental Impact Assessment of a School Building in Iceland Using LCA-Including the Effect of Long Distance Transport of Materials, Buildings, 6 (4), 46, doi:10.3390/buildings6040046.

Nargessadat Emami, Jukka Heinonen, Björn Marteinsson, Jani Laine, Antti Säynäjoki, Seppo Junnila, Juha-Matti Junnonen (2019), A Life Cycle Assessment of two Residential Buildings with two different LCA database-software combinations: Recognizing Uniformities and Inconsistencies, Buildings 9, 20. doi:10.3390/buildings9010020

Marwa Dabaieh, **Nargessadat Emami**, Jukka Heinonen, Björn Marteinsson (2020), A Life Cycle Assessment of a “Minus Carbon” Refugee House: Global Warming Potential and Sensitivity Analysis, Archnet-IJAR: International Journal of Architectural Research. doi: 10.1108/ARCH-11-2019-0258.

Ali Amiri, **Nargessadat Emami**, Juudit Ottelin, Jaana Sorvari, Björn Marteinsson, Jukka Heinonen, Seppo Junnila (2021), Embodied emissions of buildings - a forgotten factor in green building certificates, Energy & Buildings, doi: 10.1016/j.enbuild.2021.110962

Author contributions to the papers

Paper I: Environmental Impact Assessment of a School Building in Iceland Using LCA-Including the Effect of Long Distance Transport of Materials

Study conception and design: Nargessadat Emami (N.E.), Björn Marteinsson (B.M.) and Jukka Heinonen (J.H.); Acquisition of data: **N.E.,** B.M, and J.H.; Analysis and interpretation of data: **N.E.,** B.M, and J.H.; Drafting of manuscript: **N.E.;** Critical revision: **N.E.,** J.H., and B.M.

Paper II: A Life Cycle Assessment of two Residential Buildings with two different LCA database-software combinations: Recognizing Uniformities and Inconsistencies

Conceptualization, **N.E.,** J.H., and B.M.; Methodology, **N.E.**; Software, **N.E.**; Validation, J.H., B.M., Seppo Junnila (S.J). and Antti Säynäjoki (A.S.); Formal Analysis, **N.E.**; Investigation, **N.E.**; Resources, Jani Laine (J.L.); Writing-Original Draft Preparation, **N.E.**; Writing-Review & Editing, J.H., B.M., S.J. and A.S.; Visualization, **N.E.,** J.H.

Paper III: A Life Cycle Assessment of a "Minus Carbon" Refugee House: Global Warming Potential and Sensitivity Analysis

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Paper IV: Embodied emissions of buildings - a forgotten factor in green building certificates

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1 Introduction

1.1 Background

The building and construction sectors are key sectors for sustainable development. Globally, they accounted for 36% of final energy use and 39% of energy and process-related carbon dioxide (CO_2) emissions in 2018. Building operations worldwide account for 28% of energy-related Greenhouse Gases (GHG) emissions and the other 11% caused by manufacturing building materials and products such as steel, cement and glass (IEA and UNEP, 2019). The global buildings sector emissions increased 2% from 2017 to 2018, while final energy demand rose 1% from 2017 and 7% from 2010. There is an urgent need to drastically reduce the anthropogenic GHG load within the next decades (IPCC, 2018) and 2020 was a key year for countries to enhance their Nationally Determined Contributions (NDCs), especially concerning further actions to address energy use and emissions including embodied emissions in the buildings and construction sector.

In recent reports (Coninck et al., 2018; IEA and UNEP, 2019; IPCC, 2018), several organizations identified 'buildings' as an essential field of action for a number of reasons. While 'buildings' are responsible for an enormous amount of current GHG emissions, they also have significant potential to reduce GHG emissions through improved operational energy efficiency. In this context, the IPCC states that "1.5 °C-consistent pathways require building GHG emissions to be reduced by 80–90% by 2050, new construction to be fossil-free and near-zero energy by 2020", and the need for "an increased rate of energy refurbishment of existing buildings to 5% per annum in OECD countries".

The EU Directive on the energy performance of buildings was adopted in 2002. It was intended to improve the energy efficiency of buildings, reduce carbon emissions, and reduce the impact of climate change. On 19 May 2010, the Council of the European Union and European Parliament adopted a recast of the Energy Performance of Buildings Directive in order to strengthen the energy performance requirements of buildings. The Energy Performance of Buildings Directive and the 2012 Energy Efficiency Directive have been the two main pieces of legislation aimed at reducing the energy use of buildings during the operation phase. The revised directive on energy performance of buildings requires that all new buildings should be 'nearly zero energy buildings' by 31 December 2020 ("European Parliament, 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings. Directive 2010/31/EU. Brussels.," 2010). On 17 April 2018, the European Parliament gave approval to a revised Energy Performance of Buildings (EPBD) directive, to accelerate building renovation, delivering more energy efficient systems and strengthening the energy performance of new buildings, making them smarter ("Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 Amending Directive 2010/31/EU on the Energy Performance of Buildings and Directive 2012/27/EU on Energy Efficiency (European Commission, 2018)," 2018).

In April 2018, the European Commission officially opened the two-year testing phase for Level(s) to organizations looking to be part of Europe's shift towards circular and lifecycle thinking. Level(s) promotes lifecycle thinking for buildings and provides a robust approach to measuring and supporting improvement from design to end of life, for both residential buildings and offices. Level(s) uses core sustainability indicators, tested with and by the building sector, to measure several impacts including carbon, materials, water, health and comfort, climate change impacts, taking into account lifecycle costs and value assessments. Level(s) also supports the essential assessment over the full lifecycle through design, construction, use, and end of life (Dodd et al., 2020).

In autumn 2020 the Nordic Ministers for Housing and Construction approved a new action plan for 2021–2024 seeking a more climate-friendly Nordic construction sector. This initiative is part of work to realize a vision of the Nordic countries as the world's most sustainable and integrated region by the year 2030. The emission database services opened by Finland and Sweden today are an important step towards ambitious goals for the Nordic construction industry, which has significantly lower environmental and climate impacts. Based on a recently introduced policy, all new buildings are required to submit a climate declaration on emissions from production and construction phases (A1-A5) from 2022. (Nordic council of Ministers, 2021).

In line with the objectives of EU directives, the term 'net zero energy building' (net ZEB) has been introduced to emphasize the concept of an annual balance between energy imported from and exported to the energy grid (Sartori et al., 2012). The concept of a Zero Emission Building is correspondingly defined, except it uses emissions of CO_2 equivalents as the balancing indicator instead of primary energy.

The construction sector is usually a heavy user of materials and energy for the building process, and transition towards more sustainable settlements may put an extra demand on initial (embodied) materials use in structures. In fact, there has been little consideration in such policy frameworks around the materials and construction processes associated with buildings (Hernandez and Kenny, 2010). There are substantial emissions implications arising from the extraction of raw materials, processing, manufacture, transportation, on-site delivery, construction, maintenance, renovation, final demolition as well as all the activities and processes along the supply chain that constitute the building. These are collectively known as embodied emissions.

Traditionally the embodied emissions from materials have not been considered of high importance, but since the construction of energy efficient buildings and modern infrastructure causes more GHG emissions than conventional ones, the embodied emissions are now becoming more crucial (Chester et al., 2014; Khasreen et al., 2009; Müller et al., 2013; Säynäjoki et al., 2012). Another key development is that anything built in the future likely causes a lower impact than if built now per material or space unit – due to improving energy production systems and due to material innovations. Thus, it magnifies the impact of today's emissions being more harmful. Moreover, the reported decades long carbon payback times are not acceptable in the current situation with the carbon budget to reach the 1.5 degree warming target running out quickly (IPCC, 2018; Le Quéré et al., 2018). In addition, the impacts of emissions at different times have different implications for climate change (Kendall, 2012). According to Schwietzke, Griffin and Matthews (2011), GHG emissions released today may be more harmful than those released in the future. Carbon emissions are cumulative and remain in the atmosphere for several hundred years (Karimpour et al., 2014). This means that carbon emissions released today can contribute to the greenhouse effect several centuries in the future. When considering long-term impacts, releasing CO_2 emissions today compared to 50 years from now has a higher cumulative impact on the climate (Schwietzke et al., 2011).

The European Commission released the integrated policy product approach (European Commission, 2003) in 2003, to select products with the highest environmental mitigation potential. However, evaluating the environmental burden of construction materials has proved problematic and despite the significant research around the world (Biswas, 2014; Seppo Junnila, 2004; Junnila and Horvath, 2003; Kofoworola and Gheewala, 2008; Röck et al., 2020; Thiel et al., 2013), the reliability of estimates is still highly questionable (Säynäjoki et al., 2017a). More precisely, the estimates tend to significantly underestimate the actual impacts (Paleari et al., 2016), which can hinder us from achieving the mitigation targets. Moreover, more reliable information from the construction sector is urgently needed for advised decision-making (Heinonen et al., 2016; Säynäjoki et al., 2017a). In response to such concerns, a modified definition for Zero Emission Buildings (ZEB) was proposed by Dokka et al., (2013) that captures different ambition levels depending on which emissions are included and compensated for. Two fundamental levels are the "ZEB-O" level, which aims to balance out all operational emissions (O) from energy use, and the "ZEB-OM" level, which aims to compensate for both operational emissions (O) and material (M) emissions.

Röck et al., (2020) reviewed more than 650 life cycle assessment (LCA) case studies to explore the global trends of GHG emissions arising across the life cycle of buildings. The results show a clear reduction trend in life cycle GHG emissions due to improved operational energy performance, while the relative and absolute contributions of the embodied GHG emissions increase. While the average share of embodied GHG emissions from buildings following current energy performance regulations is approximately 20–25% of life cycle GHG emissions, this figure escalates to 45–50% for highly energy-efficient buildings and surpasses 90% in extreme cases.

A similar pattern (an increase in the relative importance of embodied emissions) has been observed as a result of the continuous narrowing of the building regulations' requirements to reduce emission from the operation of buildings (Isaksson and Karlsson, 2006; Karlsson et al., 2003). Another reason could be that it is due to the pre-use phase emissions happening right now, and the use phase lasting 50 to 100 years and the emissions being low annually in comparison to the pre-use part, and not necessarily taking place at all due to improvements in the grid energy GHG intensities (Säynäjoki et al., 2012). This is already the case for Iceland which for the operation of buildings uses almost entirely renewable energy sources. Besides, enhancement in the energy efficiency of buildings may also bring in use of materials and energy systems that might possibly increase the embodied greenhouse gas emissions (Georgiadou, 2014; Tingley and Davison, 2011).

Since the early 1990s, an increasing number of methods have been suggested to evaluate the embodied as well as total life cycle environmental impacts of buildings. Life Cycle Assessment (LCA) is nowadays the dominant assessment method for the embodied impacts that measure the emissions, usage of natural resources, and effect on health that can be related to different products or services over their complete life cycle (Chau et al., 2015; Fenner et al., 2018). It is also the most utilized method in environmental assessments of buildings (Säynäjoki et al., 2017a). It quantifies the interactions with the surroundings, whether they are inputs to the system, such as natural resources, land and energy, or as an output of the considered system, for example emissions to air, water and soil (Klöpffer, 1997).

The two prominent green building rating system widely used across the globe are (i) the U.K. developed Building Research Establishment Environmental Assessment Method (BREEAM) (ii) the U.S. developed Leadership in Energy and Environmental Design (LEED) systems (Suzer, 2019). LEED is aiming at reducing the energy and material needs of buildings (Donghwan et al., 2015; Jeong et al., 2016; Nilson, 2005; Pearce, 2006). Compared to conventional buildings, LEED-certified buildings have sale price, rental and occupancy premiums that motivate the investors to consider applying this certification to the construction project (Leskinen et al., 2020). However, LEED strongly focuses on energy use and emissions produced during operation phase and almost entirely omits the embodied emissions.

A handful of studies have showed that the relative importance of embodied energy and embodied greenhouse gas emissions can also be high over the building lifetime. An investigation on the energy consumed in a low-energy building in Gothenburg, Sweden showed that the embodied energy in one family home was responsible for around 45% of the total energy need over 50 years (Thormark, 2002). Rawlinson and Weight, (2007) suggest that the embodied energy in residential buildings can be equal to 10 times the annual operational energy use, or as high as 30 for complex commercial buildings in the UK, depending on the heating and cooling loads. Stephan, Crawford and De Myttenaere, (2012) developed a software to conduct the life cycle energy analysis. Focusing on two case studies, the share of embodied energy in the total life cycle energy (over 50 years) was found to be 44% for the Belgian passive house and 29.6% for the Australian 7-star house. The contribution of embodied energy can be even higher than 56% for passive houses (excluding transport energy requirements), as shown by Crawford and Stephan, (2013). In terms of embodied greenhouse gas emissions, the analysis by Sturgis and Roberts, (2010) illustrated that for some building types, up to 62% of the whole life-cycle carbon may be due to embodied greenhouse gas emissions.

To assess the mitigation capacity of alternative materials, several studies have compared the embodied energy and environmental impact of alternative materials with conventional ones (González and García Navarro, 2006; Morel et al., 2001; Salcido et al., 2016; Thormark, 2006; Utama et al., 2012). For example, Utama et al., (2012) evaluated the embodied GWP impacts of using traditional clay instead of concrete in houses in Indonesia. They estimated that substitution of concrete with traditional clay could reduce the GWP impacts by 9 million tons of CO_2 eq by 2030. There are a number of studies that have concentrated on the embodied energy and the corresponding global warming potentials (GWP) (see for example Du et al., (2015), but significantly fewer have included other impact categories (such as the ozone depletion potential -ODP, the acidification potential - AP, the eutrophication potential - EP, the photochemical ozone creation potential - POCP, etc.) (Khasreen et al., 2009; Robertson et al., 2012). Yet, they have suggested that the materials are an important source of several impacts. For example, Blengini and Di Carlo, (2010) developed a detailed LCA over several impact categories including GWP, ODP, AP, EP and POCP for a house located in Morozzo, Italy. The analysis has emphasized that, when addressing the performance of low-energy buildings, it is vital to account for the contribution of all life cycle phases and subsystems. In 2012, Passer et al., (2012) analyzed the influence of five residential buildings in Austria on seven environmental indicators (AP, EP, GWP, ODP, POCP, cumulative energy demand-non-renewable - CEDnr, cumulative energy demand-renewable - CEDr). This analysis indicates that although the operation phase is the most dominant phase in all impact categories, still, the contribution of impacts may differ considerably for construction products and the operation phase in many categories.

Temporary shelters is one form where alternative materials often come to play and few studies so far have aimed at estimating GHG emissions or other environmental impacts of temporary construction. Kuittinen and Winter, (2015) assessed the carbon footprint and primary energy demand analyses of eight transitional shelters. The lowest impacts were found from shelter models made from bamboo or timber, while the highest emissions were caused by shelters that have either a short service life or that are made from metal-intensive structures. Kuittinen, (2016) assessed the carbon footprint of the alternative structure types and materials used for the reconstruction of schools in Haiti. He concluded that the choice of concrete mix can have a significant impact and has the potential to reduce the emissions from the manufacturing of the floor slab by 35%. Focusing on temporary homes in Japan, Kuittinen and Takano, (2017), analyzed three alternative types of temporary shelters; prefabricated shelters, wooden log shelters and a shelter settlement made from sea containers. The results confirmed that container shelters cause the largest GHG emissions over their life cycle (187% higher than log shelters and 142% higher than prefabricated shelters). As expected, the embodied emissions account for 89% of total emissions for container shelters, whereas they only account for 25% and 18% of total emissions in prefabricated and log shelters.

Thus far, we recognized a gap in the literature on estimating the environmental impacts of alternative materials. There is another important aspect about the environmental impacts categories that has been overlooked in previous LCA studies. Soust-Verdaguer et al., (2016) reviewed 20 case studies primarily in order to compare system boundary definitions, sources of information, the selected life cycle phases, and estimated environmental impact categories focusing on simplification approaches (read Kellenberger and Althaus, (2009) for further elaboration) and secondly, to promote further developments on LCA. Heinonen et al., (2016) also recently depicted how GWP cannot be used as an indicator for the majority of the environmental impact categories in the context of the embodied emissions in the building and construction sector.

Very few studies have captured the broader environmental impacts of construction materials, which can have a significant implication on conducting a comprehensive assessment of the environmental effects of alternative materials. Thus, in order to enhance our understanding of other environmental impacts, in this study, a broad system boundary was selected and several environmental impact categories in addition to GWP are assessed. The fifteen impact categories include Climate Change (kgCO_2 eq), Ozone Depletion (KgCFC11 eq), Terrestrial Acidification (kgSO_2 eq), Freshwater Eutrophication (KgP eq), Marine Eutrophication (kg N eq), Human Toxicity (kg1.4DB eq), Photochemical Oxidant Formation (kg NMVOC), Particulate Matter Formation (kgPM10eq), Terrestrial Ecotoxicity (kg 1.4DB eq), Freshwater Ecotoxicity (kg1.4DB eq), Marine Ecotoxicity (kg1,4DB eq), Ionizing Radiation (kgU235 eq), Water Depletion (m^3), Metal Depletion (kgFe eq), and Fossil Depletion (kg oil eq).

Another aspect concerning the reliability of results relate to the selected LCA tool used for the assessment. Säynäjoki, et al., (2017) in a comprehensive building sector review, discovered that in general there is a considerable variation in the published results which is not explicable by building characteristics but rather by the subjective choices of the LCA practitioner and in particular the choice of the LCA tool used for the assessment. Until now, comparison studies of these LCA tools have been conducted mostly on a general database level, e.g.,(Herrmann and Moltesen, 2015) , and for industry sectors other than the building industry, e.g., (Brogaard et al., 2014; Laurent et al., 2014; Verghese et al., 2012; Zhou et al., 2014).

