Improving the Sustainability Performance of Building Materials

An Approach from Life Cycle Thinking

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Department of Architecture and Civil Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2018

Thesis for the degree of Doctor of Philosophy

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Abstract

The construction industry is expected to play a vital role in meeting the global societal challenge of ensuring sustainable development. Due to the increasing importance of the embodied impact of materials, this thesis investigates how the sustainability performance of building materials can be improved. The investigation is conducted by exploring the influence and the relation of the following aspects to the materials: the different dimensions of sustainability (environmental, social and economic); technical requirements (functional performance); and the exposed systems (material-building-regions). Sustainable product development is considered an effective approach for improving building materials' sustainability performance. However, there is a need for further investigation to determine how to better implement it. The thesis aims to understand what kind of information can support the sustainable product development of building materials.

To analyze the sustainability performance of building materials, methods with a life cycle perspective are employed. In addition to the life cycle based methods, which reflect the recent developments in the field, investigations are conducted regarding the phase of product development in which existing sustainability assessment methods can be utilized. In the thesis, two types of building materials are analyzed: thermal insulation materials, and green concrete. An investigation at the level of components and buildings is conducted with focus on a case building constructed in Sweden in 2013.

The investigation of how different sustainability assessment methods and indicators can support product development is conducted by considering the phases of product development. It is found that few indicators and methods are able to support the early phase of product development and act mainly as proxy information for setting the goal of the developed material. However, various measures are able to support the later phase of product development, especially the production planning step. Furthermore, in the investigated case materials and building, trade-offs are seen between the dimensions under investigation: the material level, the component/building level, the social and environmental pillars of sustainability. The observed trade-offs highlight the importance and value of the product development phase as an effective measure to handle the occurring compromises. Sustainable product development can offer a platform for more holistic sustainability thinking about and realization of the developed building materials. The thesis emphasizes the value of and the role sustainable product development can play in ensuring the sustainable development of the construction industry.

Keywords: Life cycle assessment, Social Life Cycle Assessment, LCA, sustainable product development, sustainable building.

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これまでお世話になった皆様、本当にありがとうございました。
そして、これからもよろしくお願いします。

Jun Kono (高野　惇)
Gothenburg, May 2018

List of Publications

This thesis is based on the following appended papers:

Paper 1. Jun Kono, Yutaka Goto, York Ostermeyer, Rolf Frischknecht and Holger Wallbaum *Factors for eco-efficiency improvement of thermal insulation materials.* Key Engineering Materials (2016), 678: 1–13. DOI: 10.4028/www.scientific.net/KEM.678.1

Paper 2. Jun Kono, York Ostermeyer and Holger Wallbaum. *The trends of hourly carbon emission factors in Germany and investigation on relevant consumption patterns for its application.* The International Journal of Life Cycle Assessment (2017), 22(10): 1493–1501. DOI: 10.1007/s11367-017-1277-z

Paper 3. Martin Anderson, Jonas Barkander, Jun Kono and York Ostermeyer. *Abatement cost of embodied emissions of a residential building in Sweden* Energy and Buildings (2018), 158: 595–604.
DOI: 10.1016/j.enbuild.2017.10.023

Paper 4. Jun Kono, York Ostermeyer and Holger Wallbaum.*Investigation on Regional Conditions and Sustainability Indicators for Sustainable Product Development of Building Materials* Journal of Cleaner Production (2018) (Revision submitted).

Paper 5. Jun Kono, York Ostermeyer and Holger Wallbaum.*Trade-off between social and environmental performance of green concrete: case of 6 countries* The International Journal of Life Cycle Assessment (2018) (Submitted).

Other relevant publications authored or co-authored by Jun Kono:

Jun Kono, York Ostermeyer, Holger Wallbaum. *Utilization of Multi-Criteria Assessment on Building Thermal Insulation Materials.* Proceedings of The 5th International Conference on Green and Sustainable Innovation, 2015

Jun Kono, York Ostermeyer, Holger Wallbaum. *The influence of difference of life cycle inventory data and life cycle assessment system model on life cycle impact assessment of geosynthetics applications: comparison of two cases.* Geosynthetics International, 2016 (Accepted)

Jun Kono, York Ostermeyer. *When to consume electricity? View from cost and carbon emission: case in Germany.* Proceedings of EcoBalance 2016. 2016

Corinna Salzer, Holger Wallbaum, York Ostermeyer, **Jun Kono**. *Environmental performance of social housing in emerging economies: life cycle assessment of conventional and alternative construction methods in the Philippines.* The International Journal of Life Cycle Assessment (2017), 22 (11): 1785–1801. DOI: 10.1007/s11367-017-1362-3

Holger Wallbaum, **Jun Kono**. *International Energy Agency Annex 65, Long-Term Performance of Super-Insulating-Materials in Building Components & Systems, Subtask 4: Life Cycle Assessment, Embodied energy and Life Cycle Cost Assessment.* Technical report. International Energy Agency, 2017.

List of Acronyms

AHP	–	Analytic Hiearchy Process
B2B	–	Business-to-business
B2C	–	Business-to-consumer
CPR	–	Construction Product Regulation
DfX	–	Design for X
DLCA	–	Dynamic Life Cycle Assessment
EE	–	Eco-Efficiency
EF	–	Emission Factor
EN	–	European Standard
EPD	–	Environmental Product Declaration
EPS	–	Expanded Polystyrene
GHG	–	Greenhouse Gas
GWP	–	Global Warming Potential
GRI	–	Global Reporting Initiative
IEA	–	International Energy Agency
ISO	–	International Organization for Standardization
LCA	–	Life Cycle Assessment
LCI	–	Life Cycle Inventory
LCIA	–	Life Cycle Impact Assessment
LCSA	–	Life Cycle Sustainability Assessment
LCT	–	Life Cycle Thinking
MCDA	–	Multi Criteria Decision Analysis
ODP	–	Ozone Depletion Potential
PD	–	Product Development
PEF	–	Product Environmental Footprint
PUR	–	Polyurethane
QFD	–	Quality Function Deployment
SETAC	–	Society of Environmental Toxicology and Chemistry
SLCA	–	Social Life Cycle Assessment
SPD	–	Sustainable Product Development
SDGs	–	Sustainable Development Goals
TBL	–	Triple Bottom Line
UNEP	–	United Nations Environmental Program
VIP	–	Vacuum Insulation Panel
VPP	–	Virtual Power Plant
vRES	–	Variable Renewable Energy Sources
XPS	–	Extruded Polystyrene

Contents

Chapter 1

Introduction

1.1 Aim of the thesis

This study aims to understand how building materials' sustainability performance can be improved by exploring the influence on and relation of the following aspects to building materials: the different dimensions of sustainability (environmental, social and economic); technical requirements (functional performance); and the exposed systems (material-building-regions). As methods to assess the building materials' sustainability performance that support the decision making regarding its improvement, methods based on life cycle thinking (LCT) are mainly employed.

1.2 Sustainability: The global challenge

In September 2015, UN General Assembly adopted the 2030 Agenda for Sustainable Development (United Nations 2015) as a successor of the Millennium Development Goals (MDGs) adopted in 2000. The agenda *"is a plan of action for people, planet and prosperity"* and sets 17 Sustainable Development Goals (SDGs), which *"balance the three dimensions of sustainable development: the economic, social and environmental"*.

The potential consequence of failing to balance the dimensions of sustainable development mentioned in the SDGs can be identified in the stories of the deforestation of Easter Island and Iceland (Diamond 2005). It is said that the Polynesian inhabitants of Easter Island did not succeed in managing the timber supply on the island, which was an essential resource to sustain the population's livelihood, and depleted the forest. The deforestation that happened 1,000 years ago in Iceland was also due to the mismanagement of the land, stemming from the culture to which they were accustomed. What these two stories (among others) indicate is that the balance point of sustaining the resource supply can easily be surpassed. Although such phenomena have been seen over the history of mankind across the globe, the concept of maintaining the balance, termed "sustainability", is said to have been coined by the German silver mine superintendent Hans Carl von Carlowitz in his 1713 publication "Sylvicutura Oeconomica". In his publication, he recognized the basic law of renew-ability as the basis for sustainable forestry, which he needed to run his business, and mentioned the relationship between environmental, economic and social factors (Kloepffer 2008).

Various definitions of the term "sustainability" have been introduced in the last few decades. The three-pillar model adopted in SDGs, including the environmental, social and economic is one of the most frequently used models to describe the components of sustainability. There can be additional pillars concerning governance and technology (Salzer et al. 2016), or technical and functional requirements can be considered as prerequisites for sustainability, in the case of buildings (European Committee for Standardization 2010). The idea of the "triple bottom line" (TBL) (Elkington 1998) is another commonly used accounting term considering the environmental, social and economic perspectives. Palousis et al. (2010) developed the "integrated bottom line" (IBL) as a concept which adapts the TBL to integrate the environmental and social domains as part of the economic bottom line.

It is not just the pillars of sustainability that are subject to discussion: the concept of sustainability also has different interpretations. The two common conceptualizations of sustainability are "strong" and "weak" sustainability. "Strong sustainability", coined by Daly (1991), is grounded in biophysical principles and claims *"that certain properties of the physical environment must be sustained"* (Hediger 2006). Meanwhile, "weak sustainability" (Solow 1993) is founded upon neoclassical capital theory, claiming that *"natural capital can be substituted by human-made capital"* (Gudmundsson et al. 2016). All of these definitions and conceptualizations may end up suggesting different choices in a decision-making context, depending on what the decision-maker is basing their decision on. However, regardless of such differences, one fundamental principle of the term seems to be shared by most of the definitions mentioned above, which is the consideration of intergenerational equity.

Sustainability as a term became widely recognized when it was adopted in the context of global development by the so-called Brundtland report (WCED 1987), which is the source often cited for the definition of sustainability. In this report, the term sustainable development was defined as *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs"*. The concept of sustainable development as an urgent issue was further elaborated on in Agenda 21 of the Earth Summit in 1992 in Rio (UN 1992). Ten years later, a summit was held to review the progress that had been made since the Rio Conference. During the World Summit on Sustainable Development (Johannesburg Summit), sustainable production and consumption was recognized as one of the key requirements for sustainable development (UN 2002). At the Rio+20 Conference in 2012, the message from the 1992 Rio Conference regarding the decoupling of economic development from environmental damage was revisited. Although the conference received criticism for having failed to produce a comprehensive framework or to set any commitments or targets (Gudmundsson et al. 2016), the decision to launch the SDGs as successors of the MDGs was made (UN 2012).

After decades of effort from the global community, the SDGs were put into place, which *"represent[ed] a huge step forward towards a common definition of sustainability"* according to (Maier et al. 2016). To achieve the SDGs, all responsible actors, including industry, are expected to necessarily play their role (UNDP 2016).

1.3 Sustainable buildings: Addressing the challenges of the construction sector

The construction industry is one of the key sectors affecting the sustainability of society both socio-economically (European Comission 2012) and environmentally (European Commission 2011; Herczeg et al. 2014; IPCC 2014; UNEP 2003). The sector represents:

- 6% of global gross domestic product (GDP) and employs more than 100 million people (Philipp Gerbert and Renz 2016)
- 32% of global final energy use and 19% of global greenhouse gas (GHG) emission (Lucon et al. 2014)
- 3 billion tonnes of global raw material consumption (Philipp Gerbert and Renz 2016), 50% of all resource extraction and 30% of water consumption in Europe (European Commission 2011)
- 50% of the solid wastes in the US (Philipp Gerbert and Renz 2016) and approximately 33% of total waste generation in Europe (Eurostat 2014)

Furthermore, nearly 90% of the people's time is spent indoor in the US and Europe (Philipp Gerbert and Renz 2016; Klepeis et al. 2001; Dimosthenis A. Sarigiannis 2014; ASHRAE 2011). With such a significant impact, it is vital for the global community that the construction sector align with the goals for the sustainable development of society. For this reason, increasing efforts are being made to make the sector more sustainable, including those to make buildings more sustainable.

In Europe, the technical committee CEN/TC350 (CEN 2005) has described how sustainable buildings should be assessed and achieved in European Standards (ENs). EN 15643-1 (European Committee for Standardization 2010), the overarching framework for sustainability assessment of buildings, includes environmental, social and economic pillars. This framework also touches on three aspects related to the assessment of buildings. These are the construction work, the building level, and the product level. Within the framework, EN 15804 (European Committee for Standardization 2012) is the only standard that has been issued concerning construction products to date.

Other policy-related initiatives concerning sustainability in the construction industry include the Construction Product Regulation (CPR) (European Parliament 2011), which identifies the sustainable use of natural resources as one of the basic requirements. The Energy Performance of Buildings Directive of the European Commission (European Parliament 2010) is another such political initiative concerning the environmental sphere of sustainability that requires all new public buildings to be nearly zero-energy by 2018 and for this requirement to be met by end of 2020 for all other new buildings. However, as is the case with product-related EN standards regarding sustainability performance, the effort so far has been directed mainly towards the environmental pillar.

1.4 The increasing importance of building materials for sustainable buildings

The life cycle environmental impact of buildings has historically been dominated by the use phase energy consumption (Dean et al. 2006). Even with state-of-the-art energy-efficient buildings, the use phase energy consumption makes up around 50% of the building's entire impact (Blengini and Carlo 2010; Mosteiro-Romero et al. 2014; Ostermeyer et al. 2013). With the Energy Performance Directive requiring energy consumption to be nearly zero, the importance of emissions associated with material production will increase in order to reduce the overall impact of the building sector. Moreover, other sustainability issues relevant for the sector, such as resource depletion and the impact on human health in developed nations where people spend majority of their time indoors, are important concerns that are affected by the properties of building materials.

The important role building materials are expected to play can be anticipated from the growth in urban areas around the world. According to the United Nations (2014), 54% of the global population lived in urban areas in 2014, and this figure is expected to reach 66% by 2050. Currently, more than 70% of the population in Northern America, Latin America and the Caribbean, and in Europe lives in urban areas. In contrast, most of the African and Asian population remains in rural areas, where the urban population is expected to increase from ca. 40% in 2014 to ca. 60% by 2050, creating the need for construction work to accommodate this increase in the urban population. Furthermore, in 2010, around 33% of the population in developing nations did not have access to adequate housing. Given such circumstances and the need to meet the SDGs, there is substantial demand for newer buildings to be constructed in Asian and African urban areas, where building materials will play a vital role to ensure the sustainable development of the society. In not just these two regions but also in OECD countries, efforts are needed to allow buildings to be made more efficient, which indicates the demand for materials. This implies the importance of materials' sustainability performance in both the developed and emerging countries for the sustainable development of society.

Although sustainability requirements are increasing in importance, the main function of buildings have remained the same throughout their existence: providing shelter from the external environment. In fact, CEN (2005) states the prerequisite of sustainable buildings is to meet functional and technical needs. These prerequisites and the three pillars outlined in EN 15643-1 (European Committee for Standardization 2010) are the basis for sustainability in this thesis. Meeting these functional and technical requirements, which may differ depending on the region, is thus vital for the survival of businesses in this sector.

1.5 Business environment of building materials

The construction industry is a significant business sector in terms of the economy as well, considering the size of its economic impact. The sector is considered to contribute

6% of global GDP (Philipp Gerbert and Renz 2016). Various actors are involved in the value chain of the construction industry, including raw material suppliers, contractors, and building material manufacturers. The business sector of building material manufacturers is mostly in the business-to-business (B2B) market. In this market segment, the product or service quality is considered the most important functional quality of the brand, according to Leek and Christodoulides (2012). As stated in the previous section, meeting the functional and technical requirements is the prerequisite for sustainable buildings (CEN 2005). With the characteristics of the business segment in which building materials are active as well as the need for sustainable buildings, it is no surprise that technical and functional performance may be the main focus when developing building materials, with sustainability aspects being considered secondary.

Furthermore, the construction industry is recognized as one of the less innovative sectors (Davis et al. 2016; Havenvid 2015). This may make it challenging to embed sustainability considerations, which may be beyond the scope of the industry's traditional considerations, as part of their business agenda. The conservative nature of the industry could be partly be due to its project-based character and the strict regulations that must be complied with (Havenvid 2015). In addition, fewer projects/products are sold in the construction industry than in other innovative industries, which in turn can make it risky to change things that are currently working. In fact, in KPMG's global survey (Armstrong and Gilge 2016) regarding the technological innovation in engineering and construction companies, the risk of adopting cutting-edge technologies was highlighted as one of the causes of their conservative attitude towards this adoption. According to the survey, while the risks in the industry are increasing with larger and more complex buildings are demanded, the profit margin of the industry seems not to be increasing. This encourages the industry to keep innovative technology on the shelf until someone else has experimented with it and proven that it can work, as the profit margin of most companies seem insufficient for conducting such an exercise themselves. Such a conservative attitude could also be expected in relation to sustainability issues, especially when considering the characteristics of brand value recognition in the B2B market.

These circumstances in the market and the sector in which building materials are active—the functionality-first mindset together with considerable organizational inertia in the face of change—could be seen as a challenge for sustainable development of the global community, concerning the size of the economic, social and environmental consequences that the construction industry is and expected to be responsible for in the upcoming decades.

1.6 Corporate sustainability and financial performance

Although most of the incentives concerning the improvement of sustainability issues typically originate from the regulatory push, especially for the construction industry, there are signs of market pulls for companies to improve their sustainability performance. According to several studies, it is financially beneficial for companies to proactively improve their sustainability performance (Alikaj et al. 2017; Harjoto and Salas 2017; RobecoSAM SI Research & Development 2014). The studies have shown that companies with better sustainability performance tend to have better corporate financial performance, in terms of both stock market and accounting performance, in the longer run. This improved financial performance is achieved as a result of better governance (Di Giuli and Kostovetsky 2014) and higher risk-adjusted returns (Borgers et al. 2013) due to the improved sustainability performance. Hence, improving building materials' sustainability performance would make sense for manufacturers, not just to meet the regulatory push of the sustainability requirements but also to improve profits, which may ease the financial stress that has been hindering the innovation in the construction industry.

1.7 Making businesses sustainable

To improve companies' sustainability performance and given the importance of manufacturing activities for society's transition towards sustainability (Gaziulusoy et al. 2013; Hallstedt et al. 2013), various attempts have been made to support the companies' decision making. For implementing sustainability principles into business activities, three prominent approaches have been identified. These are: business model, product design, and product development. In order to understand how building material manufacturers can approach making their businesses and products more sustainable, this section reviews the three approaches.

1.7.1 Sustainable Business Model

Business models conceptually describe how a company does business (Magretta 2002). Given their vital influence, Bocken et al.'s (2014) study focuses on how to make sustainability concepts operational at the level of business model. The study introduces archetypes of sustainable business models that aim to speed up the development of business models for both research and practice. Boons and Lüdeke-Freund (2013) view business model innovation as the key to creating sustainable values, which builds on the view of Lovins et al. (1999) and Hart and Milstein (1999) to achieve sustainable development.

The sustainable business model could be described as a top-down approach for embedding sustainability concepts in products, where the management of the firm creates the company's sustainability vision and aligns corporate activities to the vision.

1.7.2 Sustainable Product Design

Design principles for achieving product-related sustainability have received considerable attention over the last few decades. Design for X (DfX) is one of the well-recognized design guidelines and is "an umbrella term for many design philosophies and methodologies that help to raise designers' awareness of the characteristics that are most important in the finished product" (Ijomah et al. 2007). The "X" in the term may represent any aim for a design, for instance, environment or disassembly. Design for Multiple Life-Cycles (Go et al. 2015) is one such DfX guideline which aims for a more sustainable design and development of products by combining several DfX strategies for multiple life-cycles. Other studies have looked into applying quality function deployment (QFD), a tool that captures and reflects the "voice of customers", regarding functions and expectations, into product features, to DfX (Masui et al. 2003) and have created a design framework on this basis (Sakao 2007).

Sustainable design could be described as a bottom-up approach for a company to achieve sustainability targets, as compared to the SBM which is a top-down approach.

1.7.3 Sustainable Product Development

Sustainable product development (SPD) functions as something in between the abovementioned two approaches to improving business sustainability. Figure 1.1 illustrates how the three approaches to embedding sustainability on the product scale fit together.

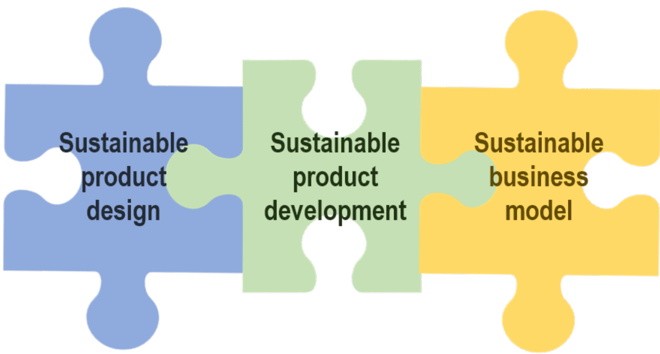

Figure 1.1: An illustration of the relation between the three approaches for industries to incorporate sustainability issues at the product level

Sustainable product development is considered an effective approach to make products more sustainable, as the life cycle socio-ecological impact of a product is largely dependent on the early phase of product development (McAloone and Tan 2005). In Figure 1.2, the phases and steps of product development are shown. Within this approach, several tools are available, such as the Method for Sustainable Product Development (MSPD) and the Template for Sustainable Product Development (TSPD) (Hallstedt et al. 2013; Ny et al. 2008). A study by Aschehoug and Boks (2013) has investigated how sustainability information can support product development and has sorted the related stakeholders and life cycle stages. Furthermore, a framework has been created to define the sustainability criteria and matrix, that have been applied in companies (Hallstedt 2017).

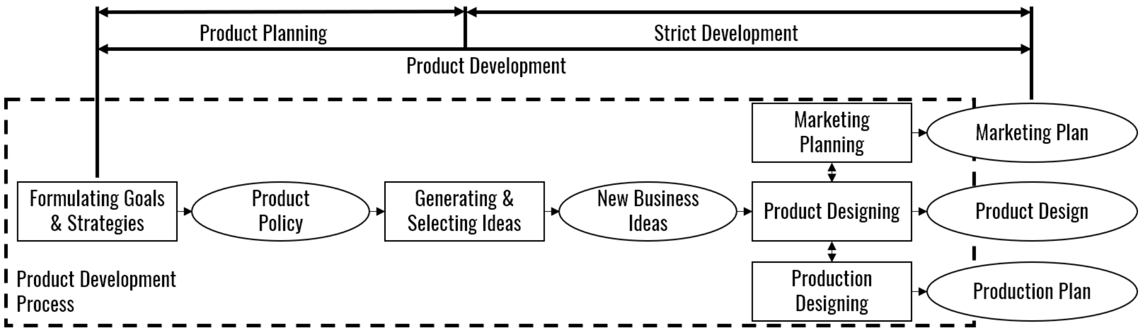

Figure 1.2: Illustration of a product development phases adapted from (Hallstedt et al. 2013)

Although the advantage of affecting the leverage point for making products more sustainable is becoming understood, the field of SPD seems to have received less attention than that of sustainable design in terms of the availability of tools (Byggeth et al. 2007). Moreover, poor practical applicability is often identified as an issue preventing SPD from being used more widely (Zetterlund et al. 2016).

1.8 Research questions

Given the growing importance of building materials to addressing the sustainability challenges faced by the construction industry, as well as the significance of and challenges involved in the product development (PD) phase for producing materials more sustainably, this thesis aims to address the following research questions.

Q1: What is the relationship between technical requirements and environmental performance?

Q2: How can building material manufacturers address the three pillars of sustainability issues for PD using existing methods?

Q3: What are the relevant aspects for supporting the SPD of building materials?

In the thesis, different types of building materials are investigated. One, which is studied in Paper 1, examines thermal insulation materials. These insulation materials have been well utilized in some parts of the globe, though they are still underutilized in other readily applicable areas. According to (IEA 2013), many countries still construct new buildings without considering the energy performance of the building envelopes. Given the increasing demand for reducing the operational energy demand, the market demand for thermal insulation materials is expected to increase or at the very least remain constant. This fact highlights the importance of improving the materials' sustainability performance, which was one of the main reasons for investigating this issue.

Another material that is investigated is concrete, one of the most frequently used building materials in the world (Petek Gursel et al. 2014; Turk et al. 2015). This building material is investigated in Paper 5. The consumption of cementitious material, the main constituent of concrete, is projected to increase by approximately 50% by 2050, due mainly to the demand from non-OECD countries (Scrivener et al. 2016). Given the trend of urbanization in non-OECD countries as well as the construction industry's challenge of meeting the SDGs, in which concrete will likely play an important role, Paper 5 investigated how concrete's sustainability performance can be improved.

1.9 Structure of the thesis

In chapter 2, an overview of life cycle assessment (LCA), the foundational methodology of this thesis, is briefly introduced. The recent developments in methods for LCA and its gaps to be filled are also provided in the chapter. The methods used in the published papers are briefly described in chapter 3. The findings of Papers 1 to 5 are presented in chapter 4, aligned with the story line of the thesis. Based on the findings from the appended papers, chapter 5 summarizes how the presented results relate to the research questions. Chapter 6 touches upon the findings of the papers and discusses how the information should be utilized to improve building materials' sustainability performance. Chapter 7 provides the conclusion, including an indication of how the findings could support the different phases of the SPD of building materials, and chapter 8 identifies the research gaps that remain to be filled.

Chapter 2

LCA for Assessing Sustainability

Life cycle thinking (LCT) is recognized as an important approach to products' sustainability performance (Hallstedt et al. 2013). Life cycle assessment (LCA) is one of the well-recognized and established methodology in this approach, developed in the 1960s (Bjørn et al. 2018). It began as a methodology to track the material and fuel consumed across the entire life cycle of a product and evolved into a methodology to evaluate potential environmental impacts, such as global warming, resource depletion, and air and water pollution. Since the development of LCA, various attempts have been made to develop methods to provide valuable information to tackle the global challenge concerning environmental impacts. As its methods evolved, the need for standardization for the consistency of LCA results was identified. The process of standardization was initiated by the global Society of Environmental Toxicology and Chemistry (SETAC) in 1990 (SETAC 1991), resulting in the first official guidelines for LCA in 1993 (SETAC 1993). Efforts to create an international standard for the method were continued, and as a result ISO 14040 was first released in 1997 and revised in 2006.

ISO 14040 (International Organization for Standardization 2006) was created to allow for the standardization of environmental consequences assessed using LCA. It provides the basis for how the assessments should be made. In the standard, the fundamental principles and LCA framework were described, and defined the following four steps to be followed: goal and scope definition, inventory analysis, impact assessment, and interpretation. The standard has played an important role in increasing the transparency of the analysis via the introduced principles and steps, which is vital for the communication and use of LCA results. At the goal and scope definition step, for instance, the decision context of the assessment is expected to be clarified, which determines how an appropriate assessment can be made. This determination of an appropriate assessment includes setting a system boundary and a unit for the assessment. Concerning the system boundary, EN 15804 (European Committee for Standardization 2012) introduced modules of life cycle phases for the building sector to improve the communication of such boundaries. These modules are shown in Figure 2.1. The unit of assessment in LCA is usually referred to as a "functional unit", which is set to best represent the aim of the assessment. When different options are compared via LCA, the functional unit is defined to allow a fair comparison of the options taking the function of the objects into account. Based on the defined system boundary and the functional unit, a life cycle inventory (LCI) analysis is conducted by collecting the data for the assessed product or service. These LCI data are typically created by utilizing existing LCI databases, such as ecoinvent and GaBi which are well-recognized databases. These LCI dataset created via LCI analysis are often termed as foreground LCI while the LCI datasets from the databases are termed as background LCI. Based on the LCI data, impact assessments are conducted by applying methods with various characterization and weighting factors to quantify impacts on respective environmental issues. After these key concepts of LCA were introduced, the standard allowed the surge of LCA related publications from less than 100 in 1998 to more than 1,300 in 2013 (Bjørn et al. 2018).