1.2 Summary of existing literature

Many organizations recognized the significant potential of buildings sector to reduce GHG emissions (Coninck et al., 2018; IEA and UNEP, 2019; IPCC, 2018). Several EU Directives have previously focused on energy performance requirements of buildings ("Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 Amending Directive 2010/31/EU on the Energy Performance of Buildings and Directive 2012/27/EU on Energy Efficiency (European Commission, 2018)," 2018). As a result, a strong reduction trend in life cycle GHG emissions due to improved operational energy performance has been documented by Röck et al., (2020) after reviewing more than 650 LCA case studies. On the other hand, the relative and absolute contributions of the embodied GHG emissions increase. In response to that development, in October 2020, the European Commission officially launched the Level(s) framework to promotes lifecycle thinking for buildings and provides a robust approach to measuring and supporting improvement from design to end of life, for both residential buildings and offices (Dodd et al., 2020). At the same time, the Nordic Ministers for Housing and Construction have also approved a new action plan for 2021–2024 seeking a more climate-friendly Nordic construction sector. One of the proposed policies requires all new buildings are required to submit a climate declaration on emissions from production and construction phases (A1-A5) from 2022. (Nordic council of Ministers, 2021). While GWP impacts are the most commonly assessed impact category, several studies have investigated a few more impact categories other than GWP impact (Allacker, 2010; S. Junnila, 2004; Oregi et al., 2015). Yet, comprehensive assessment of all environmental impact categories is usually overlooked. Several studies have compared the environmental impacts of alternative materials with conventional ones, (González and García Navarro, 2006; Morel et al., 2001; Salcido et al., 2016; Thormark, 2006; Utama et al., 2012), but the contributions of materials (available in the Nordic countries), as well as building components and transport are not sufficiently studied. Säynäjoki, et al., (2017) reported a substantial disparity in the results of different LCA tools. Thus, comparison studies of these LCA tools have been conducted mostly on a general database level, e.g.,(Herrmann and Moltesen, 2015) , and for industry sectors other than the building industry, e.g., (Brogaard et al., 2014; Laurent et al., 2014; Verghese et al., 2012; Zhou et al., 2014). So, there is a need for consistency assessment between the two LCA tools for the different construction material groups.

Reviewing the literature, a couple of topics worthy of further investigation are identified. The contributions of different materials, building components and long-distance transport to broader environmental impacts, which is assessed in Paper I. The inconsistency between the two LCA databases for the different construction material groups, which is explored in Paper II. Obtaining a better understanding of the effects of material choice on initial embodied emissions, which was the focus of Papers III and IV. In this dissertation the term "initial embodied emissions" means the emissions from production and delivery chains (modules A1-A4, according to EN 15804/EN 15978 (CEN, 2013, 2011). Moreover, assessing broader environmental impacts of construction materials (apart from GWP), which was done in Papers II and IV.

1.3 Structure of the dissertation

The dissertation is divided into seven chapters. Chapter two briefly presents the context of the research and an overview of the research. The third chapter focuses on the methodology of the dissertation, the multiple case study approach and LCA. Chapter four presents descriptions of the case studies forming the dissertation entity. Chapter five presents the key results of each individual papers. Chapter six presents the answers to research questions, discusses the implications of results, evaluates the quality of the research, and provides some suggestions for future research. Chapter seven closes the dissertation with concluding remarks.

2 Research description and questions

The significance of initial embodied emissions from materials have not been considered of high importance compared to the operational phase. Yet, several studies including Fay et al., (2000) and Säynäjoki et al. (2012) report very significant contributions towards embodied energy, GHGs and other embodied environmental flows (40%+ over 50 years) since the early 2000s.

Recently, in a comprehensive review by Röck et al., (2020), they illustrate a clear reduction in life cycle GHG emissions due to improved operational energy performance, while the relative and absolute contributions of the embodied GHG emissions increase. As a result, it was concluded that there is a need for more LCA studies focusing on initial embodied GHG emissions of buildings, due to several gaps in the existing literature.

First, while GWP impacts are the most commonly assessed impact category, several studies have investigated several impact categories other than GWP impact (Allacker, 2010; S. Junnila, 2004; Oregi et al., 2015; Heinonen et al. 2016). Yet, comprehensive assessment of all environmental impact categories is generally overlooked. Secondly, the environmental impacts of alternative construction materials are not sufficiently explored. Thirdly, the uncertainties due to different methodology, LCA database and different scope are not fully investigated. And finally, the transport of materials is rarely given explicit consideration even though distances are often long.

Focusing on Iceland, there has been limited research on environmental impacts of construction materials, with the exceptions of (Emami, 2016; Emami et al., 2016; Emami et al., 2015; Marteinsson, 2002; Úlfarsson, 2011). Reykjavik's new objective is to reduce GHG emissions by 73% in 2050, relative to 2007 (Reykjavík Municipal Plan 2010-2030, 2014), however, the impacts of construction materials are currently excluded from the city's emissions inventory as they are mainly produced outside of the city. Besides, they can be in a decisive role from the global perspective, and as a result, there is an urgent need for a broad assessment framework to analyze the overall environmental impacts of construction materials in Iceland, the vast majority of which are imported from around the globe. It is the primary step to identify the effective mitigation measures accounting for regional variations.

The main emphasis of dissertation is on initial embodied environmental impacts, modules A1-A4 in the standardized methodology (explained in chapter 3), which will be estimated using the LCA approach. Thus, two research questions are structured as follows:

1. *What are the initial embodied emissions caused by different types of buildings with material choices in the Nordic context, and what are the relative importance of building components, materials and transport?*
2. *How strongly does the LCA database choice affect the assessment outcome, and what are the implications to the reliability of the results in different impact categories?*

Based on the identified research questions, the **primary objectives** of the dissertation were to:

I. Use the multiple case study approach to estimate the relative importance of building components, materials and transport in initial embodied environmental impacts

II. Assess how different material choices in the Nordic context can affect the outcome of LCA

III. Expand our knowledge on the differences between the two widely used material-level LCA database-software combinations and the reasons behind the differences

The dissertation includes four journal articles as presented in the "List of Publications" section. Each paper presents a distinct viewpoint on the research problem and makes a unique contribution to the conclusions presented in the dissertation. The two Research Questions (RQ), contribution of each paper to Primary Objectives (PO), as well as a brief description of the case studies are presented in table 1. Considering the two RQs and three POs defined for this dissertation, the objective of each paper is determined to address them. Paper I addresses RQ1 and POI, while Paper II focuses on RQ2 and POIII. Paper III is completed to contribute to RQ1 and help to achieve POI and POII. Finally, the research for Paper IV is conducted to answer RQ1 and contribute to reach POI and POII.

After defining research questions and primary objectives, the following chapter will cover the methodology, the research design, the LCA framework and how it has been implemented to address the research questions.

Table 1: Overview of papers and their objectives

Research Questions	*What are the initial embodied emissions caused by different types of buildings with material choices in the Nordic context, and what are the relative importance of building components, materials and transport?* *How strongly does the LCA database choice affect the assessment outcome, and what are the implications to the reliability of the results in different impact categories?*				
		Paper I	**Paper II**	**Paper III**	**Paper IV**
Paper title		Environmental Impact Assessment of a School Building in Iceland Using LCA-Including the Effect of Long-Distance Transport of Materials	A Life Cycle Assessment of two Residential Buildings with two different LCA database-software combinations: Recognizing Uniformities and Inconsistencies	A Life Cycle Assessment of a "Minus Carbon" Refugee House: Global Warming Potential and Sensitivity Analysis	Embodied emissions of buildings - a forgotten factor in green building certificates
Objective		Estimate typical initial embodied environmental impacts in Iceland	Explore the differences between the two widely used LCA database-software combinations	Estimate the carbon storage potential of selected natural materials and associated uncertainties	Evaluate the effect of material choices on initial (pre-use) embodied emissions using LCA
Description of case studies	Case study	School building, Vættaskóli-Engi, Iceland	Multi-story apartment building, Pyry & Detached wooden house, KÄPYLÄ, Finland	Temporary refugee shelter, Sweden	Modern educational facility, Veröld Iceland
	Method	Process LCA, ILCD method	Process LCA, ReCiPe Midpoint	Process LCA, ReCiPe Midpoint	Process LCA, ReCiPe Midpoint
	Impact categories	GWP, ODP, HT, AP and EP	15 impact categories	GWP	18 impact categories
	System boundary	Modules A1-A4	Pyry: Modules (A1-A5) KÄPYLÄ: Modules (A1-A3)	Modules (A1-A5, B1-B6 and C1-C4)	Modules A1-A4
	Gross floor area	5000 m^2	Pyry: 3085 m^2 KÄPYLÄ: 149 m^2	37 m^2	4013 m^2

3 Methodology

In order to find the answer to the defined research questions, four case studies (**Papers I to IV**) have been analyzed using LCA to assess the initial embodied environmental impacts of construction materials. This chapter presents the theory of single and multiple-case designs, and describes the research design. Besides, the LCA framework is described as a method to quantify the environmental impacts of products and processes throughout their entire life cycle, i.e., from cradle-to-grave'. Furthermore, the sensitivity analysis is explained as a systematic process to quantify the uncertainty in LCA findings, utilized in **Paper III**.

3.1 Case study as method

Several researchers have applied case studies as a way to conduct an examination (Kitzes et al., 2018).

Yin, (1984, Page 23) defined the case study method as "an empirical inquiry that investigates a contemporary phenomenon (the 'case') in depth and within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident and the investigator has little control over events". The case study is also defined as an ideal methodology when a holistic, in-depth investigation is needed (Joe R. Feagin et al., 1991). Moreover, Stake (1995) suggested that case study research is an investigation and analysis of a single or collective case, intended to capture the complexity of the object of study (Robert E. Stake, 1995). Case studies are designed to suit the research question and objectives and published case studies demonstrate wide diversity in study design by Hyett et al., (2014). Jack Meredith, (1998) identified three major strengths of the case study method:

- the phenomenon can be studied in its natural setting and meaningful, relevant theory generated from the understanding gained through observing actual practice;
- the method allows the questions of why, what, and how, to be answered with a relatively full understanding of the nature and complexity of the complete phenomenon; and
- it lends itself to early, exploratory investigations where variables are still unknown and the phenomenon not at all understood.

Flyvbjerg, (2006) argues that concrete, context-dependent knowledge as can only be created by a case study is of more value than general, theoretical knowledge. He also claims that diving deeper into single cases can be more informative than a more superficial study of broader samples. Dul and Hak, (2008) also acknowledged that most of the researchers consider case study research as a useful research strategy (A) when the topic is broad and highly complex, (B) when there is not a lot of theory available, and (C) when "context" is very important.

Yin (2006) has identified four types of designs for case studies (see Figure 1). The 2 x 2 matrix shows that every type of design will include the desire to analyze contextual conditions in relation to the "case," with the dotted lines between the two signaling that the boundaries between the case and the context are not likely to be sharp. The matrix then shows that single- and multiple-case studies reflect different design situations. Also, there can be unitary or multiple units of analysis within each case study. The resulting four types of designs for case studies are (Type 1) single-case (holistic) designs, (Type 2) single-case (embedded) designs, (Type 3) multiple-case (holistic) designs, and (Type 4) multiple-case (embedded) designs.

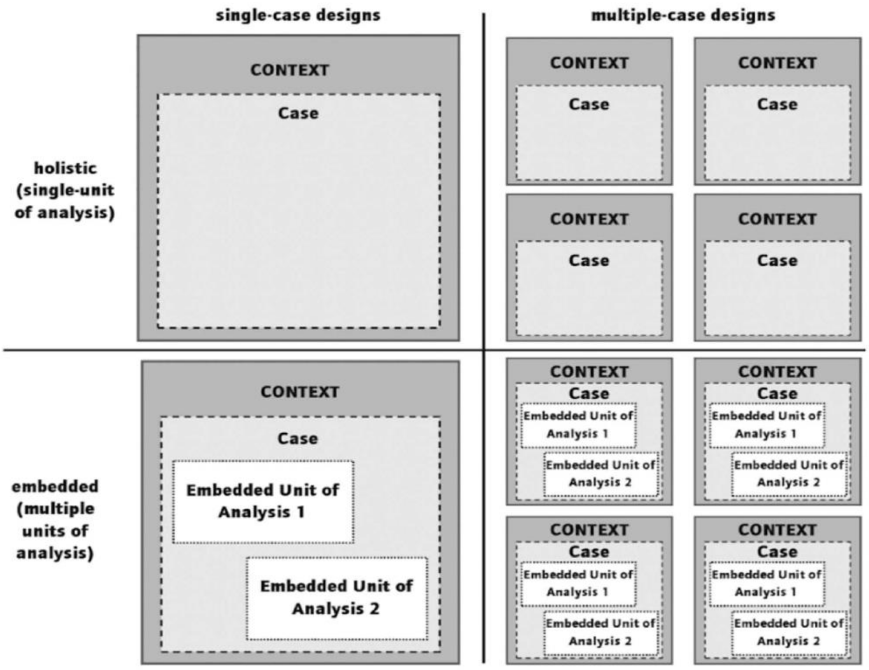

Figure 1: Basic types of designs for case studies – Source: Yin, 2006, p.46

The following subsection 3.2 describes how this study fits in the design matrix.

3.2 Research Design

LCAs are practically case studies with the focus on the evaluation of environmental impacts and decision-making process assistance in the building sector (Ortiz et al., 2009). In this study four different single-case studies were conducted leading to a multiple-case embedded design, Type 4 according to Yin's definition (Figure 2).

Multiple-case designs have distinct advantages and disadvantages in comparison to single-case designs. The evidence from multiple cases is often considered more compelling, and the overall study is therefore regarded as being more robust (Herriott and Firestone, 1983). Yin, (2003) also recommends multiple case study over single case study because the analytic conclusions coming from at least two cases will be more powerful than that from a single case.

The multiple case study methodology made it possible to seek evidence with respect to the first research question. Besides, while a single-case study usually focuses on a single subject of analysis, the multiple case study analysis can also be designed as comparative investigations that highlight the relationship between two or more subjects (the purpose of **Paper II**).

On the other hand, the conduct of a multiple-case study can require extensive resources and time beyond the means of a single student or independent research investigator. This limitation can be resolved through building collaborations to conduct multiple-case studies (**Papers III and IV**).

As illustrated in Figure 2, the research design covers multiple-case studies with multiple units of analysis within each case study, while the broad context (Embodied environmental impacts) is similar across the case studies. The common component of analysis across all case studies is the evaluation of the contribution of construction material, whereas each case study covers a particular unit of analysis, (Impact of long-distance transport in Paper I, Consistency assessment between LCA database-software combinations in Paper II, sensitivity analysis of sequestration potential in paper III and Scenario analysis for alternative construction materials in paper IV).

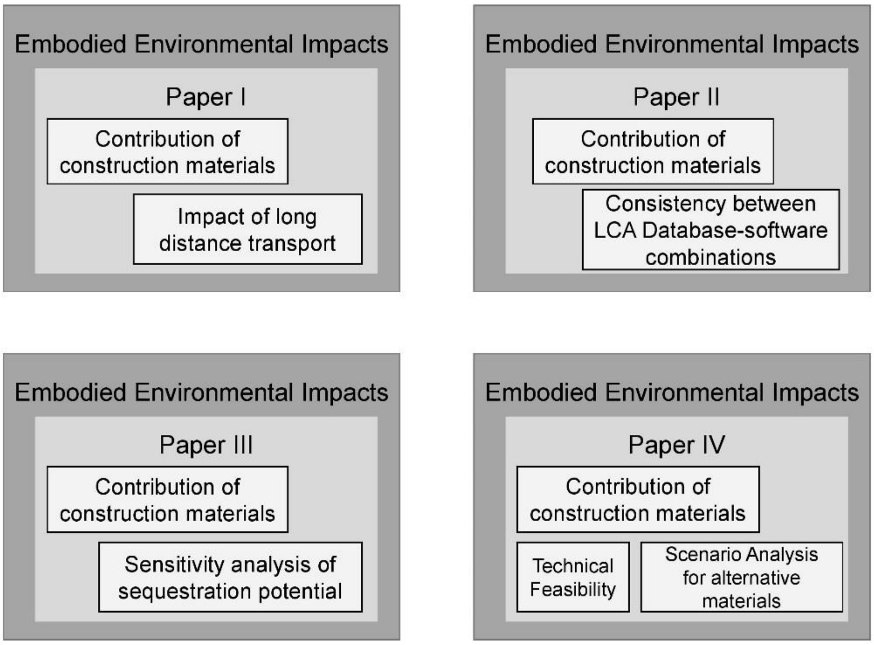

Figure 2: Research Design for the multiple case study research – adjusted from Yin (2006)

The use of similar LCA applications at multiple construction projects with similar results indicates the benefits of replication (Yin 1994). Although the number of cases in the dissertation is modest, they have a multiple analytic power compared to a single case study (Eisenhardt & Graebner 2007). Thus, using multiple cases typically leads to a more robust, generalizable, and testable theory compared to a single case study.

3.3 Life Cycle Assessment Framework

LCA aims to evaluate all the direct and indirect environmental impacts from the production, transport, use, and end-of-life of a product, service or process (Crawford, 2011; Klöpffer, 1997). LCA has become the central way of environmental assessments in the building sector (see e.g., the review of Säynäjoki et al., (2017a).

The European committee for standardization developed a set of horizontal standards which enables the sustainability assessment of buildings. At the product level, EN 15804 standard defines the product category rules to develop Environmental Product Declarations (EPD) of construction products (CEN, 2013). EPDs are Type III environmental declarations, according to ISO 14025 (ISO, 2006) and are often a good source of environmental data for a life cycle analysis. In case of wood-based products, complementary product category rules (PCR) are available in EN 16485 (CEN, 2014). LCA data for building products in line with EN 15804 and EN 16485 provide the necessary information for the assessment of the environmental performance of whole buildings as defined in EN 15978 (CEN, 2011). EN 15978 (2011) provides calculation rules for the assessment of the environmental performance of new and existing buildings based on a life cycle approach. It is intended to support the decision-making process and documentation of the assessment of the environmental performance of a building (CEN, 2011).

The ISO 14044:2006 specifies requirements and provides guidelines for LCA and allocate the LCA framework into four steps: goal and scope, inventory analysis, impact assessment and interpretation (Figure 3) (International Standard 14040, 2006; International Standard 14044, 2006).

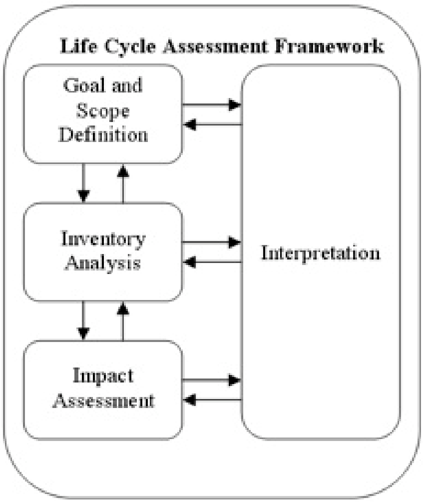

Figure 3: Life cycle assessment framework (International Standard 14040, 2006)

1. Goal and scope outlines the envisioned application, the motivations for conducting a study, defines the methodological framework to satisfy the intended goals, outlines the boundary of the system and defines impact assessment methodology (International Standard 14040, 2006). Figure 4 illustrates the life cycle stages (product, construction, use stage, end of life) according to EN 15804 (CEN, 2013). While the reporting of the production stage (modules A) is mandatory, the use stage of buildings (modules B), the processes that take place in the end of life stage (modules C) and the benefits and loads beyond the defined system boundary (module D) can be considered optionally.

Life cycle stages		Product			Construction		Use stage							End-of-life				Benefits and loads beyond the system boundary
							Related to the building fabric					Related to the building operation						
Modules		A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
		Raw material supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Demolition	Transport	Waste processing	Disposal	Reuse / Recovery / Recycling potential
					Scenarios													
Type of EPD	Cradle to Gate[1]	M	M	M														
	Cradle to Gate with option(s)[2,4]	M	M	M	O	O	O	O	O	O	O	O	O	O	O	O	O	O
	Cradle to Grave[3,4]	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	O

Key: M mandatory; O optional

Notes: [1] for a declared unit

[2] for a declared unit or functional unit

[3] for a functional unit

[4] Reference Service Life to be included only if all scenarios are included

Figure 4: Life cycle stages according to the standard EN 15804 (CEN, 2013)

2. Inventory analysis captures all inputs and all outputs that cross the selected system boundary.

3. The Life Cycle Impact Assessment (LCIA) recognizes and estimates the extent and importance of the environmental impacts and the contribution of construction materials and building systems. The most popular methods include:

    - ✓ The CML 2002 LCA Handbook (Guinée et al., 2002), a follow-up of the CML 1992 (Heijungs et al., 1992) which defines the best practice for midpoint indicators, based on the ISO14040 series of Standards.

    - ✓ Eco-indicator 99 allows the calculation of single-point eco-indicator score that can support designers in decision-making (Goedkoop and Spriensma, 2000).

    - ✓ ReCiPe (Goedkoop et al., 2009) combines Eco-indicator 99 and CML 2002 methods by integrating midpoint and endpoint approaches in a rational scheme. All impact categories have also been updated excluding ionizing radiation (De Schryver et al., 2009).

4. Interpretation depicts the results of the inventory analysis and/or impact assessment to reach clear, defensible conclusions.

3.3.1 Life Cycle Assessment Approaches

Process LCA and Input-Output (IO) LCA are two main approaches, whereas their combinations are called hybrid LCAs (e.g., Crawford et al., (2018); Suh et al., (2004a)). We have employed the process LCA, primarily because it is predominantly considered as the more accurate approach of the two for the quality of tracking the actual processes and material and energy flows associated with the production, and delivery chain of the studied object (Säynäjoki et al., 2017a), while input–output LCA runs usually with monetary flows. On the other hand, the input–output LCA approach inherently has a more inclusive system boundary than process LCA, particularly in including capital goods and overheads (e.g., Suh et al., (2004a)). Hybrid methods can thus achieve both qualities of high accuracy and comprehensive coverage

(Crawford et al., 2018; Majeau-Bettez et al., 2011; Pomponi and Lenzen, 2018; Stephan and Crawford, 2019), but they suffer from a few issues that have slowed down their wider application. First, they are much more data-intensive than the individual approach and hybrid data are not easily available. Secondly, IO and hybrid LCAs suffer from aggregation error, arising from the aggregation of several potentially different industry sectors into each IO table sector, which can lead to the assessment either underestimating or overestimating the impacts (Säynäjoki et al., 2017a). In addition, there is a lack of clarity in the description of the methods used in particular studies, making the reproduction of these methods difficult. The fourth is a lack of understanding of the potential benefits of using hybrid data over conventional process or input-output data although some literature can be found on the subject (Crawford, 2008; Lenzen, 2000). Yang et al., (2017) conducted a counterexample and concluded that because of the error due to the aggregation of heterogeneous processes in Input-output models, hybrid LCA does not necessarily provide more accurate results than process-based LCA. Finally, there are no automated tools or software that would allow these methods to be easily used by non-hybrid LCA specialists (Crawford et al., 2018).

3.3.2 Life Cycle Assessment databases

Since conducting a comprehensive LCA is very data intensive, it is justified to utilize the precompiled LCA databases to reduce the workload and then focus on the interpretation of their outputs. Bach and Hildebrand, (2018) reviewed more than 20 LCA tools for environmental assessment of materials, components and buildings. Then, they classify them based on the level of analysis; material, component, and building levels. LCA on the material level calculates the energy and emissions related to the depletion of resources, the generation of energy, and the steps of production. The results are indicators per material, which can be used to compare different products. Computer programs like SimaPro/ecoinvent (PRé Consultants, 2012), GaBi (PE-international, 2015), OpenLCA ("OpenLCA," 2020) and One Click LCA (Bionova Ltd., 2015) are suitable for this purpose. The second level accumulates different materials for a building element. Different planning solutions within a product can be compared against each other.

Athena (Impact Estimator for buildings) can be used for that purpose. In order to conduct a whole-building LCA, other tools such as Tally (KT Innovations, 2016) can be used.

3.3.3 Two types of Life Cycle Assessment

There are two types of LCA: Attributional LCA (ALCA) and Consequential LCA (CLCA). ALCA offers information on the impacts of the processes used to produce (and consume and dispose of) a product, but does not consider indirect effects arising from changes in the output of a product, which is useful for consumption-based carbon accounting. On the other hand, CLCA provides insight on the consequences of changes in the level of output (and consumption and disposal) of a product, including effects both inside and outside the life cycle of the product. Yet, it suffers from high uncertainty, because it relies on models that seek to represent complex socio-economic systems that include feedback loops and random elements (Brander et al., 2008; Plevin et al., 2014).

3.3.4 Carbon Sequestration potential of bio-based materials

Because one of the main objectives of this work was to assess the impact of material choices on the embodied impacts, it is essential to explore the carbon sequestration potential of bio-based materials. In particular, wood has been extensively promoted in the Nordic countries due to its reported low climate change impacts; however, there is a high variability in climate change impact scores, making comparisons with non-wood materials difficult (Head et al., 2020). Levasseur et al., (2013) recognized in their earlier research the significance of considering the biogenic carbon and timing of GHG emissions in both LCA and carbon footprint analyses in a consistent manner. (Peñaloza et al., 2016) researched the climate impact of increasing of bio-based materials in Swedish buildings. They used traditional and dynamic LCA in their assessment process and concluded that increasing the content of bio-based materials in buildings reduces their climate impact when biogenic sequestration and emissions are accounted for. The researchers noted that the level of these reductions is considerably sensitive to the end-of-life scenario for buildings. Pittau et al., (2018) investigated storing carbon potential in biogenic materials together with lime-based products. They concluded in their research that the carbon stored in fast-growing biogenic materials is fully captured after one year from building construction because of the crop regrowth. This conclusion was supported in Pittau et al., (2019) which again proved that using fast-growing biogenic materials, especially straw, capacitates carbon storage and is effective in the short-term when compared to timber.

3.4 Implementation of Life Cycle Assessment

This section describes how LCA was applied in this study to provide answer to research questions.

3.4.1 Goal and scope

Focusing on initial embodied emissions, the common system boundary across case studies include A1-A4 modules because it is the most certain and most important in defining the overall embodied impact. The main reason for excluding embodied impacts from the use phase (such as modules B4, B5) was that replaced materials and products likely cause a lower impact than if built now per material or space unit – due to improvement in the production process and innovative use of material. The secondary reason was the lack of data on replacement schedule and required material. Similarly, Module C1 was excluded due to missing data. Among case studies, the details of information varied, in two cases (Pyry in Paper II and Veröld building in paper IV) very extensive information was found, thus minor materials were included to explore their impacts. Similarly, the system boundaries vary as well due to available data, but all capture the key initial embodied emissions. Further details can be found in chapter four.

3.4.2 Inventory analysis

The main source of inventory data for each case study is briefly explained here. Because of the limited scope of the first case study (Vættaskóli-Engi school building), only the environmental impacts of materials used (including the manufacturing and transportation) in the structure and envelope of the school building are estimated. The inventory data were taken from various sources, including the tender documents, drawings, descriptions and quantity estimates. The life-cycle inventory data for the Pyry and KÄPYLÄ buildings are taken from the bill of quantities which was provided by the contracting companies Skanska, and Design Talo (Design Talo, n.d.), respectively. The main materials used in eight building systems of the temporary refugee shelter are obtained directly from the designer. The inventory data for eight building systems of Veröld building is provided by FSR. Further details for each case study can be found in chapter four.

3.4.3 Life cycle Impact assessment Method

In paper I, the European Commission is the International Reference Life Cycle Data System (ILCD) method, which is fully described in the Life Cycle Assessment handbook (Curran, 2012) and International Reference Life Cycle Data System (ILCD) handbook (EC-JRC, 2010).In Paper II, III and IV the ReCiPe method (Goedkoop et al., 2009) was utilized in the impact assessment with both GaBi and SimaPro/ ecoinvent. In particular, of the ReCiPe Midpoint method (e.g., (Dong and Ng, 2014)), fifteen categories were included in the study. The reason for choosing the Midpoint method was that when stepping into the endpoint method or even into using a single-score indicator, there is a high variation in the understanding of how to assess the different impact categories (Dahlbo et al., 2013). Furthermore, comparisons on individual impact categories like those conducted in this study can only be done on the Midpoint level. Regarding the sensitivity of the results on the GWP impact with carbon sequestration in Paper III, the range of the GWP intensity of each material was obtained from GaBi and SimaPro based on two methods of LCIA–CML 2001 & ILCD 50 years.

3.4.4 Life Cycle Assessment Type

As mentioned earlier, ALCA informs comparisons between the direct impacts of products, and is used to identify opportunities for reducing direct impacts in different parts of the life cycle (Brander et al., 2008). Thus, because the focus was on the impacts of production process, An ALCA approach with no credits for the end-of-life use was selected to capture the impacts induced at the time of construction, or until the beginning of the use phase.

3.4.5 Selection of Life Cycle Assessment database

Since, the objective of this work was to explore the impact of different material on initial embodied emissions, GaBi (PE-international, 2015) and SimaPro/ecoinvent (PRé Consultants, 2012), which are both material and component level tools are selected. Also, it worth mentioning that at the time of conducting the research, both GaBi and SimaPro were the most widely utilized tools at least in the context of academic research. The GaBi software provides the user interface, the environmental information database, and the options for the impact assessment method for the LCA practitioner. In SimaPro, several databases are available, the most widely utilized of which in the building sector is ecoinvent (Säynäjoki et al., 2017a). GaBi includes its own building and construction sector database, and both software packages provide several impact assessment method options. The GaBi version used was 6.4.1.20 (Compilation), with database version 6.108. The SimaPro version 8.0.5.13 with the ecoinvent 3.0 database was employed. Only the existing processes were used and no tailoring according to the actual life cycles of different materials was done, as is the most common practice in the building sector (Säynäjoki et al., 2017a).

3.4.6 Assumptions for the estimation of carbon sequestration potential

While, capturing the sequestration potential of construction material was not the focus on this work, in paper III, based on data from GaBi, Ecoinvent and Environment Product Declaration (EPD), the sequestration potential of a few biogenic material (used in the temporary house in Sweden) is investigated to assess how the choice of different materials can affect the outcome of LCA.

For the wood fibre insulation board (hereafter referred to as 'wood fibre'), information from the EPD for STEICO joist wood-fibre boards was used (Steico SE, 2016). According to EcoInvent, (2010) over its life cycle, quicklime can re-absorb 0.571 kg of CO_2; whereas, Ip and Miller, (2012) report a re-absorption of 0.99kg. In this study, the average value of these two studies, 0.78 kg of CO_2, was applied. In terms of the carbon storage capacities of timber, numerous studies were reviewed (Abbott, 2008; Boutin et al., 2006; PE-international, 2015; Sodagar et al., 2011; Vogtländer et al., 2014). Based on the estimated average value, timber has a negative cradle-to-gate carbon footprint of 1.25 $KgCO_2/kg$. The total CO_2 sequestered in straw is 1.35 $KgCO_2/kg$, based on research conducted by Atkinson, (2008); Sodagar et al., (2011).

3.4.7 Sensitivity Analysis

Sensitivity analysis is a systematic process to quantify the uncertainty in findings by estimating the effects of variation in assumptions, methods, and data on the outcome of the study (International Standard 14040, 2006; International Standard 14044, 2006). Different types of sensitivity analyses and uncertainty importance analyses were reviewed by Björklund, (2002). Quantitative uncertainty importance analysis can be implemented using known uncertainty ranges of input variables, while a Tornado Diagram can be applied to visualize the variations in outputs as a result of the uncertainty of using single parameters (Björklund, 2002). In paper III, an uncertainty importance analysis was conducted to estimate the impact of input uncertainties (selection of material from the database and the method) on the total GWP impact of the refugee house with and without sequestration. It was decided that focus be paid to the four materials with the highest carbon sequestration potential: lime, timber, wood fibre insulation and straw.

After describing the methodology, the following chapter presents descriptions of the case studies. Also, the main features of the analysis, including the scope, method, system boundary, and inventory data are defined.

4 Description of Case Studies

This chapter provides a brief narrative of case studies, including the scope, system boundaries, the method and life cycle inventory (LCI). The justifications for each case study are also given.

4.1 Paper I

4.1.1 Vættaskóli-Engi School Building

The Vættaskóli-Engi school building is in Reykjavik, Iceland, and it was chosen because (i) it is a typical building representative of buildings in Iceland in terms of the architecture, construction technology and basic material use; (ii) this choice enabled us to assess the environmental effects of construction materials as near as possible to the "as built" situation.

The school building has a gross floor area of 5000 square meters. The construction of the building began in 1996 and was commissioned in 1997. The school consists of two main buildings connected with by hallway; one of the main buildings has a basement and two floor levels, the other one is on one level. Foundations, outer walls, floors slabs, and roof slabs of the main buildings are of concrete and part of the interior walls, though some of the interior walls are of lightweight gypsum. The outer walls are insulated on the outside, partly with the rendering/insulation system and partly with ventilated aluminum cladding. The roofs are built as up-side down systems on concrete slabs. The central hallway has an insulated lightweight timber structure which is cladded on the outside with aluminum sheets. Windows and doors are of aluminum, with double glazed insulation glass panes.

The **scope** of the analysis focused on the environmental impacts of materials used (including the manufacturing and transportation) in the structure and envelope of the school building. Besides, because Stone wool is produced in Iceland, using hydropower electricity, it was decided to assess the embodied environmental impacts and compare them with the impacts from stone wool produced in Europe. To account for major environmental concerns, a set of five impact categories were evaluated: global warming potential (GWP), ozone depletion potential (ODP), human toxicity (HT), acidification (AP) and eutrophication (EP). While there is a clear benefit from reporting the non-renewable energy use, due to lack of information regarding the use of non-renewable energies used to produce imported materials, the impacts on non-renewable energy sources are not reported in this study. Two functional units were utilized: the entire school building and one square meter gross floor area of the school building.

The European Commission suggested the International Reference Life Cycle Data System (ILCD) as the official modelling guideline. Thus, the impact categories were assessed using the ILCD method, which is fully described in the LCA handbook (Curran, 2012) and International Reference Life Cycle Data System (ILCD) handbook (EC-JRC, 2010).

The **system boundary** includes four modules of A1-A4: extraction of raw materials (A1), delivery to manufacturing site (A2), fabrication of construction materials (A3) and transportation to the construction site (A4), and thus all initial embodied emissions except for from the construction site activities. The analysis covered the materials utilized in the structure and the envelope of the school building (foundation, beams and columns, floor slabs, exterior and interior walls, roofs, windows, and paint). Surface materials, fixture, fittings, stone filling material in the foundation, electric and heating systems and plumbing were excluded from this analysis. It should be noted that due to the scope of the study being cradle-to-grave (A1-A4), the lifespans of different materials and items are not entered in the assessment in the way they do in assessments over the whole life cycle of a building.

The life-cycle inventory data for analysis were taken from various sources, including the tender documents, drawings, descriptions and quantity estimates. About 95% of buildings in Iceland are built of reinforced concrete. Cement as the central component of concrete was locally produced until 2012, whereas gravel and sand are available in abundance in Iceland. Stone wool insulation is also produced in Iceland, while nearly 79% of the required raw materials by weight are domestic, and the needed electricity is almost entirely generated by hydropower. Other building materials such as lumber, reinforcing steel, metal claddings, structural steel, aluminum window frames, window glass, raw materials for paints, as well as electrical and plumbing materials are imported from different European countries, China, Canada and the US. Table 2 presents a list of materials within the study scope, with the details of the estimated amount and information regarding where the materials are produced. The total weight of building materials for the scope of the school building was around 1.3 ton per one square meter of gross floor area. As expected, the biggest part was due to concrete, which represents 85% of the total weight of the building.