Life cycle stage modules			Name of the sub-module
Building life cycle information	PRODUCT stage	A1	Raw material supply
		A2	Transport
		A3	Manufacturing
	CONSTRUCTION PROCESS stage	A4	Transport
		A5	Construction, installation processes
	USE stage	B1	Use
		B2	Maintenance
		B3	Repair
		B4	Replacement
		B5	Refurbishment
		B6	Operational energy use
		B7	Operational water use
	END OF LIFE stage	C1	De-construction, demolition
		C2	Transport
		C3	Waste processing
		C4	Disposal
Suppl. information beyond the life cycle	Benefits and loads beyond the system boundary	D	Reuse-, recovery- and/or, recycling potentials- potential

Cradle-to-Gate (A1–A3)

Cradle-to-Grave (A1–C4)

Cradle-to-Cradle (A1–D)

Figure 2.1: Life cycle modules for buildings defined in EN15804

Although progress has been made in the field of LCA to allow its effective use for ensuring the sustainable development of our society, further efforts need to be made. In the following sections, recent developments in LCA methodology are reviewed and the research gaps are identified.

2.1 Relevance of regionalization

Life cycle assessment can be used as a method to quantify the environmental impact of a product along its life cycle. In the field, the idea of the regionalization of the method has recently been discussed to improve the quality of impact assessments (UNEP 2011). Efforts have been made to quantify the influence both from and on regions, although it is said that traditional LCA is not a spatially explicit model (Heijungs et al. 2002). The study by O'Keeffe et al. (2016) reviewed how to include regional and spatial information in the goal orientation and life cycle inventory (LCI). They state that regional information has been included by various researchers in the foreground LCI data. The three main contexts of regional investigations in LCA are within the region, the region and rest of the world, and the differences between regions. Each type meets a certain goal orientation to address the environmental burden of the product or activity. In the study, the authors define a region as “a spatial scale below a nation, usually including two or more communities with naturally or arbitrary determined boundaries”, which follows the definition of (Loiseau et al. 2012).

Various attempts have been made concerning regionalized environmental impact assessments. For instance, an impact assessment method that considers the intercontinental variation of toxic emissions has been developed by Kounina et al. (2014). Dressler et al. (2012) conducted an assessment of relevant regional parameters, such as soil and climate, for biogas production from maize in Germany. Rosenbaum et al. (2015) have developed an impact assessment method to evaluate the impact of indoor pollution on human health that considers four different regions (Europe, USA, OECD countries and non-OECD countries).

Regarding buildings and regional LCA, Saner et al. (2014) studied the optimization of the environmental performance of buildings in a Swiss municipality where spatial and temporal constraints were introduced. The role of regionality played the importance in creating relevant and realistic alternatives of foreground LCI for optimizing the impact of buildings.

2.2 Relevance of time resolution

Another aspect that has been actively discussed in the field of LCA is the influence of time, which is known as "dynamic life cycle assessment" (DLCA). The temporal aspects related to LCA can be seen in the LCI as well as the impact assessment methods, as was the case with the regional aspects, to improve the accuracy and precision of the assessment.

The Shonan principles (UNEP 2011) list impact categories whose results may vary as a function of time. A study concerning impact assessment that takes dynamic characteristics into account was conducted by Levasseur, Lesage, Margni, et al. (2010). This study created time-dependent characterization factors for assessing the impact on climate change, showing a case in which the result of LCA may vary significantly when taking the temporal aspects into consideration. Kendall’s (2012) study characterized the influence on global warming regarding when the emission of greenhouse gases (GHGs) takes place. Their case study of a commercial building with 75 years of building life showed a larger deviation between their results and those using the static characterization factor from the IPCC with an analytical time horizon of 100 years than with one of 500 years. The case study highlights the potential mismatch of the assessed impact of the emission on global warming at a specific point in time within a period shorter than 100 years. Kendall and Price (2012) also investigated the implication of the inclusion of temporal information in LCA through a vehicle case study, where they pointed out the importance of emissions during the production stage when taking the temporal influence on climate change into account.

Regarding investigations concerning the LCI, Beloin-Saint-Pierre et al. (2014) addressed the challenge of implementing the temporal aspects of LCI into LCA databases. In the study, the challenge of handling the temporal distribution of emissions that take place over the entire life cycle was addressed by introducing a new method to calculate the LCI. Pinsonnault et al. (2014) adopted the method proposed by Beloin-Saint-Pierre et al. (2014) to assess the influence of incorporating the dynamic characterization factor into the global warming potential (GWP). Their study showed that most of the product systems affected by taking the temporal information into account showed a decrease in GWP scores.

2.3 Assessing social impact

A newer tool related to LCT is social LCA (SLCA), which attempts to integrate social aspects into LCA (Petti et al. 2016). Social LCA is an evolving field in which many efforts have been made in the last decade, with the SLCA UNEP/SETAC Guidelines (UNEP Setac Life Cycle Initiative 2009) released in 2009 being one of the major outcomes achieved. Following the release of these guidelines, the number of publications in SLCA increased significantly; in 2013, the number increased 700% compared to the previous year (Petti et al. 2016).

While there are ongoing discussions and developments taking place related to the methodological aspects of SLCA, there are several studies that have investigated the social impact of the construction sector. Dong and Ng (2015) developed a social impact assessment method for construction projects, taking Hong Kong as a case study. The study identified the positive links between environmental and social performance in the construction practices that were investigated. Hosseinijou et al. (2014) developed a method for comparative SLCA, where they introduced the analytic hierarchy process (AHP) from multi-criteria decision analysis (MCDA). In this paper, they present a case study of building material selection between steel/iron and cement/concrete in Iran. Another study focusing on material selection was conducted by Hossain et al. (2017), who developed a single score-based SLCA methodology. As a case study, they assessed the performance of recycled and natural construction materials in Hong Kong. Wang et al. (2017) investigated the life cycle sustainability impact, using environmental and social LCA and life cycle costing (LCC) of fly ash concrete. Broadening the scale and moving further along the life cycle stages, Yu et al. (2017) investigated the social impact of demolishing urban housing in Shanghai, China. They focused on social indicators that were considered relevant and important based on interviews and collected their data via questionnaires.

2.4 Gaps in assessing the sustainability of buildings

2.4.1 Regional considerations for buildings

Regional considerations are not only important for improving the quality of LCA but also for the sustainability performance of a building. As the core function of a building is to provide shelter from the external environment to keep humans safe and comfortable, it must withstand the conditions to which it is exposed. External environments differ across regions, which may pose different stresses on buildings. Such stresses can be hygrothermal due to the climatic conditions (Goto et al. 2012; Pakkala et al. 2014) or can be mechanical due to natural disasters such as typhoons or earthquakes. It is not just the condition of the natural environment but also socio-economic conditions such as market demands and indoor habits that may differ across locations. Meeting the functional requirements for buildings indicate the importance of taking regional conditions into account during the operational phase not just for the technical but also the environmental and socio-economic challenges that materials face for the sustainable development of the building industry. To also reflect the practicality issues that have been identified as a bottleneck for SPD methodologies, literature that considered the relation between regional conditions and sustainability performance has been investigated, including the methods from LCA.

2.4.2 DLCA of electricity

As was seen from the studies on DLCA, temporal aspects do affect LCA results. For an LCA, electricity is one of the key inventories; it is frequently used to describe the LCI of various products (F. Mendoza et al. 2012; Torrellas et al. 2012; Treyer and Bauer 2013). The prevalence of the electricity inventory's use in LCA studies suggests that the accuracy of the inventory may significantly impact the result of an LCA. A tremendous variety of electricity inventories are available in ecoinvent, with 71 geographical regions being represented (Wernet et al. 2016). Currently, the inventory of electricity is based on the annual share of energy sources in the electricity grid mix of a country. Based on this mix, the annual average carbon emission factor (EF) of electricity is calculated and used to quantify the emissions resulting from electricity consumption.

However, the electricity mix has changed rapidly over the last few decades in response to the emission reduction goals set by many countries to combat climate change. For example, the EU set an emission reduction target of 20% by 2020 through the Climate and Energy Package (Commission of the European Communities 2008). In keeping with the commitments outlined, the share of renewable energy sources in the electricity grid has increased in several countries. Germany is one of the countries that has successfully increased their share of renewables in the grid, with the share of renewable energy in the German electricity grid increasing tenfold in 25 years (BDEW 2016; BMU 2013). This increase was mainly due to the contributions of variable renewable energy sources (vRES) such as solar and wind. A characteristic of electricity generation from vRES is its time-dependency, which restricts the ability to plan electricity generation in the same manner as is possible with conventional power plants. Furthermore, the study by Paraschiv et al. (2014) indicates that the renewable energies in the electricity spot market enhance the deviations in electricity price in Germany. As such, the potential of virtual power plant (VPP) that includes demand response is discussed as a way to manage the grid beyond the conventional manner to meet and respond to this new challenge.

With the energy mix varying with the increase in vRES, both the price and the corresponding carbon emissions of consuming 1 kWh of electricity may vary depending on the time. This indicates the weakness of the current usage of annual average EF for quantifying emissions from electricity consumption, depending on when the electricity is consumed. Indeed, previous studies identify the lack of temporal information in LCA as an important limitation of LCA (Levasseur, Lesage, and Margni 2010; Pinsonnault et al. 2014; Reap et al. 2008). To better quantify the respective emissions for a specific consumer, higher resolutions of EFs may become relevant. With the adoption of the Paris Agreement in COP21 (UNFCCC 2016), an upwards trend in the share of vRES can likely be expected in other nations and continents as well. Thus, this thesis study investigated the hourly EFs taking German electricity grid as a case study, and assessed its implications and relevance for the SPD of building materials.

2.4.3 SLCA for PD

As was seen in chapter 2.3, several attempts have been made to assess the social impact of the construction sector. However, to our knowledge, no studies have discussed the potential role of PD and how it can contribute to improving the social sustainability performance. Since the PD phase is considered an effective phase in which to affect product performance (McAloone and Tan 2005), taking social performance into account during PD should theoretically be effective in improving the overall sustainability performance of building materials. Thus, the thesis investigates the role of PD to improve the social sustainability performance of the developed materials by taking green concrete as a case study.

Chapter 3

Research Methods

In the following section, the methods employed in the appended papers are introduced. The two main methods used to assess the sustainability performance of a building and building materials are environmental and social LCA. The method used to explore the value of existing sustainability assessment methods for the PD of building materials is also explained. In Table 3.1, an overview of the methods and topics of the appended papers is provided. It is also indicated which journal the paper has been published or submitted to.

Paper	Method	Topic	Journal
Paper 1	Eco-efficiency	Thermal insulation material	Key Engineering Materials
Paper 2	DLCA	Hourly electricity emission factor	International Journal of Life Cycle Assessment
Paper 3	LCA	Residential building	Energy and Buildings
Paper 4	Misc.	Sustainability assessment methods	Journal of Cleaner Production
Paper 5	SLCA, LCA	Green concrete	International Journal of Life Cycle Assessment

Table 3.1: Overview of the methods and topics of the appended papers

3.1 Analysis of existing sustainability assessment methods

To contribute to the field of SPD by assembling and structuring the existing sustainability assessment methods, Paper 4 examined how manufacturers can address the relevant indicators during the PD phase by taking their operational boundaries into consideration. For this purpose, SCOPUS was mainly used as the platform for investigating the relevant academic documents. In addition to the life cycle based methodologies mentioned in the previous chapter, a review of literature published in the last 10 years was also conducted in March 2017, using the keywords “sustainability; indicator; building”. From the resulting literature, studies that were identified as highly relevant by reading the title and abstract were investigated further, as defined in design research methodology (Blessing and Chakrabarti 2009). To obtain a comprehensive overview of the existing sustainability assessment schemes and indicators, not just the academic documents but also the international initiatives on sustainability, such as the Global Reporting Initiative (GRI) (Global Reporting Initiative 2014), Product Environmental Footprint (PEF) (Manfredi et al. 2012), and sustainable development indicators (Eurostat 2015) were taken into account. The indicators from studies related to regional conditions were also included for the sake of holistic coverage of the assessment of sustainability performance.

In order to sort the identified indicators for further analysis, the indicators were organized into three tiers: category, aspect, and indicator. The identified indicators and aspects were merged and sorted to avoid redundancy. From the sorted aspects, categories were introduced to structure them based on the characteristics of the aspects. Since most of the collected indicators had a hierarchical relationship between the tiers within the respective schemes, most of the links were maintained in so far as possible when applying the three tiers introduced in this study.

At the ’aspect’ tier, classifications were made by reflecting the consideration of the manufacturers’ operational boundaries. The three classes introduced were as follow: product, company, and regional conditions. These classifications were chosen to clarify the aspects that companies can address (product- and company-specific aspects), and those external to the companies (region specific aspects).

Further clustering was done on the indicators assigned to the product- or product and region-specific aspects. Based on the observed characteristics of the indicators, these product-specific sustainability indicators were sorted into the following three groups: product-property-related indicators, inventory-related indicators, and impact-related indicators. Figure 3.1 represents the grouping of sustainability indicators within the information structure introduced in the study.