Table 2: Inventory data for building materials used in the Vættaskóli-Engi School (Emami et al., 2016)

Building Materials	**Quantities**	**Unit**	**Density (kg/m³)**	**Export country**
Reinforcing steel	175000.0	kg		Lithuania
Reinforcing mat	17197.8	kg		Lithuania
Concrete	2505.0	m³	2278	Iceland
Glued laminated timber	15.42	m³	515	Norway
Corrugated steel cladding	2820	m²	7850	Finland
insulation, hard pressed stone wool	12.3	m³	100	Iceland
insulation, hard pressed stone wool	306.8	m³	80	Iceland
insulation lightweight stone wool	234.4	m³	32	Iceland
Polyethylene High density	575	m²	950	Germany
Gypsum plaster board	8908.0	m²	800	Denmark
Aluminum window	625	m²		Germany
Expanded Polystyrene	210.0	m³	25	Germany
Extruded polystyrene	400.5	m³	32	Germany
Underroof membrane	2670.0	m²		Germany
Plywood board	13.4	m³	575	Finland
Built up asphalt	3845.0	m²		Denmark
Concrete roofing tile	131.8	m³	2100	Iceland
Plaster	148.6	m³	2000	Iceland
Paint	2.1	m³	1350	Norway

4.2 Paper II

One of the main findings of the first paper was the significant difference in the Ozone Depletion Potential (ODP) intensities between GaBi and SimaPro databases. Therefore, the **scope** of the second paper was to test the uniformity of the two LCA database-software combinations (see the review of (Säynäjoki et al., 2017), called tools herein, ecoinvent with SimaPro software (Pre-sustainability, 2012) and GaBi software-database (PE-international, 2015), in providing estimates for initial embodied environmental impacts of residential construction. Two different types of residential buildings, a concrete-element multi-story residential building and a detached wooden house, both located in Finland, were assessed as if both tools were used independently of each other; using the best fitting sectors/processes case by case. Only the existing processes were used with both tools. Two perspectives were analyzed: key building systems and key material categories. The assessments were conducted in the manner of a typical practitioner, using the tool as it is without adjustments or localization, to see how significant the discrepancies potentially are in building assessments with different tools. The ReCiPe method (Goedkoop et al., 2009) was selected due it having been recommended by the LCA community for several impact categories.

Pre-use life cycle stages according to the standard EN 15804 (CEN, 2013) were included in the paper II. For the concrete building, the **system boundary** included the modules A1–A5: A1 "raw material supply", A2 "processing phase transport", A3 "production of construction materials", A4 "transportation to the construction site" and A5 "construction site activities". Due to data limitations for the wooden house (KÄPYLÄ), the **system boundary** only covers three modules of A1–A3.

4.2.1 Multi-story Concrete Element Apartment Building, Pyry

The first building is a typical contemporary concrete element low-energy apartment building, built in the new residential area of Härmälänranta in Tampere, Finland, in 2012. The building, named Pyry, has 28 apartments and altogether 3085 m2 of gross floor area. Following the Finnish Building Classification System Talo2000 (Building2000) (The Building Information Foundation RTS, 2015), the building includes eight systems. In this study, materials used in all except the first system (which covers earth and groundwork) are included, (see Heinonen et al., (2016) for a detailed description).

The life-cycle inventory data is taken from the bill of quantities was provided by the contracting company Skanska, following the Finnish Building Classification System Talo2000 (Building2000), including the distribution of approximately 700 items. Some material quantities were calculated based on building drawings. The current study encompasses close to 100% of all the construction materials and construction site energy and materials, and the assessment has been updated. Only the items not listed in the bill of quantities fall outside of the scope of this study, like screws and nails, plus the site preparation and the external environment: site clearing, excavation, and driveways and parking lot. All waste from the site was incinerated for energy, which was also excluded from the assessment. Table 3 presents eight building systems split according to main materials in each system.

Table 3: The main materials in eight building systems of Pyry (Emami et al., 2019)

Building System/Sub-System	Main Material	Quantity	Unit
1. Earth and ground work *			
2. Foundations and external structures			
Footings	Reinforcing steel	15,284	kg
Enclosure walls, foundation columns	Concrete	256	m^3
Bearing ground floor	Polystyrene foam slab	5262	kg
Civil defense shelters	Polypropylene, granulate	47	kg
Special structure	Bitumen adhesive compound	421	kg
External structure	Gravel	3908	kg
3. Frame and roof structures			
Bearing walls	Reinforcing steel	72,238	kg
Hollow core slabs	Concrete	1242	m^3
Stairs	Steel, low-alloyed	7545	kg
Concrete external walls	Rock wool	10,261	kg
Wooden external walls	Polyurethane, flexible foam	11,856	kg
Balconies, special external decks	Sawn timber	7.90	m^3
Attic floor and roof	Lightweight concrete block	3228	kg
4. Complementary works			
Windows	wood-aluminum frames	355	m^2
External doors	aluminum frames	80	m^2
Internal doors	Wood	271	m^2
Lightweight partition walls	Brick	11,994	kg
Railings and ladders	Steel, low-alloyed	1587	kg
Flues	concrete	59	m^3
5. Finishes			
Roofing	Bitumen adhesive compound	8691	kg
	Steel, low-alloyed	7.50	kg
	Polyvinylchloride	16	kg
Interior wall claddings	ceramic tiles	10,416	kg
Ceilings	Gypsum plaster board	4270	kg
	Glass wool mat	588	kg
Floorings	Cement cast plaster floor	4380	kg
	Ceramic tiles	5323	kg
Saunas	Sawn timber	2.31	m^3
	Plywood	7.00	m^3
	Polyurethane	586	kg
Painting	Paint	1572	kg
6. Fittings, equipment and installations			
Kitchens, Hallway, and Closets	Chipboard	29,369	kg
	Steel	380	kg
Bathrooms	Ceramic tiles	1976	kg
Accessories	Steel, low-alloyed	123	kg
	Aluminum	67	kg
7. Mechanical works			
HVAC and electrical systems	Steel	1950	kg
	Powder coating steel	9150	kg
	plastic	1046	kg
	Polyvinylchloride	519	kg
Elevator	Steel	505	kg
	Aluminum	254	kg

	Copper	1252	kg
	Polyethylene, LDPE	2402	kg
8. Construction site			
Energy	Electricity	339,355	MJ
	Diesel	456,300	MJ
	Heat	402,127	MJ
Water	Water	329,478	kg
Crane foundation	Reinforcing steel	445	kg
	Concrete	10	m^3

* Not included in the assessment.

4.2.2 Detached Wooden House, KÄPYLÄ 149E

The detached wooden house is called KÄPYLÄ and has been designed by Design Talo (Design Talo, n.d.), which provided the bill of quantities. The house is currently being built in Espoo Finland. It has two floors and a gross floor area of 149 m^2 (each floor about 75 m^2). The analysis covered the materials utilized in all parts of the primary and secondary structure of the wooden low-energy detached house; foundation, frame and roof structure, cladding, roof equipment, rainwater system, walls, floors, exterior and interior cover materials, all insulation materials, electrical system, heating, ventilation and air conditioning (HVAC), and complementary work such as windows and external doors. The internal doors and finishes such as the sauna, partition walls, painting, home appliances, and fixed inventory are not included. Installation tools like screws, tapes, and similar objects with no major influence were not assessed.

The life-cycle inventory data for analysis is taken from the bill of quantities provided by the company. These quantities were converted to the different utilized materials according to descriptions and drawings provided by the company. As with Pyry, some material quantities, such as electrical and plumbing systems, were added to the list of materials based on the material requirement calculations of the authors. In the assessment, it was not always possible to find the exact material or product in the databases. In such a case, the material that was the best fit to the inventory data was selected. Table 4 presents the eight building systems split of KÄPYLÄ along with the main materials in each system.

Table 4: The main materials in eight building systems of KÄPYLÄ (Emami et al., 2019)

Building System/Sub-System	Main Materials	Mass	Unit
1. Earth and Groundwork *			
2. Foundations			
Foundation	Pre-cast concrete	15	m³
	Reinforcing steel	420	kg
3. Frame and Roof Structures			
Roof (structure, cladding, roof equipment, rain water)	Glued laminated timber	1.99	m³
	Pine wood, timber	1.28	m³
	Steel hot rolled coil	231	kg
	Zinc, special high grade	54	kg
	Aluminum, primary, ingot	13	kg
Walls	Gypsum plasterboard	730	m²
	Pine wood, timber	23	m³
	Medium density fiberboard	1.29	m³
	Steel hot dip galvanized	1.80	kg
	Plywood	0.19	m³

Floors	Reinforcing steel	486	kg
	Pre-cast concrete	5	m³
Insulation	Rock wool	30	m³
	Glass wool	71	m³
	Polystyrene foam slab	18	m³
	Extrusion, plastic film	14	kg
4. Complementary Works			
Windows	Wooden frame window	65	m^2
Doors	Door, outer, wood-glass	6.87	m^2
Flooring	Cement cast plaster	200	kg
Roofing	Bitumen adhesive compound	0.18	m³
5. Finishes *			
6. Fittings, Equipment and Installations *			
7. Mechanical Works			
Electrical system	Aluminum, primary, ingot	5.35	kg
	Polyethylene	118	kg
	Chromium steel	49	kg
	Copper	96	kg
HVAC	Pine wood, timber	1.34	kg
	Polyethylene	108	kg
	Chromium steel	9.32	kg
	Copper	10	kg
	Brass	2.48	kg
	Porcelain	106	kg
8. Construction Site *			

* Not included in the assessment.

4.3 Paper III

Temporary shelters normally carry a high environmental burden due to their short lifespan, and the majority are fabricated from industrially manufactured materials. Paper III assesses the carbon impact of a refugee house in Sweden using LCA, selected to provide insight on the impacts of using natural materials (plant-based fibres, such as straw, reeds and wood) in new building construction. The other objective was to improve our understanding of the previously recognized uncertainty related to including or excluding the carbon storage capacity of natural materials.

4.3.1 Minus carbon temporary refugee shelter

The house is 37 m^2 and designed to suit the needs of a refugee family (two adults and one child). The main construction materials were plant-based fibres (straw, reeds, and wood) together with clay brought to the building site from the surrounding area. The project is in Brunnshög, Lund, which is in the Scania region (Skåne) located in the southern part of Sweden. This study focuses on a LCA carried out through an experimental urban living lab whereby a 37m² minus carbon temporary refugee shelter was designed and constructed. The mission was to build an affordable, low-impact house in only 11 working days with the help of 7 refugees who are amateurs in the construction industry. The key idea of this shelter was to achieve net minus carbon emissions during material extraction, building construction, operation and after end-of-life. The design of the building was intended to boost the energy supply for heating and cooling to extend beyond the current passive building standards. The house is designed to be energy self-sufficient and is equipped with renewable energy sources.

The scope was limited to Global Warming Potential (GWP) impact of the refugee house over its entire life cycle (production, operation and maintenance, and end-of-life). A sensitivity analysis was performed to explore the impact of input uncertainties (selection of material from the database and the method) on the total GWP impact of the refugee house with and without sequestration. The LCA focuses only on its GWP due to the central role of climate friendliness in the house's design, which is clear from the minus carbon target set for it.

The **system boundary** of the LCA for the shelter, according to the standard EN 15804 (U.S. Green Building Council, 2012), includes A1-A5, B1-B6 and C1-C4 stages: A1 "Raw material supply", A2 "Processing phase transport", A3 "Production of construction materials", A4 "Transportation to the construction site", A5 "Construction site activities", B1 "Use", B2 "Maintenance", B3 "Repair", B4 "Replacement", B5 "Refurbishment", B6 "Operational energy use", C1 "Demolition", C3 "Waste processing" and C4 "Disposal".

Based on the Finnish Building Classification System, Talo2000 (Building Information Foundation RTS, 2015), each building includes eight systems. In this study, the materials used in all except System 5 (Finishes) are included. The reeds on external walls, the solar PV and wind turbine that are classified under Systems 3 and 7, are excluded from the analysis. Table 5 presents the building systems split, along with the main materials in each system. It shows the quantities of the principle materials used in each system also in addition to the material's name, selected from the SimaPro/ecoinvent and GaBi databases.

Table 5: The main materials in eight building systems of the temporary refugee shelter (Dabaieh et al., 2020a)

Building system / sub-system	Mass	Unit	Material's name in SimaPro/ecoinvent & GaBi
1. Earth and ground works			
Excavation			
Digging for earth pipes	18	m^3	Excavation, hydraulic digger {RER}(SimaPro)
Drains & pipelines			
Subsurface drains and piping	83.83	m	Polypropylene, granulate {RER}(SimaPro)
2. Foundations			
Foundation walls, columns and ground beams			
Rammed earth	13.5	m^3	Rammed earth wall (DE) (GaBi)
STEICO joist cross section	120	kg	Cleft timber, measured as dry mass {SE}[1] (SimaPro)
HDF	54	m^2	High density fiberboard (HDF) (DE) (GaBi)
Wooden beam	59	kg	Cleft timber, measured as dry mass {SE}[1](SimaPro)
Lime base	450	kg	Lime, hydrated, packed {CH}(SimaPro)
Concrete block	400	kg	Autoclaved aerated concrete block {CH}(SimaPro)
Metal base	100	kg	Steel, low-alloyed, hot rolled {RER}(SimaPro)
3. Frame and roof structures			
Wooden framework	311.5	kg	Cleft timber, measured as dry mass {SE}[1](SimaPro)
Casein	1.26	m^3	Milk protein for paint

[1] Density: 350 kg/m^3

Breather membrane	63	m^2	Rock wool, packed {CH}(SimaPro)
Wood board	2.835	m^3	Cleft timber, measured as dry mass {SE}[1](SimaPro)
STEICO joist	25.2	m^3	Wood fibre insulation board (dry process) (DE) (GaBi)
Airtight membrane	63	m^2	Kraft paper, unbleached {RER}(SimaPro)
Timber ceiling	1.26	m^3	Cleft timber, measured as dry mass {SE}[1](SimaPro)
Load bearing internal walls and columns			
Wood framework	115.5	kg	Cleft timber, measured as dry mass {SE}[1](SimaPro)
Straw bales	3.25	m^3	Straw {CH}| barley production (SimaPro)
Lime	0.2	m^3	Lime {CH}| production, milled, loose (SimaPro)
Clay	0.4	m^3	Clay plaster {CH}| production (SimaPro)
Sand	0.4	m^3	Sand {CH}| gravel and quarry operation (SimaPro)
Stairs			
Rammed earth	0.2	m^2	Rammed earth wall (DE) (GaBi)
External walls			
Wood framework	1610	kg	Cleft timber, measured as dry mass {SE}[1](SimaPro)
Straw bales	17	m^3	Straw {CH}| barley production (SimaPro)
Lime	1.2	m^3	Lime {CH}| production, milled, loose (SimaPro)
Clay	2.4	m^3	Clay plaster {CH}| production (SimaPro)
Sand	2.4	m^3	Sand {CH}| gravel and quarry operation (SimaPro)
4. Complementary works			
Windows			
Wooden frame	66.5	kg	Cleft timber, measured as dry mass {SE}[1](SimaPro)
Glass	6.7	m^2	Flat glass, uncoated {RER}(SimaPro)
Trombe wall			
wooden frame	24.15	kg	Cleft timber, measured as dry mass {SE}[1](SimaPro)
glass	11.5	m^2	Flat glass, uncoated {RER}(SimaPro)
wooden shutters	0.009	m^3	Cleft timber, measured as dry mass {SE}|(SimaPro)
Green wall			
wood frame	3.15	kg	Cleft timber, measured as dry mass {SE}[1](SimaPro)
glass	11.4	m^2	Flat glass, uncoated {RER}(SimaPro)
irrigation pipes	15.95	m	Polypropylene, granulate {RER}(SimaPro)
plastic plant pot	0.499	m^3	Polypropylene, granulate {RER}(SimaPro)
Doors			
Standard exterior single door	33.08	kg	Cleft timber, measured as dry mass {SE}[1](SimaPro)
Standard interior single door	66.15	kg	Cleft timber, measured as dry mass {SE}(SimaPro)
5. Fittings, equipment and installations			
Kitchen & Bathroom			
Kitchen cupboards	159.95	kg	Cleft timber, measured as dry mass {SE}[1](SimaPro)
Kitchen sink	1	pieces	Steel, low-alloyed, hot rolled {RER}(SimaPro)
Bathroom cupboards	3.12	kg	Cleft timber, measured as dry mass {SE}[1](SimaPro)
Bathroom sink	1	pieces	Sanitary ceramics {CH}(SimaPro)
Shower head	1	pieces	Steel, low-alloyed, hot rolled {RER}(SimaPro)
Drain	1	pieces	Steel, low-alloyed, hot rolled {RER}(SimaPro)
Toilet	1	pieces	Sanitary ceramics {CH}(SimaPro)
6. Mechanical works			
Electrical system			
Electric copper cables in plastic pipes	14	m	Polyethylene, low density, granulate {RER}| production (SimaPro) Copper {SE}(SimaPro)
Electricity plastic sockets	3	piece	Polyethylene, low density, granulate {RER}| production (SimaPro) Steel, chromium steel 18/8 {RER}(SimaPro)

7. Construction site			
On-site fuel use			
Electric power station (generator) (Petrol)	10	Litres	Petrol, unleaded {CH}| petroleum refinery operation (SimaPro)

* CH: Switzerland, DE: Germany, RER: Europe, SE: Sweden.

4.4 Paper IV

Given the range of environmental impacts caused by the buildings and given the pressing need to rapidly develop sustainable solutions to mitigate the current global climate crisis, one suggestion is to modify LEED to work toward initial embodied emissions targets beside energy reductions. Therefore, the fourth paper aimed to find the most environment-friendly selection of building material using LCA as a sustainability tool and evaluate its effect on the number of obtained points in a widely used green building certificate i.e. LEED.

4.4.1 Veröld building

The case building is a modern educational facility at the University of Iceland in Reykjavik (Iceland), the full name of the building is Veröld – the House of Vigdís, named after the former President of Iceland Vigdís Finnbogadóttir. The construction of the building started in March 2015 and finished in March 2017. The building houses teaching, research and events connected to foreign languages and culture.

The **scope** of the LCA study was to estimate initial embodied environmental impacts of materials used in the case building and compare the base case to alternative low-carbon options. The ReCiPe midpoint method were used in this assessment. The functional unit was one square meter of gross floor area of the case building.

The **system boundary** of the paper IV is the pre-use life cycle stages (A1-A4). These are: A1 "Raw material supply", A2 "Processing phase transport", A3 "Production of construction materials" and A4 "Transportation to the construction site". Construction (A5) and demolition phase were excluded because of their low contribution. Since the operation phase is from renewable sources it was not included in the study (Amiri et al., 2021).

The case building has four floors and a gross area (GA) of 4013 m^2 and includes an underground floor, ground floor, and two above ground floors. Underground and ground floors comprise a lobby, auditorium, and big classes, among others, while the first and second floors include offices. Table 6 presents the main materials in eight sub-systems of the building obtained from FSR (FSR, 2017). It was tried to have as much coverage as possible in order to increase the validity of results.

Table 6: The main materials in eight building systems of Veröld building (Amiri et al., 2021)

Building System/Sub-System	**Main Material**	**Quantity**	**Unit**
1. Excavation			
Facilities *			
Earth works	Excavation	23400	m^3
Removal of existing structures and cleaning *			
Facilities *			
Earth works *			
2. Structures			
Formwork, concrete *			
Reinforcement	Reinforcing Steel	285000	kg
Steel fasteners in concrete *			
Concrete	Concrete, 30-32MPa	2780	m^3
Concrete elements	Concrete, 50MPa	38	m^3
Insulation of foundation and basement slab	Polystyrene foam slab (EPS)	3387.5	kg
Steel works	Steel, low-alloyed	37007	kg
Construction wood	Sawn wood, beam, hardwood	40	m
3. Pipes			
Sewage- and drainpipes	Polypropylene, granulate	6922	kg
Tap water system	Stainless steel	514	kg
Heating system	Polypropylene, granulate	5144	kg
Snow melting system (outdoors)	Polypropylene, granulate	1062	kg
	Stainless steel	824	kg
	Polyethylene, LDPE	800	kg
Sprinkler system	Stainless steel	4628	kg
Ventilation system	Stainless steel	12345	kg
	Stone wool	1080	kg
Sanitary equipment	Sanitary ceramics	942	kg
4. Electrical wiring			
Electrical wiring lines	Steel	11920	kg
	Polypropylene, granulate	1984	kg
	Aluminum	112	kg
	Copper	215	kg
Wiring	Copper	178	kg
Low voltage system	Network cable, category 5	1764	kg
Lighting system *	Lamps		
Lighting Control system *	Installation and programming		
Control system *	Sprinkler, ventilation		
Communication systems *	Sockets/outlets		
Safety systems *	Smoke detector		
5. Interior finishing			
Insulation and rendering	Polystyrene foam slab (EPS)	3841	kg
	Cement mortar, at plant	41	m^3
	Sand, at mine	62	m^3
	Concrete, 35MPa	1.0	m^3
	Basalt	18	m^3
Light weight interior walls and claddings	Gypsum plaster board	3700	m^2
	Stone wool	3471	kg
	Saw log and veneer log-oak	5	m^3
Flooring materials	Linoleum flooring	2165	m^2
	Carpet	113	m^2
	Strip parquet	120	m^2

Ceilings	Stone wool	2093	kg
	Gypsum plaster board	284	m^2
	Saw log and veneer log-oak	3	m^3
Interior doors and windows	Door, wood-aluminum	320	m^2
	Window frame, aluminum	155	m^2
Painting	Gypsum plaster board	76	m^2
	Acrylic varnish	1669	kg
Carpeting	Saw log and veneer log-oak	0.7	m^3
Interior steelwork*	Steel		
Interior*	Cabinets		
6. Equipment *			
7. Outdoor finishing			
Painting*			
Wall claddings	Polystyrene foam slab (EPS)	26535	kg
	Stone wool	530	kg
Roof finishing	Asphalt supporting layer	216611	kg
	Underroof membrane	302	kg
	Concrete roof tile	2268	kg
Windows, glass and external doors	Window frame, aluminum	519	m^2
Various	Saw log and veneer log-oak	2	m^3
8. Finishing of outdoor plot surfaces			
Finishing of outdoor plot surfaces	Asphalt supporting layer	161563	kg
	Concrete, normal	1.4	m^3
	Prefabricated concrete ceiling	1834	m^2
Surface finishing*			
Grass and plants*			
Devices*			

* Not included in the assessment.

The case environment was selected purposefully so that all major building materials must be imported to avoid the local bias in results, whereas the operation phase is from renewable sources. However, it is worth mentioning that typically there is predefined preference of selection of building materials in different locations of the world, and thus, it is recommended to use the local material. But the situation is different in the case of countries that do not have adequate material resources or have limited selection and materials are forced to import. This study includes an evaluation of the environmental sustainability of building materials for housing construction in Iceland based on both LCA results and attainable number of points in LEED system. The results are valuable for other locations with the same situation as Iceland. We explored the impact of different decisions at the design stage on LEED rating, and discuss the adaptability of LEED in locations where operation phase has low importance, and the emission loads are largely generated during the pre-use phase.

In addition to the base case, three other scenarios were designed in order to evaluate how material selection affects the results of LCA and LEED. In all scenarios, the U-values are the same to have equal operation energy use. It should be mentioned that as energy for buildings (heating and lighting) in Iceland is geothermal and hydropower generated with low cost, the energy efficiency requirements are lower than in other countries with similar climate (Amiri et al., 2021).

Base case - Concrete building (Con)

In the base case most building components, i.e., column and beams, structural external and internal walls, non-structural walls and slabs, are made of reinforced concrete. Gypsum boards have been used mainly for partition walls in the first and second floors with rendering and painting. There is insulation for concrete external walls and slabs. Also, sound insulation has been used for auditorium.

Scenario 1 - optimized concrete building (OptCon)

We studied two types of concrete, i.e., one with a high (C30) and the other with low (C20) level of strength. In practice, it might be harder to manage in the construction phase. This will result in a lower use of cement for concrete. For this purpose, all walls that are structural, have been separated with non-structural ones. In addition, all gypsum walls in above ground floors have been replaced with concrete C20 walls. The other parts remain the same compared to the base case.

Scenario 2 - Concrete wooden building (ConWood)

Compared to OptCon, in this scenario all non-structural walls have been replaced with wooden walls with an area of 785 m^2. Similarly, gypsum walls on above ground floors have been replaced with wooden walls. In addition, flooring material for all floors has been changed to hardwood for custom areas and parquet for private ones. Furthermore, the internal windows have been replaced with wooden ones. All the alternative components in this scenario, including the non-structural wooden walls, hardwood and parquet flooring, and wooden windows have third-party green certificates and environmental product declarations (EPD).

Scenario 3 - Wooden building (Wood)

Except for the foundation and underground floor detail, in this scenario all materials, i.e., structural and non-structural walls, internal and external windows, floors and roof, have been replaced with wood. Cross-laminated timber (CLT) has mainly been used for the building; details regarding the structural and non-structural walls, floors and roof, are presented in the supplementary files. Similar to the ConWood building, the alternative components in this scenario have third-party green certificates and EPD.

After describing the main features of case studies, chapter five presents the key results of each case study and how they address research questions.

5 Results

All the case studies discussed in the dissertation contribute to both research questions. After conducting a set of LCA case studies and exploring the consistency between two LCA database-software combinations, it was found that the LCA can help with estimating the initial embodied emissions caused by different types of buildings Yet, the results should be interpreted cautiously, mainly because based on the second case study, the selection of LCA database can result in very different evaluation in almost all impact categories (the inconsistency in GWP and fossil depletion results were relatively low).

The following subsection present the findings of each paper and how they can help to answer both research questions. Each paper has a distinct viewpoint with respect to the research problem and makes a unique contribution to the conclusions presented later in the dissertation.

5.1 Paper I

5.1.1 Contribution to the RQ

In response to the first research question, the first study provides an assessment of initial embodied environmental impacts of a school building in Iceland on five impact categories, which is the essential step to find the contribution of different materials to various environmental impact categories. The share of transport in embodied impacts, often not explicitly considered forming a weakly understood uncertainty factor, was estimated for all impact categories. Besides, the environmental impacts of domestically produced materials (concrete and stone wool) have been estimated in order to capture the mitigation potential.

5.1.2 Paper summary

Overall environmental impacts

The initial embodied GHG emissions of the school building were calculated to be 1275 tons of CO_2 eq (255 kg CO_2 eq/m^2 gross floor area). Long distance transportation of material was only responsible for around 5% of the emissions. In addition, we estimated that locally produced cement can reduce GHG emissions by 14.5 kg CO_2 eq/m^2 (depending on the import assumption) in comparison to the present state of its being imported. Of the locally produced materials, the nearly carbon-free electricity system significantly benefits stone wool, but not concrete due to the limited amount of electricity used in cement and concrete production.

Table 7 illustrates the total environmental impacts and per one square meter of gross floor area impact of construction materials utilized for the structure of the school building on GWP, ODP, HT, AP and EP.

Table 7: The results of total environmental impacts and per one sqm gross floor area impact of the school building by impact categories (Emami et al., 2016)

Impacts categories	Total impacts	Total impacts per one sqm
Global warming potential (GWP)	1275 ton CO_2 eq	255 kgCO_2 eq
Ozone depletion potential (ODP)	6.80E-03 kg CFC 11 eq	1.36E-06 kg CFC 11 eq
Human Toxicity (HT)	0.16 CTUh	3.23E-05 CTUh
Acidification (AP)	4.44 kmol of H+ eq	0.88 Mole of H+ eq
Eutrophication (EP)	11.44 kmol of N eq	2.28 Mole of N eq

The contribution of construction materials to five environmental impact categories (GWP, ODP, HT, AP and EP) are compared in Figure 5. The variation is significant and depicts the considerable differences between the mitigation potential of materials across five impact categories (Emami et al., 2016).

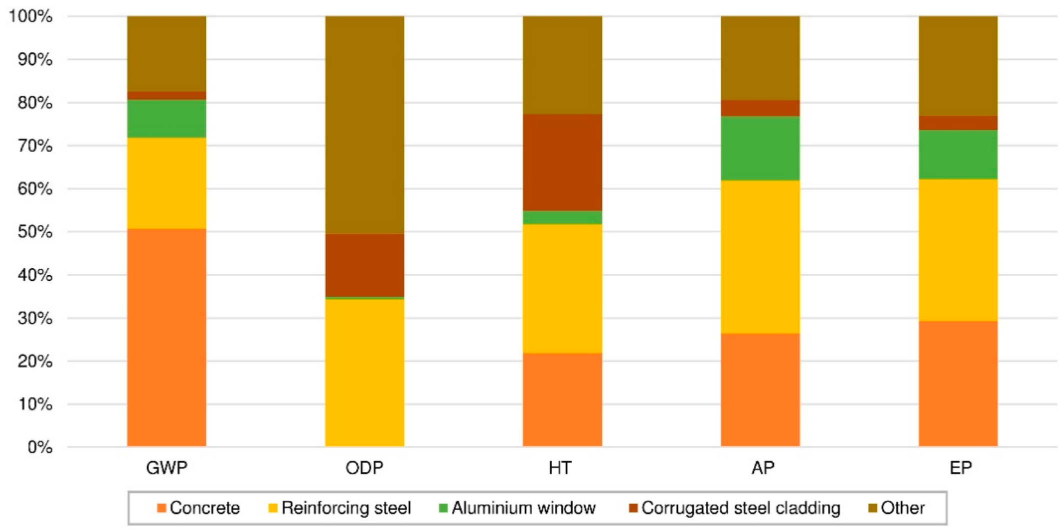

Figure 5: Total environmental impacts for modules A1-A4 by construction materials used in the school building[2] (Emami et al., 2016)

Concrete, reinforcing steel and aluminum windows represent 51%, 21% and 9% of total GWP impact from school building, respectively. It should be noted that the main component of concrete is cement, and it represents over 95% of total greenhouse gas emissions from concrete. Reinforcing steel is the major contributor for ODP, HT, AP and AP impacts, accounting for 34%, 30%, 35% and 33% of total ODP, HT, AP and AP impacts, respectively. Regarding the ODP impact, the contribution of concrete seems to be negligible. However, when comparing the ODP intensities between GaBi and SimaPro databases, it appears that the impact factors per 1 kg of concrete in GaBi and SimaPro are significantly different, 1.74E-12 and 3.71E-09, respectively. The reasons for the difference should be studied further, however, to draw further conclusions (Emami et al., 2016).

Transportation

The impact of transportation was found to be significant only on AP (25%) and EP (31%), while its impact on other impact categories were relatively small (5% or less). Two cases were

[2] The group of "Other" includes paint, plywood board, underroof membrane, glulam, stone wool, HDPE, plaster, EPS and XPS.

compared to capture the advantages of using domestic materials and also to assess the impact of transportation on selected environmental categories. It is clear that using locally produced cement can reduce the environmental impacts particularly in terms of AP and EP in the context of Iceland (Figure 6).

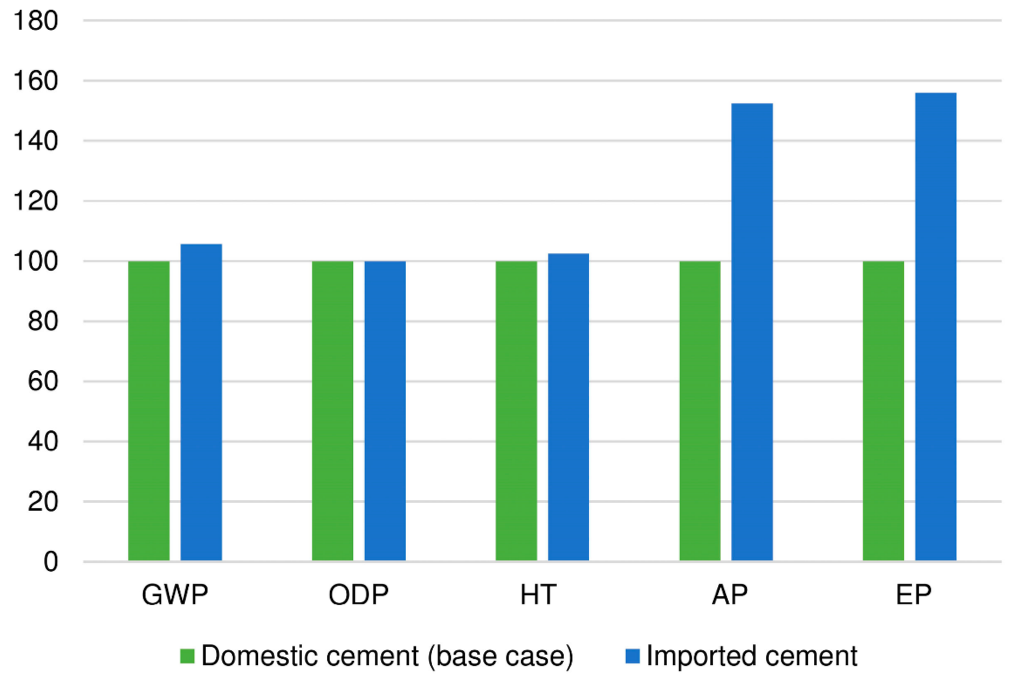

Figure 6: Normalized comparison of total environmental impacts from two cases for concrete production; Base=100 for cement produced in Iceland, imported cement: cement imported from Europe (Emami et al., 2016)

5.2 Paper II

5.2.1 Contribution to the RQ

The second study is designed to provide an answer to the second research question about the reliability of LCA results. The impact of selecting the LCA database to assess initial embodied environmental impacts of construction materials was investigated in order to recognize the consistency and discrepancies between their outputs. Two very different types of buildings, yet representing common practices in construction in Finland, were chosen to reduce the impact of the case selection. It was clear that there is little uniformity in the results for different material groups. Even for the most basic materials, Concrete and Cement Products and Steel and Other Metals, the results for different impact categories vary significantly.

5.2.2 Paper summary

Comparison of results at Building Level

There is a considerable difference between the estimated impacts with two LCA databases at building level. Figure 7a,b show GaBi estimates when SimaPro is set as 100 for each impact category. It is clear that for Climate Change category, the estimates are rather consistent for both cases, although the GaBi result for Pyry is still 16% below the estimate from SimaPro/coinvent and 13% higher for KÄPYLÄ (Emami et al., 2019).

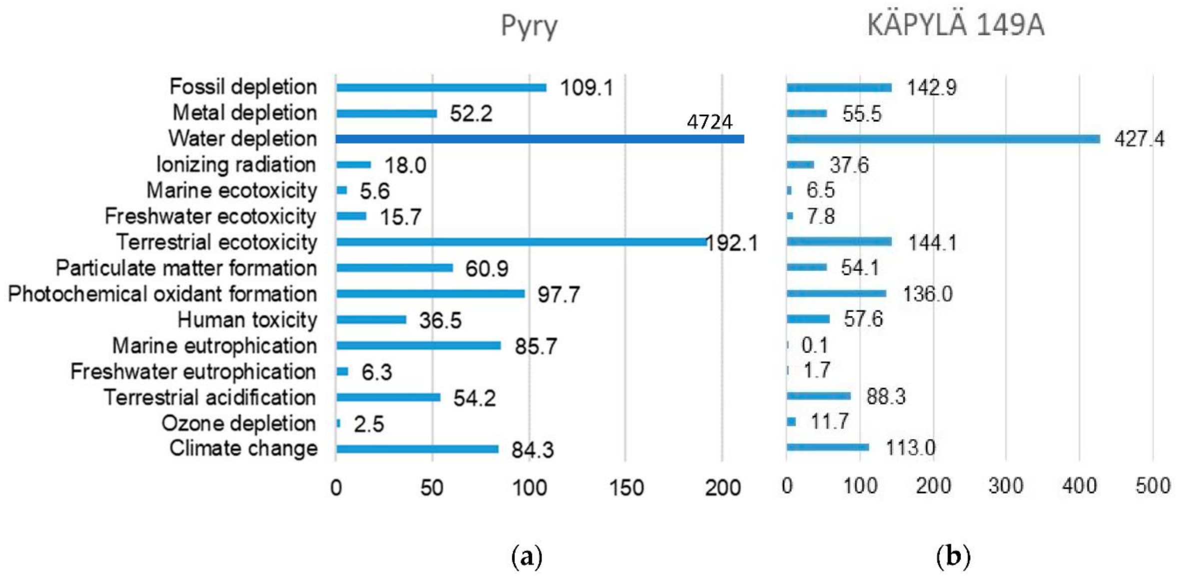

Figure 7: Assessment results for a) Pyry and b) KÄPYLÄ, GaBi estimates when SimaPro = 100 (Emami et al., 2019)

Interestingly, the GaBi assessment returned overall lower estimates, often significantly lower, as depicted in Figure 7. For Pyry, the estimates were lower in all categories, except in Terrestrial Ecotoxicity, Water Depletion, and Fossil Depletion. From this perspective, the two tools give relatively similar results. For KÄPYLÄ, the same three categories have higher estimates, plus Photochemical Oxidant Formation and Climate Change, which have only slightly lower estimates from GaBi for Pyry.