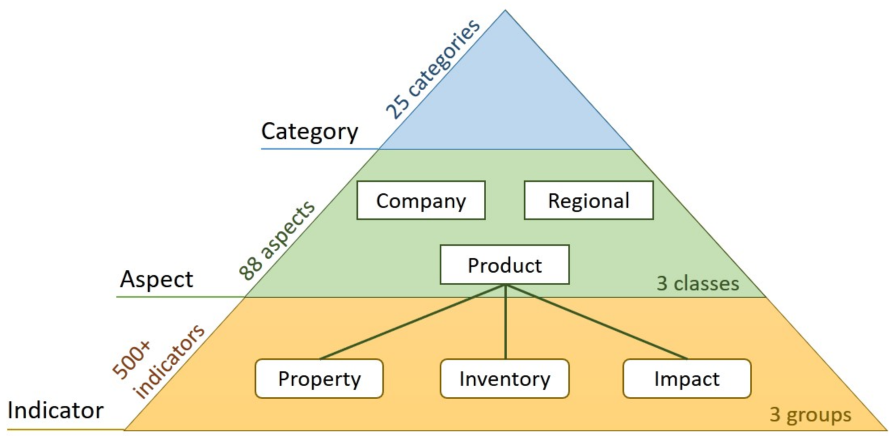

Figure 3.1: Representation of information hierarchy for sorting sustainability indicators and their classes and groups

3.2 LCA

Except for Paper 4, LCA was conducted in all the appended papers. Paper 1 mainly used ecoinvent v2 (Frischknecht et al. 2005) as the source of LCI to assess the environmental impact of products. For Papers 2 and 5, econivent v3 (Wernet et al. 2016) was used. The software used to conduct environmental LCA was SimaPro (PRé Consultants 2015). For Paper 3, data from the Swedish Environmental Institute (IVL) was used in Anavitor, LCA software specifically tailored for SKANSKA, the contractor of the building used as a case study. The life cycle modules as defined in EN 15804 (European Committee for Standardization 2012) covered in the studies were A1-C4 for Paper 1, A1-A3 for Paper 2 and 5, and A1-A5 for Paper 3. Table 3.2 summarizes the life cycle modules that were covered, the databases that were used and the life cycle impact assessment (LCIA) methods that were adopted in the respective studies.

Paper	Life cycle module covered	Database	LCIA method
Paper 1	A1-C4	ecoinvent v2	ReCiPe, IPCC GWP100a
Paper 2	A1-A3	ecoinvent v3	IPCC GWP100a
Paper 3	A1-A5	IVL	IPCC GWP100a
Paper 5	A1-A3	ecoinvent v3	CML-IA

Table 3.2: Summary of the scope of life cycle phases covered and the databases used in Papers 1-3 and 5 papers

In Paper 1, eco-efficiency was adopted in order to take the created technical value of the assessed products into account. Paper 2 examined the relevance of time of consumed electricity by applying DLCA. The influence of the technical requirements at the scale of the building/component levels was investigated by utilizing the carbon abatement cost in Paper 3. In the following section, the details of the methods employed in Paper 1 to 3 are provided.

3.2.1 Eco-efficiency

According to ISO 14045 (International Organization for Standardization 2012), the eco-efficiency (EE) of a product or service can be defined as an *"aspect of sustainability relating the environmental performance of a product system to its product system value"*. The standard can thus be expressed as in equation 3.1.

$$(\text{eco-efficiency}) = \frac{(\text{created value or functionality provided})}{(\text{environmental impact})} \tag{3.1}$$

Eco-efficiency quantifies the amount of value created in relation to the environmental impact that is caused. In Paper 1, the created value was defined as the thermal performance, and the environmental impact as the life cycle environmental impact of the material. For the thermal performance of the materials, thermal resistance was used which was set at 1 $[m^2K/W]$ for a surface area of 1 $[m^2]$ of thermal insulation materials. For the quantification of environmental impact, an

LCA was conducted. The aim of the LCA was to analyze the key contributing factors for the EE of thermal insulation materials and evaluate its effectiveness for improving the materials' EE. To quantify environmental performance, cradle-to-grave (A1-C4) LCAs of each material were conducted. The LCIA methods used were ReCiPe H/A (Goedkoop et al. 2009) and global warming potential (GWP100a)(IPCC 2007). The expected life time of the materials was 40 years, and the materials under study were cellulose fibre, fibreboard, foam glass, stone wool, vacuum insulation panel (VIP), polyurethane (PUR), expanded polystyrene (EPS), and extruded polystyrene (XPS).

The functional unit of the study was set as the required quantity of each material with identical thermal performance, as given in equation 3.2.

$$\text{F.U.} = \lambda \cdot \rho \cdot R \cdot A \tag{3.2}$$

where F.U. represents the functional unit, λ thermal conductivity $[W/mK]$, ρ density $[kg/m^3]$, R thermal resistance $[m^2K/W]$ and A surface area $[m^2]$ (Ardente et al. 2008).

For improving the EE of thermal insulation materials, two approaches can be considered. One is to reduce the environmental impact of materials. In order to assess potential measures to reduce the impact, a contribution analysis of each investigated material was conducted. The analysis was conducted by assigning the inventories of the materials to six categories: heat, chemicals, electricity, transportation, raw materials, and waste.

Another approach to improve the EE is increasing the value created from the materials. For this purpose, improving thermal conductivity is gaining manufacturers' attention. However, when transforming equation 3.2,

$$\text{R} = \frac{\text{F.U.}}{\lambda \cdot \rho \cdot A} \tag{3.3}$$

density (ρ) can also be seen as a property that interacts with thermal resistance, the created value, as shown in equation 3.3. Therefore, the present study investigated the relevance of the two thermo-physical properties, thermal conductivity, and density, which define the thermal performance of the material.

The analysis of the relevance of thermo-physical properties to EE in Paper 1 was conducted based on the existing product data. In addition to the aforementioned ecoinvent (Frischknecht et al. 2005), LCI databases such as ICE (Hammond and Jones 2011), IDEA (JEMAI 2012), AIJ (AIJ 2006), as well as Environmental Product Declaration (EPD) data were included in the analysis.

3.2.2 Dynamic LCA

In Paper 2, an investigation of the temporal influence of German electricity LCI was conducted. Hourly electricity generation data for the German electricity grid were sourced from the European Energy Exchange (EEX) (European Energy Exchange AG 2015). The data represent the net electricity generation of a specific hour from companies participating in the wholesale electricity market of the EEX. Due partly to the fact that not all electricity generation facilities are represented in the EEX market and partly to the differing representations of electricity generation data, the data in the study represent approximately 65% of gross German electricity generation (BDEW 2016). For the period studied, namely 2011 to 2015, the representation of the electricity generated by the renewables covered in this study amounted to about 60% of the gross electricity generation of renewables in Germany, whose coverage is slightly lower than that of the abovementioned overall generation. Therefore, this study can be considered to draw conservative rather than optimistic results regarding the EFs. The study did not consider the import and export of electricity between the neighboring countries.

As the share of energy source in the electricity grid may vary with the increased capacity of vRES due to its availability, the study investigated the variation of EF in several time resolutions. In the study, carbon EFs were calculated as described in equation 3.4.

$$EF_t = \frac{\sum GWP_t}{\sum G_t} \tag{3.4}$$

where EF represents the carbon EF, GWP represents the emitted CO_2 equivalent GHG based on GWP100a (IPCC 2013) from the entire electricity grid, and G represents the total electricity generation of the grid at a given time t. The highest resolution of time t was hourly.

The EFs were clustered based on three aspects of temporal resolution: the length of the time period, the time of day, and the day of the week. Each of the clustered EF was calculated based on equation 3.4. Thus, rather than averaging the hourly EF over the respective period, the clustered EF represents the corresponding emission and generation that took place during the represented period. Regarding the length of the time period, the study calculated EF at an annual, monthly, and hourly resolution. The influence of time of day was isolated by defining "daytime" and "nighttime". For the study, 6:00-18:00 was defined as the "daytime", while the remaining hours were regarded as "nighttime". The EFs of weekdays (Monday to Friday) and weekends (Saturday and Sunday) were also calculated with equation 3.4. Thus, the study investigated the potential deviation of clustered average EFs from the annual average to assess the accuracy of quantifying emissions using annual average EFs.

3.2.3 Carbon abatement cost

Paper 3 investigated a typical Swedish residential building, in terms of design, energy performance, size, and localization, as a base house for the case study. The base house is located in Solna, Sweden, and was constructed between 2012 and 2013. It is a four storey residential building with 15 apartments ranging from 50 - 100 m^2 resulting in a total apartment net floor area of 1,090 m^2.

As potential alternative designs applicable to the case building, four combinations were considered. Changes in design were considered to be implemented in the inner and outer walls and the floor, and changes to the materials in use were also considered. These alternative designs of building components were designed to be interchangeable without major changes of the base house in terms of layout, structural system, maintenance needs or shape. All the designs met the technical requirements of Swedish building standards, which include fire safety, structural stability, energy performance, and acoustic performance. In one case, the acoustic performance was lowered from class B to class C. Both classes are however sufficient for residential buildings. In Table 3.3, a description of the combinations that were investigated is given.

Combinations	Alternative design	Influence on the sound class
Combination 1	– Low impact concrete in floor slabs and interior/exterior wall	Sound Class B maintained
Combination 2	– Reduction of material in exterior walls (120mm) – Reduction of material in interior walls (160 mm) – Floor slab exchanged for HDF 190 and acoustic mat – Wooden roof trusses – Graphite EPS insulation instead of EPS/XPS in exterior walls and ground works	Reduction to sound class C
Combination 3	– Reduction of material in exterior walls (120mm) – Floor slab exchanged for HDF 270 with a layer of cast concrete – Graphite EPS insulation instead of EPS/XPS in exterior walls and ground works	Sound class B maintained
Combination 4	– Sandwich elements instead of half sandwich elements in exterior walls. (Increase in carbon emissions, sometimes preferred due to a higher level of prefabrication)	Sound class B maintained

Table 3.3: The design details of the different combinations used to investigate the carbon abatement costs for the case building

3.3 SLCA

The study presented in Paper 5 used PSILCA v1.1 (GreenDelta GmbH 2016) as the source for LCI to assess the social impact. The database is constructed based on the indicators and categorization given in the (UNEP Setac Life Cycle Initiative 2009). Among the 42 social indicators included in the database, the indicators with less uncertainty were selected for the assessment. The indicators were selected based on the data quality assessment results of the inventory, where the pedigree matrix (Weidema and Wesnaes 1996) was employed for the assessment.

In the study, the influence of three aspects on sustainability performance was assessed. One aspect concerned the influence of regions, where six datasets were created to represent green concrete using steel slag for the respective countries. These six countries were Switzerland (CH), Germany (DE), Japan (JP), Sweden (SE), Thailand (TH) and the United States of America (US). The second aspect concerned the influence of product design. For each of the countries, three datasets were created representing different product designs in which the steel slag content differed. The three slag contents assessed were 33%, 70%, and 85%. The respective datasets for the environmental LCA were investigated to assess the relation between the social and environmental performance of the green concrete product designs. The last aspect investigated was the influence of the corporate efforts that are being made regarding sustainability performance. To reflect the potential variation in the sustainability performance of the products based on the corporate efforts that are being made, the study introduced four classes of companies: Class A companies represent front-runners regarding sustainability issues; Class B represents above average performing companies; Class C represents below average performing companies; and Class D represents the worst performers concerning sustainability issues. The classification was made based on the results of Monte-Carlo analysis, where the 2.5^{th} percentile was assigned to Class A, the median to Class B, the mean to Class C, and the 97.5^{th}percentile to Class D.

To conduct the hotspot analysis, two impact assessment methods were employed in Paper 5. For the social impact assessment, the risk assessments provided in PSILCA was used. For assessing the corresponding environmental impact, the CML-IA baseline (Universiteit Leiden 2015) was used. The analysis of the hotspots was conducted by investigating the relevant inventories, which were grouped into three categories. These three were steel slag, clinker, and energy related inventories. The software used for conducting SLCA for the hotspot analysis was openLCA v.1.6 (Ciroth 2007) and SimaPro v8 (PRé Consultants 2017).

Chapter 4

Results

4.1 Proxy information for improving eco-efficiency

An investigation of the relevance of technical properties to environmental performance was conducted in Paper 1 by assessing eco-efficiency (EE). For the improvement analysis of EE, the study was conducted with two main focuses: the first investigated the factors contributing to the impact caused by production processes, and the second examined thermal performance based on thermo-physical properties. In Figure 4.1, the results of the contribution analysis for each insulation material are given.

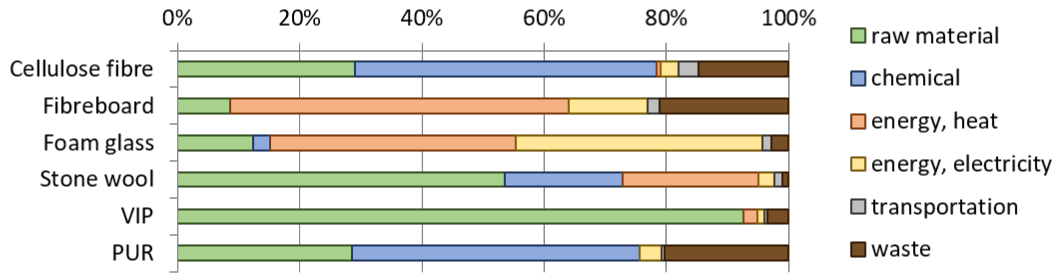

Figure 4.1: Composition of raw material, transportation and energy on the environmental impact of each thermal insulation material on ReCiPe in A1-C4 module

Among the assessed materials, there was variation in the significance of the electricity and heat that was consumed for EE. These are factors whose associated impact depends on regional conditions. Foam glass had the highest potential to improve EE by changing the sources of the consumed energy, by a factor of 1.72. This fact implies that foam glass may benefit more than the other materials if it is produced in locations with cleaner electricity mixes to improve EE. On the other hand, materials such as cellulose fibre, VIP, and PUR had limited room for improvement based on the energy that is consumed.

The analysis of the relation between the thermo-physical properties and the EE of the thermal insulation materials highlighted the importance of density as a proxy indicator upon the materials' development and use. In Figure 4.2, the correlations between the materials' density and eco-efficiency are presented. In the figure, a clear correlation can be seen in every material category, where the lower the density is, the better the materials' EE. This correlation was not observed when thermal conductivity, the other thermo-physical property whose relationship with EE was assessed, was used as the x-axis in Figure 4.2. For improving the EE of thermal insulation materials, increasing the technical value the material provides is an approach in which thermal conductivity is typically used as the value to achieve during product development. However, as seen from equation 3.3, thermal resistance, the provided technical value, has several factors that affect its values. Density is one of technical specifics affecting thermal resistance. Although density often receives less attention, the findings suggest the effectiveness of improving the EE by achieving lower density without compromising the value provided by the materials.