Impacts by Building Systems

Figure 8 provides the breakdowns by the building systems of fifteen environmental impacts of Pyry building. In overall, limited consistency between the tools was observed, except for GaBi returning lower values. For Climate Change, the category for which the highest uniformity was anticipated, the main difference with Pyry relates to the most concrete and steel-intensive system, Frame and Roof Structures. With KÄPYLÄ, see Figure 9, the estimates by GaBi and SimaPro/coinvent are comparable for most of the building systems. The main overall difference relates to the Climate Change impact of windows.

Impacts by Materials

We also assessed the uniformity of results based on seven material types: Concrete and Cement Products, Steel and Other Metals, Wood, Plastic and Oil Products, Glass, Bricks and Tiles, and Other, plus Fuels and On-Site Energy and Transport. Again, little consistency was witnessed in the results for different material groups. Even for the most basic material categories, Concrete and Cement Products and Steel and Other Metals, the results for different impact categories vary significantly (Emami et al., 2019).

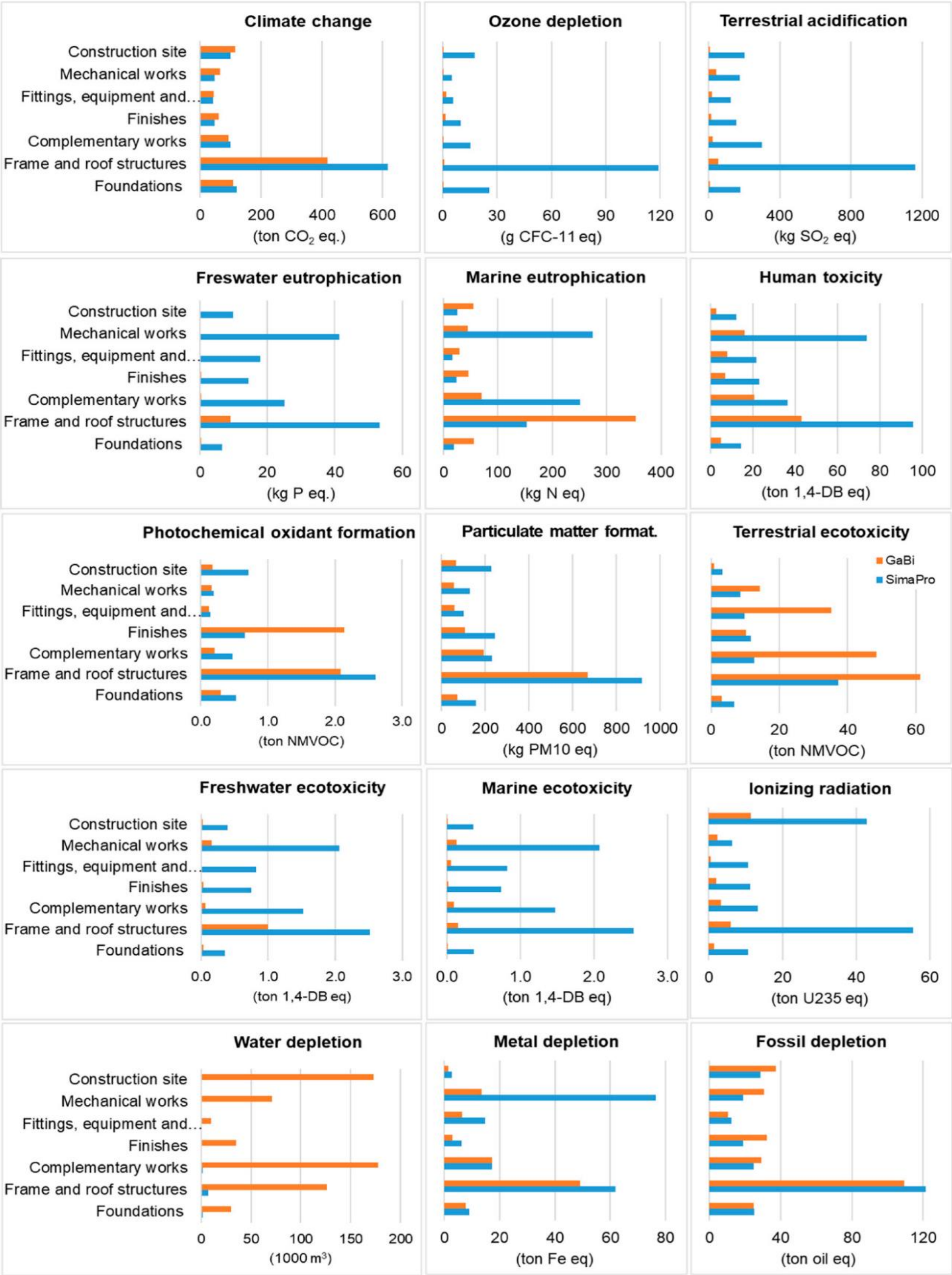

Figure 8: Breakdowns of 15 environmental impacts of Pyry by building system (Emami et al., 2019)

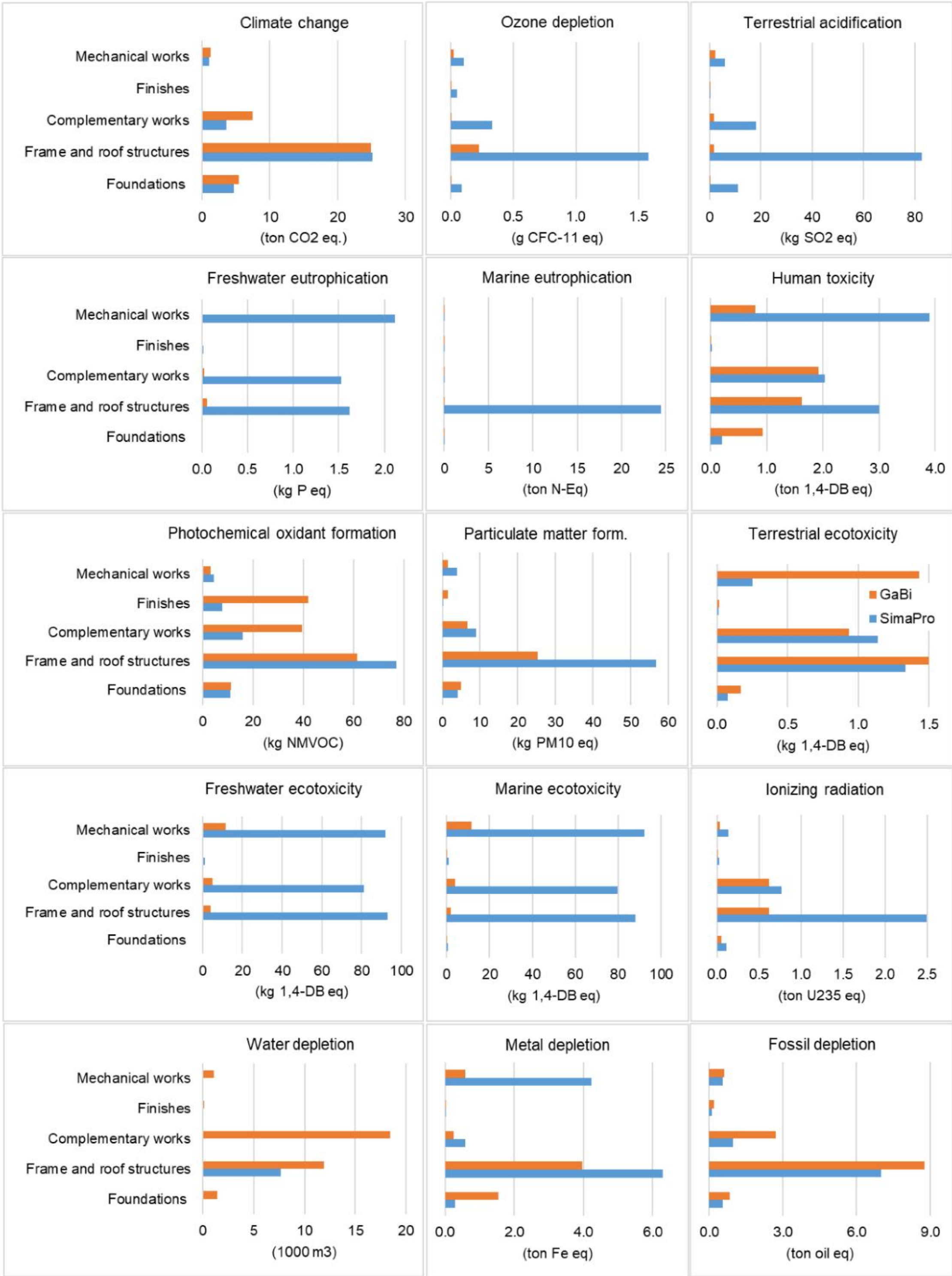

Figure 9: Breakdowns of 15 environmental impacts of KÄPYLÄ by building system (Emami et al., 2019)

5.3 Paper III

5.3.1 Contribution to RQ

The third study examines the potential of mitigating initial embodied environmental impacts by using specific natural materials (compressed straw and reed panels as the main source of wall construction material together with wood frames in the straw panels, the wooden floor, the roof structure, and wooden furniture) and quantifies the impact of uncertainties in the sequestration capacity of those materials in the overall emissions. Thus, the findings contribute to the first research question regarding initial embodied environmental impacts of natural materials.

5.3.2 Paper Summary

Overall GWP with and without sequestration

Table 8 presents the results of the total and per square meter GWP impact of the house with and without sequestration. The GWP of the shelter house without and with sequestration was found to be 254.7 kg CO_2 eq/m^2 and -226.2 kg CO_2 eq/m^2, respectively. Compared to the estimation for two temporary houses by Atmaca, (2017), the calculated GWP without the sequestration is 11-15% lower. The main contributor to the GWP impact was the frame and roof structures with around 63%. The use of compressed straw and reed panels as the main source of wall construction material together with wood frames in the straw panels, the wooden floor, the roof structure, and the wooden furniture, altogether resulted in a negative GWP impact from these building systems. B1-B6 were zero during the assumed lifetime of the shelter according to the designer.

Table 8: GWP impact of the refugee house with and without sequestration (Dabaieh et al., 2020b)

LCA Stage	Building systems	Total mass (Kg)	GWP (kg CO_2 eq) Without sequestration	GWP (kg CO_2 eq) With sequestration
A1-A3	Earth and groundwork	72	151.53	151.53
	Foundations	29101	1416.89	656.55
	Frame and roof structures	21834	4872.03	-11217.41
	Complementary works	1147	970.49	676.98
	Fittings, equipment and installations	220	101.13	-109.09
	Mechanical works	12	7.02	7.02
A4	Transportation		226.86	226.86
A5	Construction site	7.4	4.17	4.17
B1-B6	Maintenance		0	0
C2	Transportation		351.05	351.04
C3	Waste processing		1090.46	1090.46
	Total	52393	9191.62	-8161.87
	Per square meter of Gross Floor Area	1452	254.7	-226.2

Figure 10 compares the GWP impact of the house by component (a; the foundation, b; the frame and roof structure, and c; other building systems) with and without sequestration.

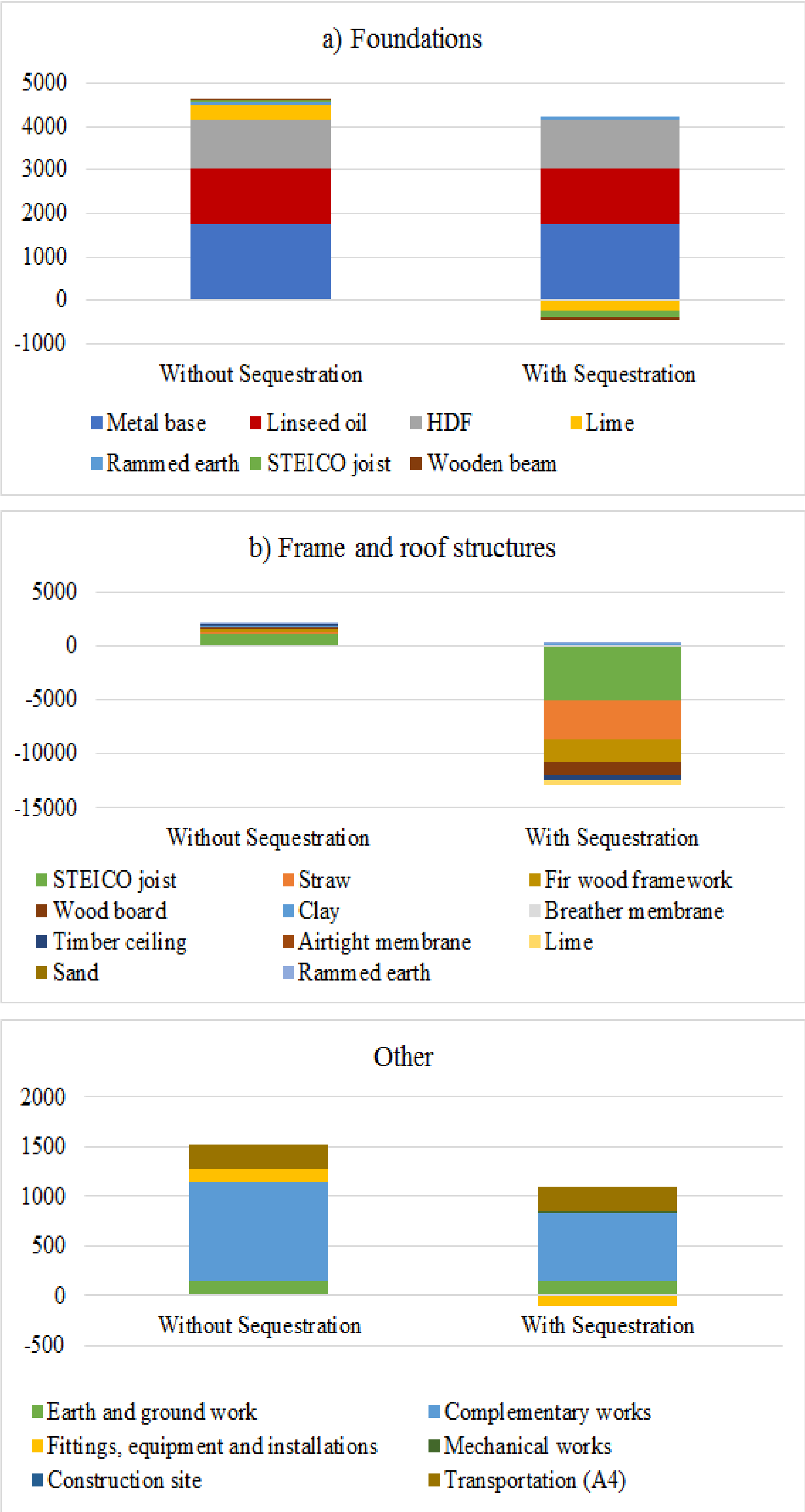

Figure 10: GWP impacts of the foundations (a), the frame and roof structure (b) and other building systems of the refugee house by component with and without sequestration in kg CO_2 eq (Dabaieh et al., 2020b)

According to figure 10a, the High density fibreboard (HDF) and lime base used in the foundations are responsible for 69% of total GWP impacts. Accounting for the sequestration potential, lime base has the potential to reduce the GWP impact by more than 500 kg CO_2 eq. Figure 10b compares the GWP impacts of the components used in the frame and roof structure, with and without sequestration. It was observed that the STEICO joist, wood fibre, straw panels and wooden framework have the highest CO_2 sequestration potential. Figure 10c shows the GWP impacts of the other building systems with and without sequestration. Due to the sequestration potential of wooden windows, the GWP impact is reduced by more than 50% (Dabaieh et al., 2020b).

Sensitivity analysis

Considering the wide range of values reported in the literature on the carbon intensity of several materials, a sensitivity analysis was conducted to examine the impact of input uncertainties (selection of material from the database and the method) on the total GWP impact of the refugee house with and without sequestration. It was found that the results are vastly sensitive to the intensity values of individual materials, as depicted in Figure 11. The x-axis captures the overall GWP impact without sequestration for different values of GWP intensities for each material. Each bar represents the range of total GWP impact when the intensity of each material is set to lower and higher limits (with the other intensities being held at the mean value). Percentage changes in terms of the whole building's impact are shown in parentheses. For example, focusing on cleft timber, the overall GWP impact is 8651 kg CO_2 when the carbon intensity was at its lower bound, while it can increase to 9381 kg CO_2 when the carbon intensity is at its higher bound. It was also observed that the overall GWP impact can be most significantly increased (49%) depending on the changes in the GWP impact of wood fibre insulation, if the higher bound is considered.

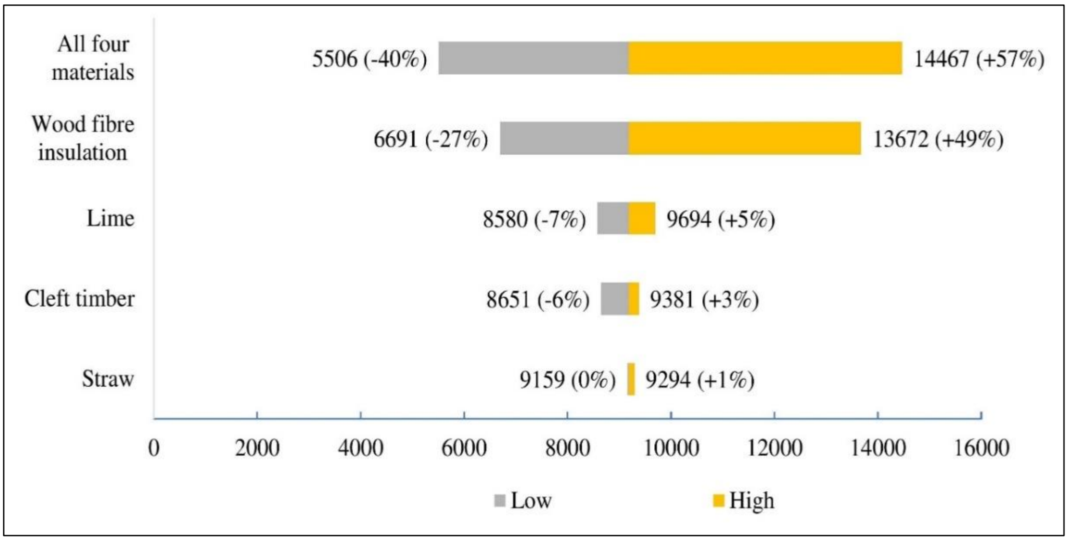

Figure 11: The variability of the overall GWP impact of the building without sequestration based on the lower and higher bounds of intensity of four selected materials in kg CO_2 eq (Dabaieh et al., 2020b)

The sensitivity of the overall GWP impact, incorporating the carbon sequestration, was also explored (Figure 12). The range of the GWP intensity of each material is obtained from GaBi, and SimaPro, based on two methods of LCIA - CML 2001 (Nov.10) & ILCD 50 years. For example, the overall GWP impact of the building is -11607 kg CO_2 (42% less than the mean value) when the carbon intensity of wood fibre insulation is at its lower bound, while it is -4801 kg CO_2 (41% higher than the mean value) when the carbon intensity is at its higher bound. Thus, this is the most critical factor for the estimation of the overall GWP impact after capturing the carbon sequestration.

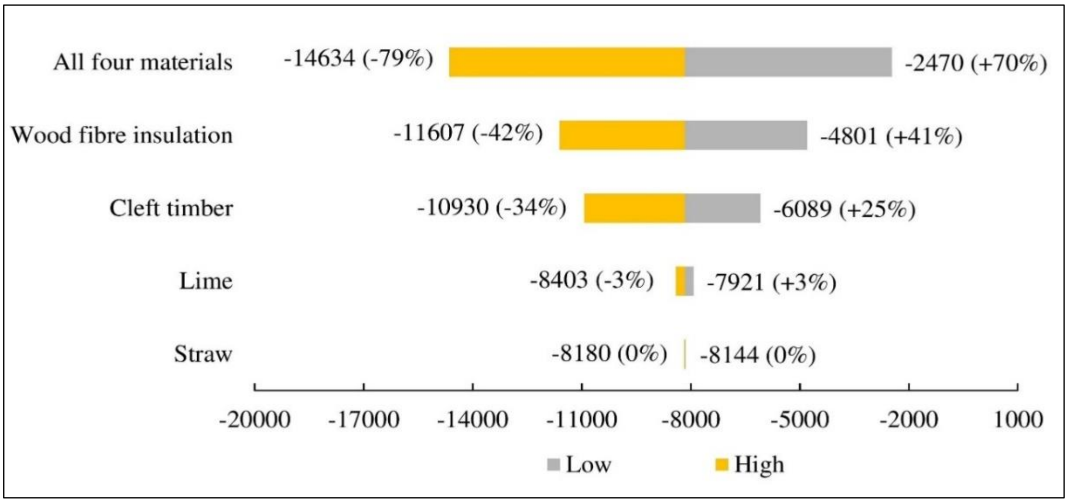

Figure 12: Changes in the overall GWP impact with carbon sequestration based on lower and higher bounds of intensity of four selected materials in kg CO_2 eq (Dabaieh et al., 2020b)

5.4 Paper IV

5.4.1 Contribution to RQ

The fourth study measures the impacts of using alternative materials in the building on several environmental impact categories which is part of the answer to the first research question. Results show that by changing the construction material used in the structure and interior walls, the climate change impact could be decreased by 43% from 644 to 379 kg CO_2 eq /m^2 by replacing the concrete structure with wood (Table 9). Besides, we assessed the impacts of alternative materials on LEED points, but the findings do not contribute to the research questions of the dissertation.

5.4.2 Paper summary

Life cycle assessment results

Results demonstrate that by changing the construction material used in the structure and interior walls (Wood scenario), the climate change impact could be significantly reduced by 43% from 644 to 379 kg CO_2 eq /m^2 (Table 9). The same improvement can be achieved in several impact categories, including Ozone depletion, Terrestrial acidification, Freshwater eutrophication, Human toxicity, Photochemical oxidant formation, Particulate matter formation, Terrestrial ecotoxicity, Freshwater ecotoxicity, Marine ecotoxicity, Natural land transformation, Metal depletion and Fossil depletion.

The differences in the environmental effects between OptCon and the Con scenarios are rather small, i.e., less than 5%. The climate change impact is reduced by around 15.5% in ConWood, since all nonstructural concrete walls were assumed to be replaced with wooden walls. However, the additional use of wood increases the urban land occupation (29.9%), and the agricultural land occupation (893%) compared to the Con building. The climate change impact is almost 43% lower in Wood building as a result of extensive use of wood in the building. Like ConWood, the proposed modifications negatively affected two impact categories, namely urban land occupation (46.7%), and agricultural land occupation (2135%).

Table 9: Environmental impact of the case building made from different building materials (alternative scenarios): results from LCA using the ReCipe method (Amiri et al., 2021)

Impact Category	**Unit**	**Con**	**OptCon**		**ConWood**		**Wood**	
		Abs.	Abs.	%	Abs.	%	Abs.	%
Climate change	kg CO_2 eq /m^2	664.42	672.99	1.3%	562.09	-15.4%	379.16	-42.9%
Ozone depletion	kg CFC11 eq /m^2	3.21E-05	3.22E-05	0.3%	2.89E-05	-10.0%	2.33E-05	-27.3%
Terrestrial acidification	kg SO_2 eq /m^2	2.77	2.79	0.7%	2.02	-27.0%	1.55	-44.1%
Freshwater eutrophication	kg P eq /m^2	0.20	0.20	0.4%	0.17	-12.3%	0.12	-37.3%
Marine eutrophication	kg N eq /m^2	0.44	0.44	-0.1%	0.66	49.8%	0.83	86.4%
Human toxicity	kg 1.4 DB eq /m^2	294.21	295.19	0.3%	266.27	-9.5%	201.56	-31.5%
Photochemical oxidant formation	kg NMVOC /m^2	2.31	2.33	1.0%	2.04	-11.7%	1.55	-32.9%
Particulate matter formation	kg PM10 eq /m^2	1.42	1.42	0.3%	1.18	-16.7%	0.86	-39.4%
Terrestrial ecotoxicity	kg 1.4 DB eq /m^2	0.21	0.21	0.6%	0.20	-1.0%	0.12	-42.6%
Freshwater ecotoxicity	kg 1.4 DB eq /m^2	8.75	8.77	0.2%	7.60	-13.1%	5.59	-36.1%
Marine ecotoxicity	kg 1.4 DB eq /m^2	8.51	8.53	0.3%	7.44	-12.5%	5.49	-35.5%
Ionizing radiation	kg U235 eq /m^2	35.43	35.27	-0.5%	37.70	6.4%	35.27	-0.4%
Agricultural land occupation	m^{2}a /m^2	35.84	34.45	-3.9%	355.76	892.7%	800.81	2134.6%
Urban land occupation	m^2 /m^2	6.39	6.51	1.9%	8.30	29.9%	9.38	46.7%
Natural land transformation	m^{2}a /m^2	0.17	0.17	1.3%	0.16	-3.2%	0.10	-37.9%
Water depletion	m^3 /m^2	28.43	27.11	-4.6%	28.12	-1.1%	44.45	56.3%
Metal depletion	kg Fe eq /m^2	244.82	244.95	0.1%	242.77	-0.8%	156.55	-36.1%
Fossil depletion	kg oil eq /m^2	137.66	138.49	0.6%	118.58	-13.9%	90.81	-34.0%

Figure 13 shows the effect of building elements on climate change, ozone depletion, terrestrial acidification and freshwater eutrophication in three scenarios compared to the Con (base case). Due to the use of wood in outdoor and interior finishing, in ConWood, the climate change impact decreases by 66% and 29% in those two elements, respectively. In addition, there is a reduction of 43%, 73%, and 60%, in terms of ozone depletion, terrestrial acidification and freshwater eutrophication in the Wood scenario compared to the Con scenario. In terms of marine eutrophication, the replacement of concrete walls with wooden walls and the substitution of aluminum windows with wooden ones causes a significant increase in interior and outdoor finishing elements.

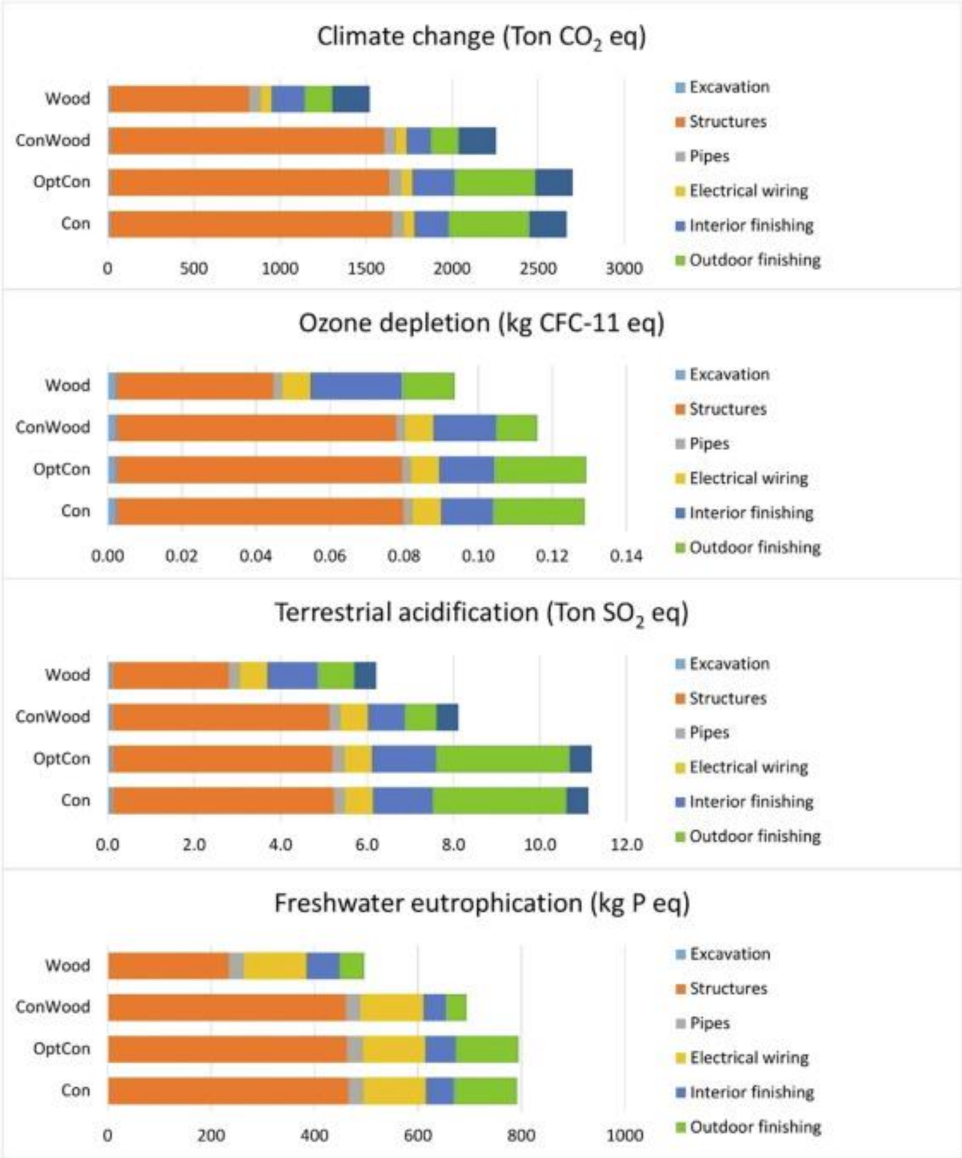

Figure 13: Environmental impact of the case building built as per different building material scenarios (Amiri et al., 2021)

Transportation

Since the majority of construction materials are imported to Iceland, the role of the transportation stage to the overall environmental impacts is a potential hotspot. Thus, the environmental impacts of transportation needed from source country to Iceland and from seaport to the construction site (A4) were studied. Only a one-way trip was considered in the LCA as the vessel needs to be used for exports from Iceland on the route back.

According to Breiðfjörð, (2011), the GWP impact of containerships traveling to Iceland is 0.0327 kg CO_2 eq/ton.km (estimated based on fuel consumption and associated direct emissions) while the value for GWP impact from container ship in SimaPro is 0.0115 kg CO_2 eq/ton.km. The justification for higher emission factor for Iceland compared to international shipping might include heavy wind, small cargo and the difficulty of shipping route to Iceland. Thus, the emission factor for other impact categories was adjusted based on the same ratio to incorporate the impact of difficulty of shipping route to Iceland.

The share of transportation varies significantly across four impact categories for different scenarios (Figure 14). Transportation's impacts represent more than 15% of the total climate change impact in the Wood scenario, and between 20-45% of the total ozone depletion and terrestrial acidification impacts for all four scenarios, while in other impact category, i.e. freshwater eutrophication, the contribution of transportation is less than 10% in different scenarios.

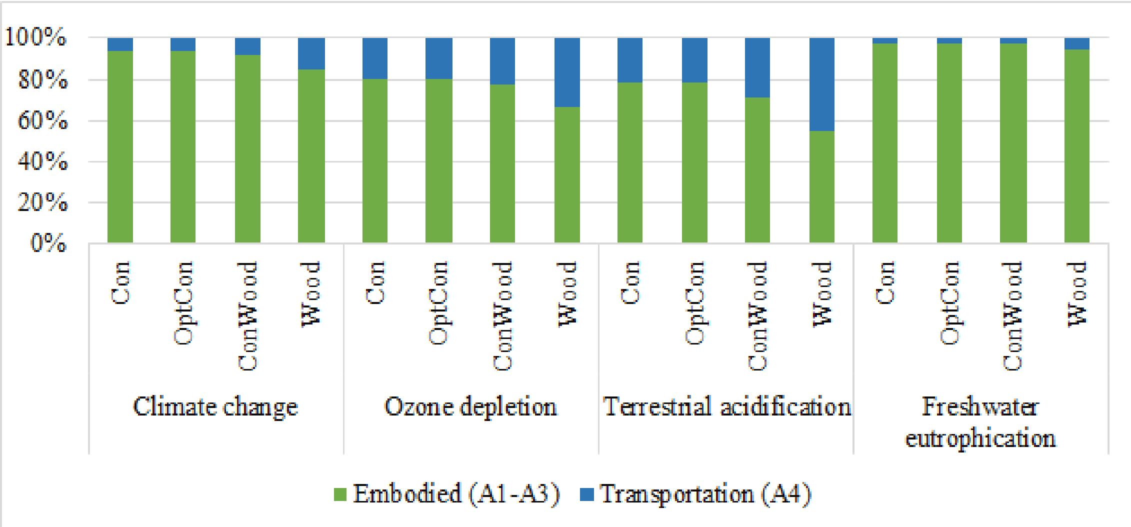

Figure 14: The contributions of impacts arising from initial embodied emissions and transportation in each impact category for the studied four building material scenarios (Amiri et al., 2021)

Figure 15 shows the difference in the climate change impacts of different building systems (structures, interior finishing, and outdoor finishing) and transportation in OptCon, ConWood and Wood scenarios compared to the base case (Con). Other building systems have been excluded, since their climate change impacts have not changed in the alternative scenarios (Amiri et al., 2021). It is obvious that the key building elements to reduce the climate change impact include structure, and outdoor finishing. Another key finding is that while using the imported wood can reduce the impacts from building elements (structure and outdoor finishing), it will increase the impact from transportation.

Figure 15: The contributions each building system in reducing the climate change impact in three scenarios compared to the base case (Amiri et al., 2021)

After reviewing the main findings, the following chapter encapsulates the overall findings and presents answers to research questions, discusses the implications of results, evaluates the quality of the research, and provides some suggestions for future research.

6 Discussion

6.1 Main findings

Two research questions of the dissertation were:

What are the initial embodied emissions caused by different types of buildings with material choices in the Nordic context, and what are the relative importance of building components, materials and transport?

How strongly does the LCA database choice affect the assessment outcome, and what are the implications to the reliability of the results in different impact categories?

After conducting multiple case studies, it was well established that the LCA approach can be utilized to estimate initial embodied impacts for GWP and fossil depletion by different types of buildings and material choices in the Nordic context, while for other impact categories, the results varies significantly between the two LCA database-software combinations. The contribution of different building components, construction materials to various environmental impact categories has been also estimated (Papers I, II and IV). Besides, the contribution of transport in initial embodied impacts, was estimated for all impact categories (in Papers I and IV). However, there are certain aspects that should be taken into consideration and reduce the robustness of LCA results. First, considering two LCA database-software combinations, the results can be very different at the level of the whole building, but also for each building system and material category separately, in virtually all impact categories (Answer to the 2nd research question). Secondly, the impact of input uncertainties (selection of material from the database and the method) as well as the uncertainties in the sequestration capacity of plant-based materials (in this study compressed straw, reed panels, and wooden elements), should be explored in detail to ensure the overall conclusions are robust. Finally, while the scenario analysis offers a framework to assess the mitigation potential of different construction material, it is critical to account for the technical feasibility of replacing existing material with natural materials.