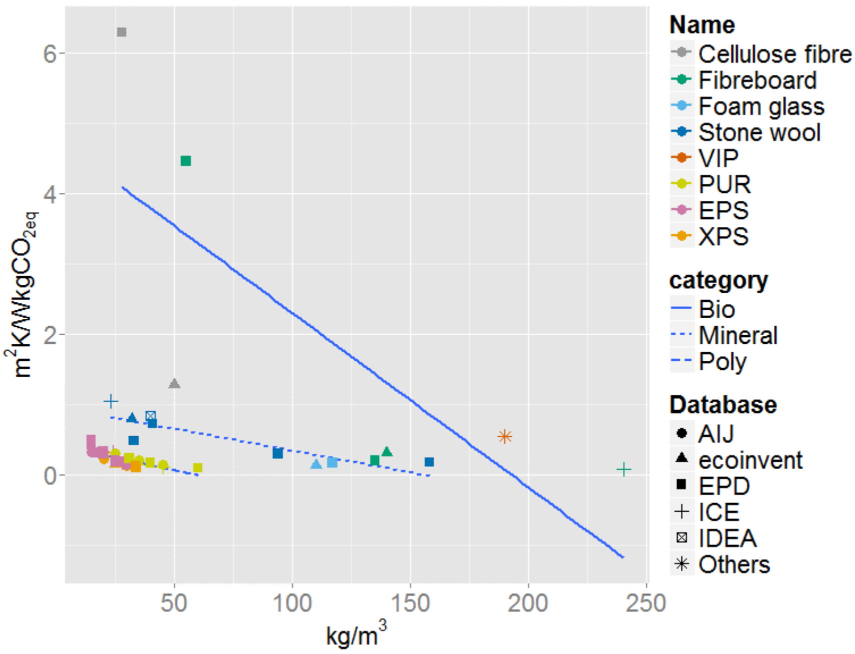

Figure 4.2: Correlation between material density and eco-efficiency of materials in GWP from multiple data sources

4.2 Influence of vRES on the electricity consumed

The share of variable renewable energy sources (vRES) in the German electricity grid has increased over the past few decades. Due to the nature of the generation pattern of vRES, the increase in vRES causes the EF to fluctuate on an hourly basis. This fluctuation raises concerns about the accuracy of quantifying emissions using the current metric of annual average EF, as the respective EF may change depending on the time at which it is consumed. Paper 2 calculated German hourly EF from 2011 to 2015 and investigated the effect of an increase of vRES on EF. The calculated hourly EF was clustered based on three aspects of time: the period of time, the time of a day, and the day of the week. Table 4.1 presents the result of the average EF clustered by months, time of a day, and the day of the week, normalized by the corresponding annual average, where the cells highlighted in green represent cleaner and the ones in red represent dirtier EF. The values were scaled to 100% by taking the annual average EF of the respective year as the reference point.

			JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2011	Weekly	Daily	94.00%	90.10%	100.00%	100.30%	109.40%	106.20%	98.90%	102.00%	101.70%	104.20%	108.10%	89.80%
		Day	95.80%	91.00%	97.70%	96.40%	103.70%	102.20%	95.10%	97.70%	98.20%	102.50%	108.50%	91.30%
		Night	92.00%	89.00%	102.60%	105.00%	116.70%	111.10%	103.50%	107.10%	106.00%	106.10%	107.80%	88.00%
	Weekday	Daily	97.70%	93.30%	100.40%	101.50%	112.60%	108.90%	103.80%	102.70%	101.80%	104.10%	111.00%	91.60%
		Day	95.80%	91.00%	97.70%	96.40%	103.70%	102.20%	95.10%	97.70%	98.20%	102.50%	108.50%	91.30%
		Night	94.60%	91.60%	102.40%	105.50%	119.30%	113.00%	108.20%	107.50%	105.70%	105.20%	110.20%	89.30%
	Weekend	Daily	85.40%	80.90%	98.70%	96.90%	100.40%	97.80%	87.40%	99.50%	101.50%	104.20%	99.50%	84.70%
		Day	84.50%	79.90%	94.60%	91.20%	92.70%	91.70%	82.40%	93.90%	97.00%	100.60%	98.40%	84.70%
		Night	86.20%	82.00%	103.10%	103.40%	109.60%	105.00%	93.10%	105.90%	106.70%	108.30%	100.70%	84.60%
2012	Weekly	Daily	91.60%	103.10%	98.70%	104.60%	94.80%	98.30%	98.80%	95.80%	98.60%	105.30%	107.60%	102.00%
		Day	92.30%	102.00%	94.50%	99.00%	87.70%	91.50%	91.40%	88.80%	92.60%	102.60%	108.10%	102.80%
		Night	90.80%	104.40%	103.70%	111.50%	104.40%	107.40%	108.70%	104.80%	106.10%	108.40%	107.10%	101.20%
	Weekday	Daily	92.80%	103.60%	101.90%	107.70%	96.40%	102.20%	100.80%	98.10%	100.10%	106.80%	108.70%	104.20%
		Day	92.30%	102.00%	94.50%	99.00%	87.70%	91.50%	91.40%	88.80%	92.60%	102.60%	108.10%	102.80%
		Night	91.10%	103.90%	106.50%	113.80%	105.60%	109.90%	110.20%	106.40%	106.60%	109.50%	108.00%	102.60%
	Weekend	Daily	87.90%	101.90%	89.10%	95.80%	89.40%	87.90%	93.00%	88.30%	95.00%	100.20%	104.10%	97.00%
		Day	86.20%	98.30%	83.30%	87.90%	81.00%	77.90%	83.90%	79.00%	86.70%	95.80%	104.00%	96.20%
		Night	89.70%	105.80%	95.80%	105.10%	100.10%	100.80%	104.40%	99.80%	104.90%	105.10%	104.20%	97.90%
2013	Weekly	Daily	103.10%	109.50%	100.20%	102.10%	99.40%	94.70%	102.50%	98.10%	99.50%	96.40%	104.10%	90.40%
		Day	103.80%	108.30%	95.90%	95.50%	92.90%	87.60%	92.80%	89.90%	94.60%	94.40%	103.80%	90.20%
		Night	102.40%	110.90%	105.10%	110.40%	107.90%	104.20%	115.50%	108.70%	105.40%	98.70%	104.50%	90.60%
	Weekday	Daily	103.10%	110.10%	105.30%	102.90%	102.10%	100.90%	104.90%	101.60%	101.70%	97.50%	106.70%	93.60%
		Day	103.80%	108.30%	95.90%	95.50%	92.90%	87.60%	92.80%	89.90%	94.60%	94.40%	103.80%	90.20%
		Night	102.10%	111.20%	109.80%	110.70%	109.60%	109.30%	116.90%	111.50%	107.00%	99.70%	106.80%	93.70%
	Weekend	Daily	103.10%	107.90%	88.00%	99.60%	90.20%	79.00%	94.20%	88.30%	93.50%	92.40%	97.40%	81.60%
		Day	102.60%	105.70%	82.50%	91.30%	80.50%	68.70%	81.20%	78.10%	86.80%	89.50%	96.20%	80.80%
		Night	103.70%	110.10%	94.10%	109.30%	102.10%	91.90%	110.80%	100.90%	101.30%	95.50%	98.60%	82.60%
2014	Weekly	Daily	102.30%	95.70%	97.90%	98.90%	97.70%	98.00%	100.60%	90.00%	104.70%	106.00%	110.90%	95.10%
		Day	102.90%	93.90%	92.30%	91.20%	89.30%	88.20%	91.80%	81.60%	99.00%	103.90%	111.20%	96.00%
		Night	101.70%	97.60%	104.60%	108.80%	108.80%	111.20%	112.40%	101.20%	111.80%	108.40%	110.50%	94.10%
	Weekday	Daily	105.00%	101.40%	102.00%	100.90%	100.70%	100.60%	102.50%	93.90%	105.40%	108.50%	115.20%	96.40%
		Day	102.90%	93.90%	92.30%	91.20%	89.30%	88.20%	91.80%	81.60%	99.00%	103.90%	111.20%	96.00%
		Night	104.70%	102.10%	108.50%	110.00%	110.50%	112.90%	113.40%	104.20%	111.70%	110.40%	114.00%	95.50%
	Weekend	Daily	93.40%	79.90%	87.90%	92.40%	88.90%	90.80%	94.30%	80.70%	102.30%	97.10%	100.40%	91.00%
		Day	94.60%	74.70%	81.20%	82.00%	77.40%	78.40%	82.70%	70.00%	93.90%	93.00%	98.40%	92.20%
		Night	92.30%	85.70%	95.40%	105.00%	103.80%	106.70%	109.10%	94.40%	112.20%	101.70%	102.50%	89.80%
2015	Weekly	Daily	96.30%	108.40%	101.90%	96.70%	87.90%	99.10%	101.80%	102.40%	104.90%	117.40%	93.60%	88.80%
		Day	96.50%	106.70%	97.70%	88.50%	80.70%	92.20%	93.00%	94.80%	100.30%	114.30%	94.90%	90.30%
		Night	96.20%	110.20%	106.90%	106.90%	97.20%	108.10%	113.00%	111.70%	110.40%	120.90%	92.30%	87.20%
	Weekday	Daily	99.00%	112.20%	104.10%	98.70%	92.50%	101.90%	103.40%	105.00%	108.00%	119.00%	97.70%	93.70%
		Day	96.50%	106.70%	97.70%	88.50%	80.70%	92.20%	93.00%	94.80%	100.30%	114.30%	94.90%	90.30%
		Night	98.40%	114.10%	109.40%	108.60%	101.00%	110.10%	114.00%	113.00%	112.70%	122.00%	96.40%	91.20%
	Weekend	Daily	88.90%	97.30%	95.30%	89.80%	76.20%	89.50%	96.50%	95.60%	94.70%	112.80%	82.70%	73.30%
		Day	87.70%	95.30%	91.30%	80.30%	66.60%	79.40%	85.50%	84.70%	87.30%	108.10%	83.70%	71.70%
		Night	90.20%	99.40%	99.60%	101.00%	87.90%	101.40%	109.40%	108.50%	103.10%	117.80%	81.70%	75.10%

Table 4.1: Normalized annual average EF of the time of a day and the day of the week for 2011 to 2015. The values are scaled to 100% by taking the annual average EF of the relevant year as the reference point. Values higher than 105% are highlighted in red whereas values lower than 95% are highlighted in green.

The study showed a higher proportion of vRES on weekend daytimes, while the weekday night times resulted in a lower share than the annual average. The potential underestimation and overestimation of emissions resulting from the use of annual average EF was highlighted and ranged from +22% (2015 weekday night time of October) to -34% (2015 weekend daytime of May). This fact suggests that the application of hourly EF may be necessary to quantify the respective emissions from consumers that use electricity during the weekday daytime and weekend nighttime. For consumers using electricity at other times, emissions can be quantified appropriately by using the conventional annual average EF.

Viewing the findings from the consumer's perspective, there seems potential for reducing emissions due to electricity consumption not just by reducing the total demand but by optimizing the time of consumption. For consumers with the flexibility of shifting their weekday night time loads to the weekend daytime, carbon emissions can be expected to be reduced for more than 10% while maintaining the demand. Even by shifting the daytime consumption from weekdays to weekends, the reduction of around 10% can be expected. Building material manufacturers who have such flexibility in production scheduling may benefit from reducing carbon emissions while maintaining economic gains.

4.3 Marginal carbon abatement costs

In Paper 3, the scope of the investigation was scaled up from the material level to the building level. The paper assessed the potential economic and environmental effectiveness of different design options applicable to a case building, taking the functional requirements of buildings into account. In Table 4.2, the results of the reduced embodied carbon emissions and associated costs of each design combination are given. All design measures except combination 4 resulted in improved environmental performance. When taking the sales price of the floor area into consideration, combinations 2 and 3 are economically more profitable, as the design measure allowed an increase in the salable area. Combination 2 was economically and environmentally the best combination and was the only design combination that down graded the building's sound class to C.

Combinations	Reduced embodied carbon emission	Economic impact related to original production costs	Economic impact including the effect of salable area
Combination 1	–6.0%	+0.14%	+0.14%
Combination 2	–24.1%	+0.22%	–3.45%
Combination 3	–13.4%	+0.23%	–3.34%
Combination 4	+4.1%	+0.6%	+4.60%

Table 4.2: The environmental and economic impact of the different combinations compared to the base case building

When considering the carbon abatement cost of the investigated design measures, it was evident that many of them enabled cost-effective abatement. Figure 4.3 gives a visual representation of the marginal cost of carbon abatement for the different solutions, where the y-axis represents the marginal cost per ton of GHG emission and the x-axis represents the reduced embodied carbon emission. Each step illustrated in the figure represents the carbon abatement cost of the design components implemented in each combination. For instance, Combination 1 replaces normal concrete with low-impact concrete in several components. As the carbon reduction per associated cost is unique for the replacement, the marginal cost (y-axis) remains the same while the value of total embodied emission reduction (x-axis) increases as much as the replacement can be used. In Combination 2, meanwhile, different design components with alternative materials resulted in several steps in the figure, where the abatement costs for each measure are reflected respectively. As references for the marginal cost of carbon, the prices given in (Stern 2007; Ackerman and Stanton 2009; IEA 2014; Swedish Transport Admistration 2015) are shown.

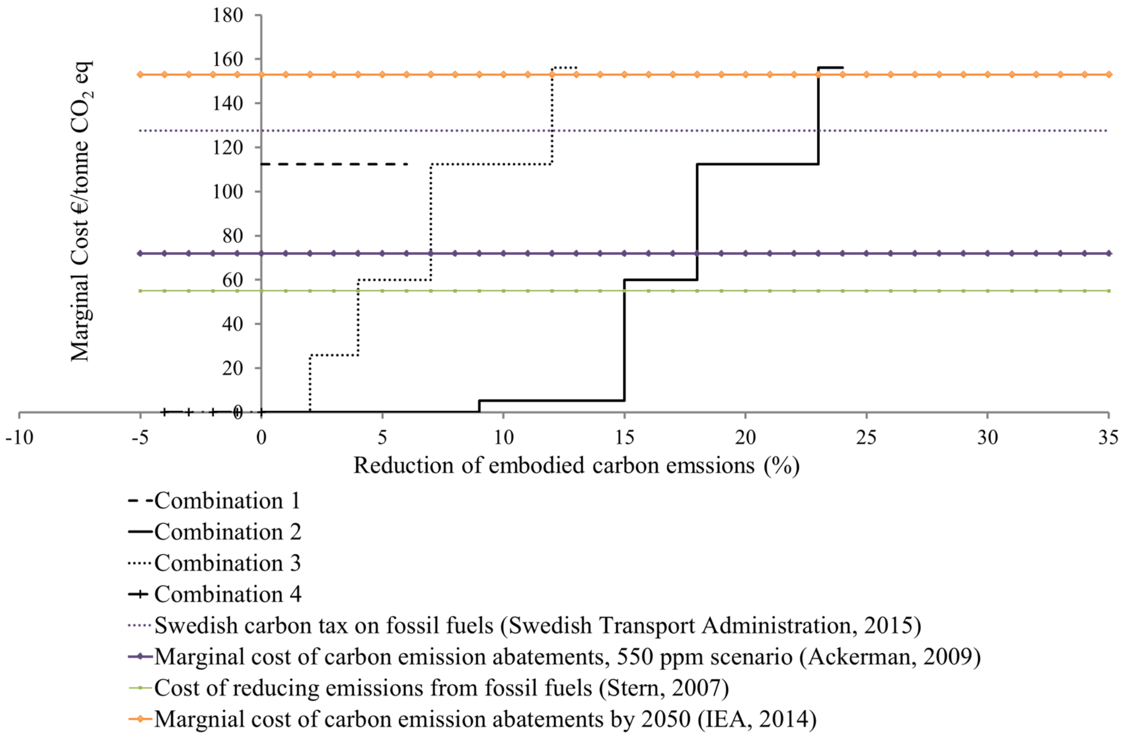

Figure 4.3: Marginal cost of emission abatement for the different combinations

The results revealed that the embodied emissions of the case building could be reduced by 15% using cost neutral or nearly cost neutral measures. Abatement up to 18% was found to be cost-effective in relation to the marginal cost of carbon mitigation with a 550 ppm scenario in (Ackerman and Stanton 2009). Abatement up to 24% was possible with minor increases in total production cost (0.22% in Table 4.2), even though some of the individual measures were found to be expensive in relation to the social costs of carbon emissions.

Furthermore, acoustic requirements were found to be a limiting factor in the abatement of embodied emissions. Yet, as was seen from the investigation, there is room to further facilitate the optimization of the environmental, economic and technical performance of residential building construction, especially when taking the economic effect of modifications in the salable area into account.

4.4 Regional conditions and sustainability assessment

Given the increasing importance of the SPD of building materials for sustainable buildings and the related industries, Paper 4 structured the existing sustainability assessment methods to understand how these methods can support SPD. The structuring of the methods was done based on a common information structure, which was classified by its categories, aspects, and indicators. The indicators were clustered into product-related, corporate-management-related, and regional-condition-related ones. The resulting sustainability indicator lists were structured into 25 categories of 88 aspects, of which 25% were product- or product- and region-related aspects. Figure 4.4 shows the mapping of the categories based on the aspects included within each class.

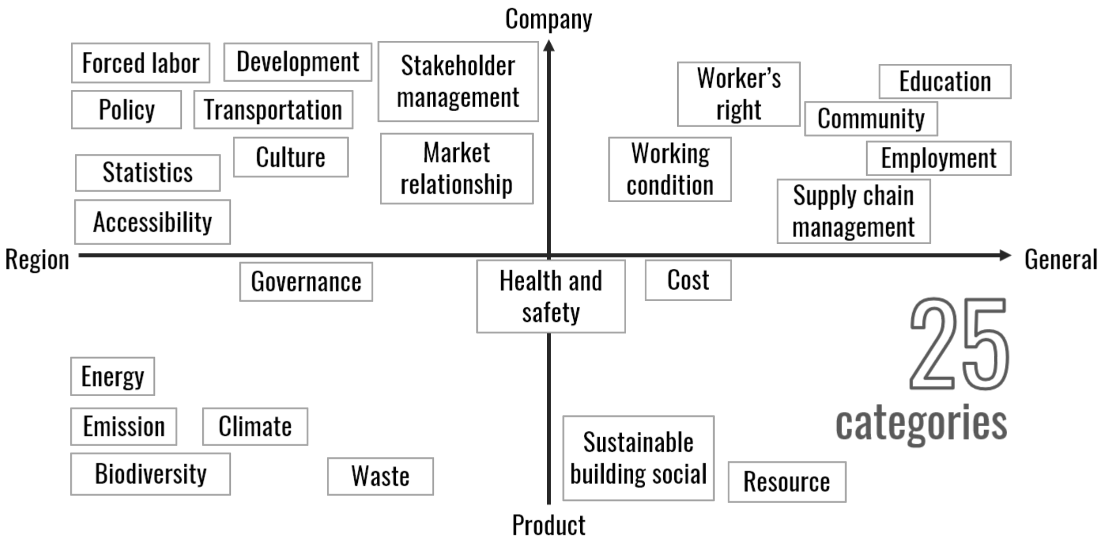

Figure 4.4: Mapping of the class of categories

Among the sorted aspects, 25% of the aspects were classified as product-specific. A further grouping was conducted to examine the applicability of the indicators to the PD phase. Most of these indicators were inventory- or impact-related, which are difficult to apply in the early phase of product development due to the lack of the required level of information (Chang et al. 2014). However, the sorted indicators could be a supportive tool for the later phase of product development, for example for the production planning step, as shown in Figure 1.2. Furthermore, as the regional conditions revealed relevant for the sustainability performance during the building's operational phase, the conditions may serve as proxy information to guide the earlier phase of product development to improve sustainability performance.

4.5 Sustainability hotspots of green concrete

Paper 5 examined the sustainability hotspots of green concrete in relation to social and environmental impact. The hotspot analysis was done by conducting social and environmental LCAs. Impact assessments were also conducted to investigate the relevant aspects of green concrete's sustainability performance. Based on the reliability of the inventory data in PSILCA, six social indicators were chosen to assess the social hotspots of the green concrete from six countries. The environmental hotspots were assessed by applying CML-IA baseline as the impact assessment method. The assessed concrete represented not just the variety of geographies but also the product designs by considering three different slag contents. To capture the potential difference in the sustainability performance due to corporate efforts, four classes were introduced based on the results from Monte-Carlo analysis. The related inventories of the hotspots were analyzed in three groups: steel slag, clinker, and energy.

Regarding the social impact of the material, the majority of the hotspots were related to the steel slag inventory group. The impact assessment showed that the introduced company classes had less influence on the impacts than the geographic representations. For social impacts, the product design with lower slag content showed better performance.

Environmental hotspots concerning GWP, ODP, and acidification each had the same inventory group as the hotspots, regardless of the geographical representation. The influence of regional conditions on environmental hotspots was mostly seen in the energy sources. Regarding the impact of abiotic depletion for non-fossil fuels, the relevance of the company classes was seen more clearly than in other aspects. An influence of product design was seen, as the higher the slag content, the better the environmental performance.

The analysis of the social and environmental hotspots and impacts of the green concrete showed the effectiveness of supply chain management for improving both the social and environmental hotspots, while highlighting the limitation of product design. Although product design may affect environmental sustainability performance effectively, the impact assessment showed the limitation of sustainable product design concerning the social sustainability performance of the investigated indicators. In fact, trade-offs between social and environmental performance were observed with the change in product design for all six countries.

To handle the trade-off, procuring the steel slag and/or steel slag mixed cement from companies that produce it using a clean energy mix with good governance could be important to improve the sustainability performance of green concrete with a high steel slag content. For forced-labour-related sustainability performance, supply chain management, which may manage the hotspots, could be the most effective way to improve the performance of green concrete. For other worker-related indicators, corporate governance and management of the manufacturer could be considered necessary to improve the categories.

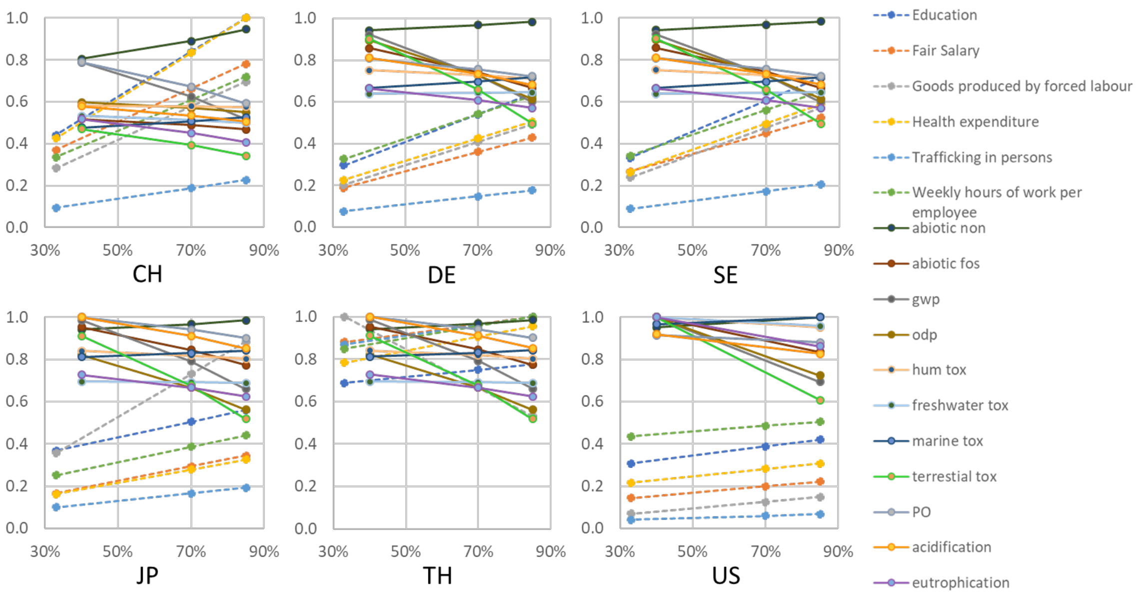

Figure 4.5: Normalized social and environmental performance of green concretes in six countries

Chapter 5

Relation of results to the research questions

To summarize the results, the findings related to the respective research questions given in chapter 1.8 are presented in what follows.

Q1: What is the relationship between technical requirements and environmental performance?

A1: Through the investigation conducted in the thesis, the relationship between technical and environmental performance was seen to involve a trade-off only in certain circumstances. In the case of the thermal insulation materials investigated in Paper 1, no trade-off was observed between the technical requirements and the environmental performance. The EE, which took thermal resistance as the value the materials provide, and the resulting life cycle environmental impact, improved when the density of the materials was reduced. While reducing the material consumption may be a straightforward design option to pursue when reducing products' environmental consequences, the uniqueness of the finding is that the technical performance was not sacrificed. This was due to the fact that for each thermal insulation material category that was investigated, the range of its density was wider than that of the thermal conductivity. While the thermal conductivity values were ranging from 0.02 to 0.04 W/mK, where the difference between the minimum and maximum was around twofold, the range of the density values was 15 to 200 kg/m^3. This wider range of density values resulted in a larger influence of this factor for improving EE over the increased performance provided by better thermal conductivity.

When investigating the relationship between technical and environmental performance at the building level in Paper 3, a trade-off between the two performances was seen. In one of the design alternatives that reduced the material use, the acoustic requirements served as a limiting factor for the environmental performance improvements. This design measure allowed for the improvement of the building's environmental performance while maintaining the technical performance such as thermal, structural and fire safety. However, a sacrifice had to be made by reducing the acoustic class to a lower grade in the design. The investigation showed that some technical requirement may result in a trade-off relationship with environmental performance, while others may be irrelevant or less crucial.

Q2: How can building material manufacturers address the three pillars of sustainability issues for PD using existing methods?

A2: The investigation conducted in Paper 4 showed that the existing sustainability assessment methods can be used to support both the early and later phases of PD. For supporting the early phase of PD, methods that concern regional aspects, such as climatic conditions during the operational phase, were expected to provide valuable information as proxy information. Most of the indicators investigated, however, were expected to be used to support the later phase of PD, such as the production planning step.

Q3: What are the relevant aspects for supporting the SPD of building materials?

A3: Various aspects were revealed as relevant for supporting a range of steps in both the early and later phases of SPD. To support decision-making during the earlier phase of PD, technical specifics or requirements and regional conditions were found to be useful, based on the findings from Papers 1 and 4. For thermal insulation material, investigated in Paper 1, density can serve as useful proxy information in the early phase to improve the materials' life cycle environmental performance. Concerning the expected life time of building materials, which can be a topic discussed in the goal formation step in the early phase of PD, regional conditions during the operational phase of the material were shown to be important.

In the comprehensive review of sustainability assessment methods conducted in Paper 4, other sustainability assessment methods were found to be suited to support the later phase of PD. The temporally explicit methods investigated in Paper 2 were also considered to be useful to support the later phase of PD. In Paper 2, the investigation of the German electricity grid, where vRES is increasing its share, showed the potential of production scheduling for optimizing the associated carbon emissions. Around a 10% reduction can be achieved by shifting the consumption from weekdays to weekend daytime. The trade-off between social and environmental performance arising from the different product design options of steel slag mixed concrete in Paper 5 revealed the limitations of sustainable product design. The findings reasserted the value of SPD, which can provide a comprehensive package of tools to handle such a trade-off caused by product design. In the paper, the potential for addressing the trade-off through supply chain management, which is part of the production planning step in the late PD phase, was shown.

Chapter 6

Discussion

Based on the findings related to the research questions, the following discussion section elaborates further on the insights regarding the relevant PD phases and its steps, the identified gaps and the limitations of the investigation.

6.1 Proxy information for the early phase of PD

The investigation conducted in Paper 4 suggests the potential of supporting the early phase of the PD of building materials via proxy information. The investigations conducted in the thesis have identified proxy information that can potentially be useful during the PD phases.