After discussing the main findings and answers to each research question, some broader implications of the results can be drawn together. First of all, while LCA outcomes are often questioned through the level of uncertainty in the conclusions, the results of this work indicate that focusing on GWP and fossil depletion categories, LCA tools can be utilized to provide a consistent assessment of construction materials, a key step towards a development of a rating scheme for them (AzariJafari et al., 2021). Secondly, considering the findings on the significant contribution of cement/concrete across several environmental impact categories, the Icelandic industry became more interested in improving their work and decrease the environmental impacts of their products. Green hydrogen has been discussed as a solution to decarbonize energy intensive industries (Oliveira et al., 2021) with the aim at producing green cement (Zhang et al., 2021) and green steel (Bhaskar et al., 2020).

6.2 Positioning among previous literature

While the LCA approach can offer a comprehensive understanding of the contribution of different construction materials to GWP and fossil depletion, in other impact categories this study found not uniformity between two LCA databases.

Regarding the included materials/components in Paper I, the GWP result falls to the same level of magnitude as in previous studies of other comparable buildings despite the long-distance transportation and considerably high concrete content of the building. Moreover, while local production of some materials reduced the emissions (due to the low-carbon stationary energy systems in Iceland), the reductions were not sufficient to make the case building stand out in comparison to other building LCAs.

Another key component that significantly affect the LCA results is the applied method. While the process LCA is applied for all case studies, yet the method has several limitations. The main deficiency of the method is the inherent truncation or cutoff error (Suh et al., 2004) due to the boundary selection. Not all the upstream processes can be tracked and included, and particularly, the shared processes are often left out, especially those related to capital goods like production facilities. Thus, even when the scope is claimed as comprehensive, excluding only negligible processes, the actual cutoff error can be of a magnitude of tens of percentages (Lenzen and Dey, 2002; Suh et al., 2004; Säynäjoki et al., 2017), and in this regard, the published LCA studies carry relatively low transparency (Säynäjoki et al., 2017). Säynäjoki et al., (2017) show how important the cutoff error can be even when not considering the capital goods (like production facilities and machinery) and other shared processes. The problem is that in any certain assessment, the magnitude of the cutoff error is very difficult to assess, particularly when assessing a wide variety of different impact categories. Another major constraint in utilizing LCA database software is that the materials and products in the available databases can, in fact, be quite different from the assessment object, both due to different production conditions but also the material not being exactly the same as utilized in the case building. Heinonen et al., (2016) and Säynäjoki et al., (2017) bring up the question of the "first tier truncation", meaning that when only the materials for a certain building component, such as a window or an elevator, are assessed, the assessment omits all the emissions from the final processing stages when the materials are processed and assembled into the final product.

For example, the estimated global warming potential impacts for the case study, in Paper I are low compared to previous studies which was due to the limited system boundary defined for the case study. An indicator that can help to interpret the results is the cutoff ratio. The cutoff for GWP impact was estimated to be between 20-25%, according to the cutoff estimations of Heinonen et al., (2016).

In Paper II, the results show that the two LCA assessment tools (GaBi and SimaPro) return mostly completely different estimates at the level of the whole building, but also for each building system and material category separately, in virtually all impact categories. Nonetheless, in both cases, the similarity in the estimates concerning Climate Change impacts was significant, which was previously observed by Takano et al., (2014). The results carry further practical value as well. For example, in decision-making informed with data from LCA, the decision-maker should understand that all LCA results should come from the same database for the results to be comparable between cases, for example when asking for tenders.

However, it can be argued that there are significant uncertainties in paper II which should be kept in mind when interpreting the findings. First, only two cases were included, which means that the generalizability is low, but according to the case study method philosophy, even one case is enough to identify potential issues and hypothesizing theories (Eisenhardt and Graebner, 2007). Moreover, if similar findings are reached in new case studies, a theory becomes stronger and stronger. In our study, we purposefully selected two completely different types of buildings to see if findings were similar or not, and based on the results we received, it seems that the inconsistencies between the two compared tools expand beyond a single building type. Secondly, the results are not exactly the initial embodied emissions in the two case buildings. Since no localization was done, the actual production conditions, technologies, and the resulting emissions can be different from those in the employed databases even though the two buildings are newly built and both represent typical contemporary residential construction in Finland.

The use of plant-based materials (straw, reeds, wood and wooden fibre) as one option to mitigate the environmental impacts has been explored in Paper III. The GWP of the house with and without sequestration were found to be 254.7 kg CO_2 eq/m^2 and -226.2 kg CO_2 eq/m^2, respectively. The *without* sequestration value is relatively low when compared to previous building LCA studies (Säynäjoki et al., 2017), but far from the lowest reported values. The *with* sequestration value shows greater sequestration than the high value. This emphasizes the sequestration potential of using straw, reeds, wood and wooden fibre in the building's main skeleton. Besides, all the natural materials were brought from local farmers and carpenters located a maximum of 5km from the site, which ensured minimal embodied GHG emissions during material extraction, production and transportation to the building site. The low-tech approach in construction eliminated carbon emissions from the heavy machinery which primarily uses fossil fuel as energy source. Only manual screwdrivers and an electric saw were used. Ten litres of petrol were also needed for the onsite charging point; however, using renewable energy as the electricity source to charge the tools on site would have further reduced the carbon emissions generated by the petrol. The HDF and lime base contributed most to the GWP impact of the house's foundations.

To estimate the carbon sequestration potential of wood fiber, information from EPD for STEICO joist wood-fibre boards was used (Steico SE, 2016). Yet, there are some concerns about the reliability of data in EPDs (Resalati et al., 2020). A detailed study of 50 Environmental Product Declarations by Gelowitz and McArthur, (2017), showed that 38% of Environmental Product Declarations were missing information required by the ISO standard. Further, the lack of harmonization between and poor quality of several underlying Product Category Rules limited the comparability between Environmental Product Declarations in the same categories (ranging from 1 to 24%).

Moreover, considering the variability in the suggested carbon intensity of several materials, a sensitivity analysis was conducted to analyse the impact of input uncertainties (selection of material from the database and the method) on the total GWP impact of the case shelter with and without sequestration. It was found that the material with the highest effect on the overall GWP impact of the building was wood fibre used for insulation, with which both the assessment assumptions and the production conditions, such as technology used) themselves can have significant impacts. Further analysis can improve the accuracy of estimating the overall GWP impact of the building with and without sequestration.

Among different alternative low-emission and carbon storing materials, wooden construction can be counted as a solution for climate change mitigation not only for countries like Iceland that mainly import their construction material but also globally. Thus, in Paper IV, the LCA study was conducted to assess the mitigation potential for four scenarios with emphasis on four indicators, i.e., climate change, ozone depletion, terrestrial acidification, freshwater eutrophication. There is noticeable potential for climate change mitigation if the carbon storage of wood as a building construction material is fully considered. It was concluded that the use of wood for all non-structural components (such as the window frames) can significantly reduce the initial embodied environmental impacts more than 40%.

The initial embodied emissions in the base case were around 650 kg CO_2 eq /m^2, which is within the range of estimated initial embodied carbon emissions in 10 case studies reviewed by Fenner et al., (2020), but 40% higher than the median value. This can be justified considering the significant use of concrete in the structure of the Veröld building.

It is necessary to mention that using the forest and wood harvesting is reasonable only if the forest is managed efficiently and its value as a habitat for biota is considered, otherwise using wood for construction will result in the depletion of forests and loss of biodiversity, which is even a worse option from the viewpoint of climate change. It is widely assumed that buildings have a life cycle of 50 years. Using wood in buildings saves biomass, which will also continue to increase at each round of 50 years. The best way to benefit from this saving is to reuse wood after demolition of wooden buildings while it can be also used as renewable fuel. According to results published by IPCC, direct or indirect replacement of fossil fuels by biomass using wood instead of energy-intensive materials, is a more efficient way of CO_2 reduction than leaving the forest untouched.

6.3 Evaluation of the study

Based on the multiple case study approach, the dissertation concludes that although the LCA approach can improve our understanding of the initial embodied impacts of different construction materials on different environmental impact categories, several key aspects such as the inconsistencies between LCA databases, and the impact of input uncertainties (selection of material from the database and the method) should be taken into consideration. Particularly, results for GWP category are somehow reliable and the inconsistency was relatively low, but one should be very cautious in interpreting the findings of other impact results.

Case studies have been explored as a tool to generate valuable insights, yet, it has been prone to concerns regarding methodological rigor in terms of validity and reliability (e.g., Yin, 1981; March, Sproull and Tamuz, 1991). One of the major limitations of the case study method is that unless you have a high number of cases confirming your hypothesis, the method is more useful to recognize how something is not. On the other hand, Flyvbjerg, (2006) argues that concrete, context-dependent knowledge that can only be developed by a case study can have more value compared to the general, theoretical knowledge. In this dissertation, following the multi case study approach, it was concluded that LCA results need to be interpreted carefully due to many limitations associated with the LCA method and databases.

The purpose of the following two subsections is to evaluate the quality of research based on the four aspects proposed by Gibbert et al., (2008) and Yin, (1994): construct validity, internal validity, external validity and reliability.

6.3.1 Validity of the research

Construct validity demonstrates whether the research evaluates what it is supposed to evaluate. It is generally challenging to validate LCA studies focusing on single cases. One of the tactics for improving construct validity is to develop a chain of evidence from the initial research questions to the conclusions of the research. Thus, in the dissertation, the chain of evidence in the LCA studies was derived directly from applying multiple case study method and the numerical frameworks in the respective papers and support the overall conclusion.

Another measure of the quality of the research is the internal validity, which indicates whether the investigated case studies explain the outcome of the study. The main conclusion of the dissertation, i.e., the environmental impacts of different construction materials and building parts, was established by exploring several LCA studies. Thus, the main concern with respect to the internal validity of studies relates to uncertainties in the LCAs. The dissertation is based on independent case studies and the research data was thus suitable for a multiple case study approach. While the focuses of Papers II and III have been on two sources of uncertainties (inconsistencies between LCA databases, and selection of material from the database and the method), the absence of a robust quantitative examination of uncertainty (such as Monte Carlo approach) causes some ambivalence to the results of the dissertation. The main reason for not conducting a full-scale Monte Carlo is that there are very few data points with similar system boundary that can be taken from the LCA database and other literature for the emission intensity of construction materials.

In addition, the author acknowledges that process-based LCA studies suffer from a truncation error, which is caused by the omission of resource requirements or pollutant releases of higher-order upstream stages of the production process. The magnitude of this truncation error varies with the type of product or process considered, but can be on the order of 50% (Lenzen, 2000). Then, Junnila, (2006), Williams, (2004), and Ferrão and Nhambiu, (2009) compared process-based LCA case studies with Input-output or Hybrid LCA and found the process-based results to be 30-60% lower. This supports the argument that hybrid LCA will likely yield more accurate results than process-based LCA (Pomponi and Lenzen, 2018). On the other hand, according to Yang et al., (2017), because of the error due to the aggregation of heterogeneous processes in Input-output models, hybrid LCA does not necessarily provide more accurate results than process-based LCA.

According to Yin, (1994), the external validity of the research indicates the level to which the findings of the study can be generalized at national and international context. All the cases have features non-common in many other places and therefore, in global sense the geographic coverage as well as the building type coverage is narrow. Yet, in the Nordic context, the external validity might be relatively strong, considering the geographical distribution of case studies (Iceland, Finland and Sweden) but buildings in many other places are different in terms of the type of construction materials used in the buildings.

6.3.2 Reliability

Reliability refers to repeatability, defined by the extent to which the same research procedures would produce the same results under constant conditions on all occasions (Yin, 1994).

The inventory data for the assessments were received directly from the developing companies. Thus, no data collection procedures were involved, which could jeopardize the reliability of the research.

Besides, due to limited data availability, minor materials were included in all case studies, except the Vættaskóli-Engi school building, in which the surface materials, fixture, fittings, stone filling material in the foundation, electric and heating systems and plumbing were excluded from this analysis.

The application of LCA as a mathematical assessment model does not allow the researcher to alter the functionality of the model. The scopes and details of the method for each case study are extensively described in the papers and thus it is very likely that independent research with the same data and similar LCA models would lead to very similar conclusions. Yet, as noted as the main conclusion of paper II, the impact of LCA database on the results is very strong. Besides, it should be noted that it is expected that even with the future version of the LCA database the results would be different. Having said that, all the individual papers in the dissertation were evaluated by several reviewers of international high quality academic journals.

6.4 Future research

While the results of the case studies helped to improve our understanding of the initial embodied environmental impacts of construction materials, they also pointed to several directions of improvement and future work.

The first route relates to the selected system boundary. Although the main focus has been on initial embodied environmental impacts, it is important to account for the additional embodied impacts due to maintenance (such as replacing old windows with new ones).

After exploring the consistencies/difference between the two LCA databases, the next step would be to investigate the sectors with the largest intensity differences in the two databases. Then, a detailed dedicated database can be developed to provide reliable information on those sectors for both LCA practitioners and policy-makers in the building sector.

In Paper III, the uncertainty importance analysis was conducted to estimate the impact of input uncertainties (selection of material from the database and the method) on the total GWP impact of the refugee house with and without sequestration. Yet, a quantitative examination of uncertainty for other case studies have not been conducted. As a widely used approach for uncertainty analysis (Janssen, 2013), it would be advisable to include a full Monte Carlo to future building LCAs to improve the general understanding about the uncertainty and assess the impacts of variance ranges of input variables. Besides, the concept of carbon handprint of buildings and construction materials can be explored as the absolute climate benefits that would not be achieved without the project (Kuittinen and Häkkinen, 2020). Combining this "positive side" with the traditional LCA approach focusing on the emissions or environmental impacts would seem to be a recommendable future development direction.

Using recycled materials have the potential to significantly reduce the initial embodied environmental impacts, since their lifetime will be extended. Another major improvement could be to select a case study with considerable share of recycled materials in the structure and compare the embodied environmental impacts with conventional buildings. In addition, a complementary step to the scenario analysis proposed in Paper IV, could be to identify the maximum capacity to reduce initial embodied environmental impacts by using alternative materials which are viable from a technical feasibility perspective.

Finally, the importance of giving attention to the initial (pre-use) embodied emissions has been a strong motivator for this study. The reasons have been discussed in this compilation part and in the papers presenting the case studies. Drawn from these reasons, one future research direction should be the development of a consistent way to discount the future emissions to a present value – similarly as is the tradition in economic investment calculations. Any production now causes a higher impact than production in the future up to any selected point in time. While this impact might be relatively low, assuming constant emissions from the production of same components in the future, and continuous utilization of the same materials over time is not in accordance with the future predictions today. This latter component truly leads any such assessments to overestimate the future emissions in which constancy is assumed over the entire life cycle of a building. One way forward is to apply what-if scenario approach and modeling future changes in technology, notably GHG emissions from power generation and other industrial processes responsible for the production of construction materials (Khan et al., 2020; Wang et al., 2019). After discussing the findings and their implications, the following chapter highlights the concluding remarks from all case studies.

7 Conclusion

All of the case studies discussed in the dissertation contribute to defined research questions. After conducting a set of LCA case studies, the initial embodied emissions caused by different types of buildings and the relative significance of material, building components and transport in the Nordic context have been estimated. Besides, it was concluded that the choice of LCA database can considerably affect the assessment results, which emphasizes the need for careful interpretation of findings.

There are certain aspects that should be taken into account. First, considering two LCA database-software combinations, the results on initial embodied emissions are very different at the level of the whole building for all studied impact categories other than GWP and fossil depletion (Paper II). Secondly, the impact of uncertainties in input data (selection of material from the database and the method) as well as the uncertainties in the sequestration capacity of a few specific materials (compressed straw, reed panels, and wooden elements), should be explored in detail to ensure the overall conclusions are reliable. Finally, while the scenario analysis offers a framework to assess the mitigation potential of different construction material, it is critical to account for the technical feasibility of utilizing those materials.

The total global warming potential impact of the school building studied in Paper I, was equal to 255 kg of CO_2 eq /sqm, which was low compared to previous studies, mainly because only materials utilized in the structure and the envelope of the school building have been included in the analysis. The effect of long-distance overseas transport of materials was noticeable in terms of acidification (25%) and eutrophication (30.5%) while it was negligible in other impact groups. The results also concluded that producing the cement in Iceland caused less environmental impact in all five impact categories compared to the case in which the cement was imported from Europe. This is an important insight for stakeholders to identify effective measures to move towards a sustainable built environment in Iceland.

The analysis in Paper III, has shown a proof-of-concept example for a low-impact refugee house prototype using straw, reeds, clay, lime and wood as the principle raw construction materials. Using natural materials, especially plant-based fibres, as the main construction materials, proved to achieve a minus carbon outcome over the life cycle of the building. The GWP of the shelter house without and with sequestration were found to be 254.7 kg CO_2 eq/m^2 and -226.2 kg CO_2 eq/m^2, respectively. Besides, the sensitivity of LCA results for using different LCA databases and EPDs was examined to suggest method improvements to improve the reliability of the results. Based on the results of the uncertainty importance analysis, the overall GWP impact without and with sequestration potential varied the most due to the variability of the GWP impact of wood fibre insulation. It was concluded that there is great potential in working with such eco- and low-impact design and construction methods for temporary housing solutions to achieve a minus carbon footprint.

The LCA was applied to assess the environmental impacts of three optional building material scenarios (optimized concrete, hybrid concrete-wood and wooden building), in addition to the base case concrete building located in Iceland (Paper IV). The results showed the lowest environmental impact for the wooden building followed by the hybrid concrete-wood building. As the most materials for building construction are imported to Iceland, this study is useful for the locations similar to Iceland while it is beneficial for the whole world regarding climate change mitigation.

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Appendix: Papers I-IV

Paper I: Environmental Impact Assessment of a School Building in Iceland Using LCA-Including the Effect of Long Distance Transport of Materials

https://doi.org/10.3390/buildings6040046

Paper II: A Life Cycle Assessment of two Residential Buildings with two different LCA database-software combinations: Recognizing Uniformities and Inconsistencies

https://doi.org/10.3390/buildings9010020

Paper III: A Life Cycle Assessment of a "Minus Carbon" Refugee House: Global Warming Potential and Sensitivity Analysis

https://doi.org/10.1108/ARCH-11-2019-0258

Paper IV: Embodied emissions of buildings - a forgotten factor in green building certificates

https://doi.org/10.1016/j.enbuild.2021.110962