The findings from Paper 1 indicate the importance and usefulness of density during the early phase of PD. Density can be used to improve the sustainability performance of all of the investigated thermal insulation materials without compromising the required functional performance. Density is one of the technical properties that is related to the functional performance of the material. As is done with the key technical performance property for thermal insulation materials, namely thermal conductivity, discussing the materials' density during the goal and strategy formulation step of the early phase of PD could effectively support the SPD of thermal insulation materials.

Another type of information that can guide the early phase of the SPD of building materials relates to the regional climatic conditions, which may allow the risk of damage during the materials' operational phase to be mitigated. In Paper 4, regional conditions during the materials' operational phase were seen as relevant information for the goal formation step in the early PD phase. These regional climatic conditions are important factors which affect the life expectancy of building materials. Not just the current climate but also ongoing climate change is an important aspect to consider, especially for products that are expected to last for a multiple of decades. Lisø's (2006) doctoral thesis investigated the impact of climate change on the temperature in Norway and how it relates to the adaptation of building envelopes of wooden and brick structures. A study from Pakkala et al. (2014) investigated the influence of climate change on precipitation in Finland and the resulting effect on concrete durability. Nik et al. (2015) examined the influence of changing moisture conditions in Sweden due to climate change as it relates to the uncertainty of the hygrothermal performance prediction of building facades. All of these studies confirm the influence of climate change on the longevity of materials. Thus, considering the effect of climate change on the region in which the product would be launched during the goal formation step of PD could effectively allow the risk of the damage to building materials to be mitigated.

6.2 Potential within production planning

Another regional condition that could support the PD phase is the electricity mix, which can be utilized to support the production planning of the material. In fact, the findings from Paper 1 indicate the importance of regional conditions relating to the electricity mix. Concerning possible improvements in the production planning step, during the later phase of PD, the regions with cleaner energy mixes were seen as key for improving the sustainability performance of foam glass in Paper 1. The same was true for the steel slag mixed green concrete investigated in Paper 5. For these materials, producing or sourcing them from a country with a clean energy mix or with a plan to implement such a mix could be important proxy information to support the SPD of the materials. Furthermore, the findings about the variation in hourly EF from Paper 2, implying the optimization of consumption to reduce the corresponding carbon emissions, could be expected to be amplified with the projection of increased vRES being supplied in various parts of the globe in upcoming decades. Over the past few years, peak-shaving or -shifting has been discussed from various stand-points, including sustainability. What the findings from Paper 2 suggest is that instead of peak-shaving or -shifting, peak-creation during the generation of vRES could be a strategy to use when considering the fluctuation of EF as dependent on the time of the day. Thus, the production planning of energy-intense building materials, such as foam glass or VIP which uses glass fiber as their core material, may need to optimizing electricity consumption based on time.

One scheme which may promote consumption optimization would be demand response, one of the newer services that power utility companies in certain regions offer. According to Waldron and Nobuoka (2017), the capacity of virtual power plants (VPP) including demand response in Europe has increased rapidly to more than 10 GW in 2017, a five-fold increase since 2014. However, in order to meet energy policy objectives, additional investments in flexible resources such as demand response is necessary (Vithayasrichareon et al. 2017). In fact, it is said that nearly 20% of global electricity consumption could be technically available for demand response by 2040 (International Energy Agency 2017a). The IEA's report indicates that while energy efficiency has improved, global CO_2 emissions have remained constant since 2014 (International Energy Agency 2017b), implying that the improvement of energy efficiency alone may not be sufficient to curtail global carbon emissions. With the expected increase in power demand as well as the share of vRES in the grid, further utilization of demand response could be a solution to be included as part of a package to tackle the challenge of climate change. As part of such a package, manufacturers with flexibility regarding production planning could be considered important players.

6.3 Trade-offs between social and environmental performance

The clustering of indicators into product-related, company-related, and regional-conditions-related introduced in Paper 4 allowed the understanding in Paper 5 that improvements in environmental performance through product design may not always lead to better social performance. Instead, indicators clustered as corporate- or regional-conditions-related were revealed to be relevant for improving social sustainability performance of the building material investigated in Paper 5. The finding suggests the limits of the effectiveness of the sustainable product design for improving sustainability performance. Although the improvement of sustainability performance via product design was limited, adapting the supply chain based on sustainability performance was revealed to be an attractive approach for improving the overall performance. This supply chain management could be considered as part of production planning included in the later phase of PD, suggesting the value of SPD as a holistic platform capable of addressing a range of sustainability issues.

Furthermore, the trade-offs observed in Paper 3 between acoustic performance and embodied carbon emissions could be considered as a trade-off between social and environmental sustainability performance. Based on the investigation in Paper 4, acoustic characteristics or comfort could be seen as a social dimension of sustainability performance that affects human health and safety. This trade-off could be handled by product design, either at the material level by developing materials with better acoustic performance or at the component level which Combination 3 in Paper 3 offered. As seen from the previous chapters and Figure 1.2, PD includes various steps at which sustainability performance can be improved by providing relevant information. SPD could provide a holistic package of a variety of approaches to improve the social and environmental sustainability performance of building materials by addressing the issues with optimal tools. These may include supply chain management or design amendment, as seen in the cases in Paper 3 and 5, as stated above. The fact reinforces the effectiveness of SPD, which allows for the consideration of more holistic issues and measures than the sustainable product design.

6.4 Missing incentives

Through the investigation in this thesis, a key implication was observed for improving the sustainability performance of buildings and its materials. This key implication is the lack of appropriate incentives.

6.4.1 At the level of products

The incentive that typically drives thermal insulation material manufacturers when considering the environmental sustainability performance of their materials is the improvement of thermal conductivity. This incentive, the pursuit of developing materials with lower thermal conductivity, can effectively support reducing the environmental burden of the building sector by reducing the energy consumption of space conditioning during the operational phase. Nonetheless, it may not result in an optimal life cycle impact when expanding the scope of buildings' life cycle phases, which for instance can be seen in the case of super insulation materials such as VIPs and aerogels. These super insulation materials are materials with low thermal conductivity, typically below 0.02 W/mK, while conventional insulation materials are around 0.03 W/mK or above. The improvement of thermal conductivity allows the energy consumed for space conditioning purposes to be minimized by reducing the loss of thermal energy to the surrounding environment. As has been seen from several political initiatives and the distribution of the life cycle impact of conventional buildings, a reduction in operational energy is of the utmost priority due to its significant impact. While the impact caused by the buildings during the operational phase has been curtailed owing partly to the development of better envelope systems with improved thermal insulation performance, the embodied impact of envelope systems may increase which outweigh the improvement made in the operational phase. If products are not developed with a life cycle perspective, this sort of sub-optimization may happen. This was the case for the super insulation materials, whose embodied impacts outweigh the improved energy-saving capabilities, resulting in a larger environmental consequence over these materials' life cycle. Thus, taking a full life cycle perspective would be crucial to avoid such a sub-optimization concerning sustainability impact. Increased emphasis on EE can play an important role to avoid such a sub-optimization, as the method does not disregard the functional performance of the thermal insulation materials. This increased focus and use of EE may lead manufacturers to broaden their scope for improving the sustainability performance of their products.

6.4.2 At the level of buildings

Another case of a lack of appropriate incentives was observed in Paper 3, where not only the building's embodied environmental impact but also the associated cost could be reduced in some design alternatives. The lack of appropriate incentives could partly be due to the conception that the more environmentally friendly option would involve higher costs, which is true for some design options, as can be seen from the results of the marginal carbon abatement cost in chapter 4.3. In addition to this stereotype, the lack of appropriate incentives was mentioned as the cause of the untapped cost and carbon reduction potential in the case of designing residential houses in Paper 3. The fact implies the need or room for further improvement regarding how the decisions are made for improving sustainability performance in the construction of buildings. The enhanced use of EE, for instance, could be an effective viewpoint to better support designers' decision making.

6.4.3 Relevance of social issues

The limitation of product design amendments for the synergistic improvement of social and environmental sustainability in the case of steel slag mixed concrete in Paper 5 highlights the value of the political agenda relates to sustainability, such as the SDGs. The trade-off between social and environmental performance observed in Paper 3 triggered by the regulatory boundaries also indicates the relevance of these measures to ensure not just one of the pillars but multiples of them. The strengthening of such political visions or agendas can play an important role in increasing people's awareness of sustainability issues, which can drive building material manufacturers to meet the social demands or requirements. This could be an important strategy, especially for the B2B market in which manufacturers operate. As brand value in the B2B market is mainly determined by functional quality, the possibility of sustainability arguments improving brand value and hence sales to direct customers in such a market maybe low. If increased awareness leads regulatory bodies to investigate the potential for amending the existing regulations or issuing new ones, the likelihood of addressing sustainability issues that are difficult to improve via design measures could be increased.

Increasing efforts are being made in the construction industry to make the industry more sustainable. Certification systems of sustainable buildings, such as LEED or BREEAM, are one such effort that is gaining momentum as these systems spread across the globe. In fact, LEED v4 (U.S. Green Building Council 2014) accredits points for building products that conduct LCA regarding the resource consumption, incentivizing building owners and planners to take a life cycle perspective into account if they wish to obtain a LEED certificate. Nonetheless, there is some room for implementing further incentives to stimulate manufacturers to optimize their sustainability performance, especially concerning the social impacts caused along the life cycle.

6.5 Limitations

6.5.1 Inherent uncertainty in LCA of buildings

In order to take the operation phase into account to cover the life cycle phases beyond the factory gate, assumptions are typically made for the LCA of buildings. These assumptions are inherently associated with certain ranges of uncertainties. Concerning Paper 1, the uncertainty of the service life of the implemented materials was one of the factors that may affect the EE results. The service life of insulation materials may depend on whether it is appropriately implemented, which may be beyond the operational boundary of the material manufacturers. Within the EPD framework, there is as of yet no standardized methodology to examine the service life or requirement to declare the decline in thermal performance over the operation phase of the material. Thus, using the expected length of the materials' service life stated by the manufacturers may result in optimistic results, depending on how they have derived the value, where the information available about the basis of this value is mostly limited. Furthermore, since the operational phase of the materials is beyond the operational boundaries of the manufacturers, where a range of variables affect the expected service life and associated performance decline, it can even be difficult for them to devise reasonable values. Paper 1 defined EE taking the thermal performance as constant over 40 years of its expected length of service life as the created value. Including the performance decline of these materials will affect the materials' resulting EE. Therefore, the uncertainties regarding the two factors of the service life and performance decline make it challenging to illustrate the comparative advantage of materials in EE that take into account the environmental impact of full life cycle.

6.5.2 Representativeness of LCI datasets

Another challenge concerning the limitations of the thesis is the representativeness of the assessed data. In Paper 2, the import and export of electricity between neighboring grids was excluded. This could be considered as a source of uncertainty for the calculated EFs. According to BDEW (2016), while the export share increased from 9% to 13% of gross electricity generation for 2011 to 2015 in Germany, the import share decreased from 8% to 5%. This decreasing share of imported electricity implies a decreasing uncertainty in the calculated EF.

Another limitation observed in the thesis regarding the representativeness of the data relates to the specificity of the geography and technology in Paper 5. The representativeness of technological aspects of the data is a challenging issue for the social LCI in PSILCA due to its availability, since the source of inventory data is the input-output database. For instance, a large number of the construction-related product inventories are represented as "Construction" as a whole. This means that the assessed social hotspots of different types of thermal insulation materials, EPS and stone wool, for instance, would be identical. This ambiguity can be a hinderance to the widespread use of SLCA for supporting the decision making of product development. Not just social LCI but also environmental LCI has limitations regarding representativeness, which in Paper 5 related to geographical representation. The assessment of green concrete in Paper 5 revealed that the energy system was the hotspots for a few environmental indicators. This fact illustrates that a higher resolution of the geographical representation of the steel slag mixed cement in the database may allow for improved accuracy of the environmental impact assessment and hotspot analysis.

6.5.3 The challenge of generalization based on limited data

The strength of the results obtained in Paper 2 is the source of data, which are real data that cover nearly 70% of the entire German electricity grid at an hourly resolution. However, the assessment of the EF conducted on monthly basis has a weakness concerning the sample size of the weekends, since in total the weekends of each month typically amount to fewer than 10 days. With such a limited sample size, the effect of extreme weather events, for instance, may have a significant effect on the corresponding EF, especially for the grids with a higher proportion of vRES. This could be considered a limiting factor when generalizing the findings.

Another limitation regarding generalizations based on the limited data could be seen in Paper 3, where only one case building in Sweden was investigated. The strength and value of the investigation are that it examined a real, existing building and not a hypothetical case. However, the assessment of the potential and the validity of the untapped carbon emission and cost savings from residential buildings in Sweden may be challenging to generalize at the national level.

In order to tackle the issue regarding the lack of data, different databases and data sources were used in Paper 1. However, there was an issue concerning the difference due to different system boundaries and allocation systems of LCA from different data sources. This challenge was experienced when collecting the data, where some data sources clearly documented the adopted system boundaries and allocations while others did not, even for EPDs. Although EPDs have significant potential to address the data shortage issues, which could be seen as a typical bottleneck not just for LCA but also for other studies, the weakness in aligning the conditions for the assessment limits its value.

6.5.4 Limitation of the impact assessment in SLCA

In Paper 5, the social impact assessment was based on the risk hours, provided as an add-on in PSILCA. In GreenDelta GmbH's (2016) guideline, they state that *"this risk assessment is to some extent subjective and dependent on cultural and even individual evaluations and conventions"* and that it is *"useful to be able to modify"* the assigned risk levels depending on the case under investigation. In fact, the database offers the possibility to modify their impact assessment or even implement an original one, if done properly. In Chhipi-Shrestha et al. (2015) and Dong and Ng (2015), the lack of a common, well-accepted scientific impact assessment method for assessing the life cycle social impact was mentioned. To meet this challenge, there are growing numbers of impact assessment methods being developed, for instance the fair wage potential from Neugebauer et al. (2017). These authors' method offers a midpoint indicator to assess the social impact related to wages by using the Gini coefficient as part of their equation. This method is compatible with input-output-based inventory data, such as PSILCA. Another attempt at quantifying social impact can be seen in van der Velden and Vogtländer (2017), which quantifies the social impact in monetary units (s-eco-cost). The method is based on the principle adopted for eco-cost (Vogtländer et al. 2001), which quantifies the required cost for preventing the burden caused to the environment. s-eco-cost calculates the impact on the social dimension using the same principle used in the calculation of the environmental impact. These efforts being made to quantify social impact that can utilize existing databases may play a vital role in the proliferation of SLCA. However, additional efforts are still needed to establish methods that are well-accepted among the SLCA community and to provide tools applicable for assessing a full life cycle scale. This could be seen as the main challenge as well as a limitation concerning the widespread implementation of SLCA.

Chapter 7

Conclusion

Sustainability issues are relevant and important for building materials, considering the role the construction industry play in the sustainable development of society. Product development is an essential phase that allows building materials to become more sustainable. This thesis has contributed to an understanding of how functional requirements and sustainability performance relate to each other and of how to support the different phases of the SPD of building materials.

The investigation of the relationship between technical and environmental performance identified further room for improvements as well as limitations for increasing environmental performance. The investigation at the product level in Paper 1 showed that focus on a specific life cycle on which technical performance has the most influence may hinder the overall life cycle environmental performance. Other technical specifics, such as density, which was examined in Paper 1, may play a key role in improving environmental performance without compromising the expected technical performance. The investigation of the relationship at the building/component level conducted in Paper 3 highlighted the limitation of design improvements for better environmental performance resulting from a regulatory requirement, causing a trade-off between the environmental and acoustic performance whilst maintaining other technical performance factors.

To support the SPD of building materials, the investigation conducted in the thesis suggested that information regarding regional conditions can be effective. In order to assess how manufacturers could utilize the existing sustainability assessment methods for PD, the thesis viewed sustainability issues from three perspectives: product-related, company-related, and regional-condition-related. The findings from Papers 4 and 5 identified regional conditions as effective proxy information to support both the early and later phases of the PD of building materials. Paper 2 hinted at the potential of production planning, the later phase of PD, to optimize emissions due to electricity consumption as well as the expected role in a grid system to meet the SDGs.

One of the unique findings of the thesis was the limits of sustainable product design for improving the three pillars of sustainability, highlighting the value of SPD. The case study in Paper 5 showed the effectiveness of SPD where synergy between the majority of the social and environmental improvements via product design amendments was limited. This fact emphasizes the importance of taking corporate-governance-related issues such as employment conditions into account during SPD to improve the product's social sustainability performance. These issues are recommended to be considered ideally during the goal formation phase and at the latest by the supply chain design in the production planning stage, which is included as a step in the late SPD phase. Regardless in which phase it is considered, SPD has steps where such issues can be taken into account and can reflect the decision on the developed materials. Therefore, the effectiveness of SPD, which offers a more holistic scope than product design, for improving sustainability performance, was shown.

Another contribution of the thesis is that it touched upon various points where sustainability performance of the materials could be improved by changing small things, such as creating incentives. Through the investigation conducted from the product to the building level and focusing on the environmental, economic and social pillars, room for creating additional or amending existing incentives was identified. The findings from Paper 1 highlighted the importance of considering technical specifics beyond the product's conventional performance criteria as a PD goal, implying the need for incentives for a broader application of life cycle thinking for building material developments. In Paper 3, it was shown that further incentives to investigate and use the tools for easier identification of low-hanging-fruit design alternatives for improving both the environmental and economic performance of building design options were in need. Eco-efficiency could be considered as a tool to allow such easier identification. The limitation regarding the synergistic improvement of the social and environmental pillars of sustainability through material design was seen in Paper 5, showcasing the importance of PD as well as political and regulatory pushes for ensuring social sustainability, such as the SDGs. An additional push from the building certification scheme could effectively encourage material manufacturers to take social issues into consideration.

Chapter 8

Future Research

From the investigation, several approaches have been identified for further exploration, which may facilitate improved support of the decision making and integration of sustainability issues into product development. One such potentially effective approach to incorporate sustainability considerations into the decision-making procedure during product development could be via risk assessment, focusing specifically the brand value risk.

The investigation in this thesis revealed the link between corporate sustainability performance and corporate financial performance. The remaining challenge is to understand which sustainability aspects are most influential for financial performance. With the ongoing efforts for quantifying the life cycle social impact of products and services, the key performance indicators for corporate sustainability and financial performance may be revealed.

One such approach could be to quantify the brand value risks related to sustainability issues. Such an approach may allow the translation of sustainability issues into economic terms, to which companies may be more responsive.

Since building material manufacturers are in the B2B market segment, brand value risk management may require a different approach from the business-to-consumer (B2C) market. According to Leek and Christodoulides (2012), the product or service quality is considered the most important functional quality of the brand in B2B markets. In this thesis, it was revealed that improvements in product design may not always lead to better overall sustainability performance. Given the market characteristics and the limitations of the design improvements, the translation of sustainability issues, especially those where product design has a limited effect on the improvement of the issue, may help motivate companies in this market segment to engage further regarding social issues when understanding the relevance to their brand value, which ultimately will affect their financial performance in the long run.

In fact, risk considerations have already been incorporated into sustainability assessment. The life cycle sustainability assessment (LCSA) methodology, GeoPolRisk (Gemechu et al. 2017) is one such approach that incorporates risk aspects in the assessment. With further development of methodologies that consider risks over the life cycle, especially in terms of monetary units, the likelihood of embedding sustainability issues in the early phase of product development will increase.

The limited synergy between social and environmental improvements via product design amendments could be investigated from other stakeholders' points of view. From a regulatory body perspective, further exploration regarding how to effectively enhance corporate activities by implementing policy measures could be valuable. For this purpose, the sorted list of sustainability aspects in Paper 4 could serve as a good basis for identifying which sustainability issues may need further regulatory/political pushes to drive corporate efforts to improve the sustainability issues. Investigating how to organize effective rules of the playing field to drive companies to improve such issues may support governments in meeting the SDGs.

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Appended papers

Paper 1

Factors for eco-efficiency improvement of thermal insulation materials

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Factors for Eco-efficiency Improvement of Thermal Insulation Materials

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Abstract. Thermal insulation material is an important component to reduce the environmental impact of buildings through the reduction of energy consumption in the operation phase. However, the material itself has embodied environmental impacts for the value it provides. Eco-efficiency is a method that quantifies relation between the environmental performance and the created value of a product system. This study investigated contributing factors of the eco-efficiency of thermal insulation materials to support decision making of material manufacturers. For the improvement of eco-efficiency, the assessment was made in two scopes: investigating the contributing factors of impact caused at production processes; and thermal performance through thermo-physical properties. For quantifying environmental impacts, cradle-to-grave life cycle assessment (LCA) of each materials were made. The life cycle impact assessment (LCIA) indicators used were ReCiPe H/A and global warming potential (GWP100a). For the assessment of production process, the inventories of the materials were assigned to six categories: heat, chemicals, electricity, transportation, raw materials and wastes. Among the assessed materials, contribution of electricity and heat within the production process was large for foam glass which had the highest potential to improve the eco-efficiency which was by factor 1.72. The analysis on relation between thermo-physical properties and eco-efficiency based on product data of the materials highlighted the importance of density as an indicator upon development and use. Although density often gains less attention, the finding suggested the effectiveness of improving the efficiency by having lower density without compensating the performance of the materials.

Introduction

The building sector plays an important role on global warming, contributing about 30-40% of anthropogenic greenhouse gas emission [1, 2]. Most reports agree that there is significant potential for reducing greenhouse gas emission from improvements of the energy efficiency of the buildings [3-5]. Regarding the energy consumption of buildings, the requirements for heating, ventilation and air conditioning (HVAC) is a substantial contributors [6]. In fact, studies show that about half of their life cycle environmental impact is caused by the operation phase while impact caused during the production phase of materials are responsible for the remaining even for state-of-the-art energy efficient buildings [7-9]. For the reduction of such HVAC load, thermal insulation material plays a key role [10]. These insulation materials have been well utilized in some parts of the globe, though still underutilized in other readily applicable areas. According to IEA [5] many countries still construct new buildings without considering energy performance of the building envelopes, which unnecessarily increases the HVAC loads. As energy demands of the building sector are expected to increase worldwide due to an increase in office and dwelling space [5], thermal insulation materials must continue to play an important role as a key component in building envelopes to cope with the climate challenge.

Various research has been made on thermal insulation materials, which include the assessment of environmental impacts. The life cycle impact assessment (LCIA) on production of thermal insulation material has been conducted by Papadopoulos and Giama [11], and Pargana et al. [12]. Studies including end-of-life phase of the materials were made by Schmidt et al. [13], Dylewski and

Adamczyk [14] where Dylewski and Adamczyk [14] included an economic perspective on the analysis that considered the payback time of several representative insulation materials. However, while the impact of the insulation material has been investigated and compared, the relation between the material properties and materials' environmental impact is less clear (e.g. the relation between the thermal conductivity and the embodied carbon of a material).

Eco-efficiency is a method which is standardized as ISO 14045 [15] that quantifies ratio of the created value and caused impact by product system over the life cycle. This method has been used in building projects such as [16] which used the space provision as the created value. As the method takes value criteria into account for assessing environmental impact of the product system, the present study looked into the contributing factors for eco-efficiency of the thermal insulation materials by investigating the inventories of production process and thermo-physical properties. The study also investigated the possible improvement potential for materials eco-efficiency. Through the analysis, the study aimed to highlight the factors for effective improvement of eco-efficiency.

Methods

Eco-efficiency of Thermal Insulation Materials and the Aim of the study. According to ISO 14045 [15], eco-efficiency of a product or service can be defined as an "aspect of sustainability relating the performance of product system to its product system value". The standard could thus be expressed as equation Eq. (1).

$$\text{(eco-efficiency)} = \frac{\text{(created value or fucntionality provided)}}{\text{(environmental impact)}} \quad (1)$$

The defined eco-efficiency (EE) quantifies the amount of value created per the caused environmental impact. For the study, the created value was defined as thermal performance and the environmental impact as life cycle environmental impact of the material. For the thermal performance of the materials, thermal resistance was used which was set at 1 [m^2K/W] for surface area of 1 [m^2] of thermal insulation materials. For the quantification of environmental impact, LCA was conducted. The aim of the LCA was to analyze key contributing factors for the eco-efficiency of thermal insulation materials and evaluate the effectiveness for the improvement on its EE.

In order to improve the defined EE in Eq. (1), two approaches could be determined: One is to reduce the environmental impact which can be achieved through the improvement in material's production process; the other is to improve the thermo-physical performance of the material. Therefore, the study investigated the factors for improving EE from the two approaches.

Quantification of Environmental Impact from Production Process. The analysis on production process was made by conducting a systematic assessment of materials' inventory, which was divided into six categories: energy input of heat, chemicals, energy input of electricity, transportation, raw materials and wastes. Every disposed inventories along the entire life cycle was categorized as wastes. For quantifying environmental impact, the LCA was conducted using a cradle-to-grave system boundary for each product. The functional unit of the study was set at the required mass for each material with identical thermal performance. This can be expressed as Eq. (2):

$$\text{F.U.} = \lambda \cdot \rho \cdot \text{R} \cdot \text{A} \quad (2)$$

where F.U. represents functional unit, λ for thermal conductivity [W/mK], ρ for density [kg/m^3], R for thermal resistance [m^2K/W] and A for area [m^2] [17]. The performance was set at thermal resistance with 1 [m^2K/W] with surface area of 1 [m^2] of the material.

In Fig. 1, the system boundary of the LCA and the scope for investigating improvement potential in production process is described: "Cradle to grave" as the system boundary; and "scope for optimization" as the scope. Within the scope, improvement potential was quantified through sensitivity analysis on inventories with significance based on contribution analysis. Note that the study had the focus on improvement within the given production process, thus any improvements of EE via reduction of the required energy or the change of raw materials was not considered.

The operation phase was considered that every material to last for 40 years without replacement or decay of the thermal performance. The material itself requires no energy consumption during its operation phase. For the disposal phase, it was assumed that mineral based materials are landfilled and the remaining ones are incinerated.

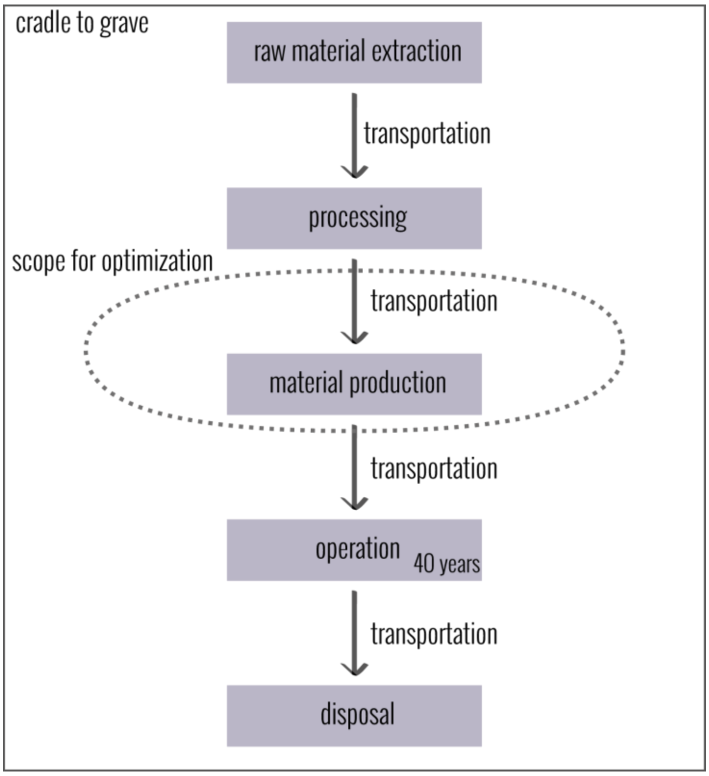

Fig. 1. Diagram of scope of the LCA on building thermal insulation material production

For the LCIA indicator, ReCiPe H/A (hereafter ReCiPe)[18] was selected to assess the production process as of its holistic coverage of the environmental impact, covering resource flows and emission flows[19]. In addition, GWP100a (hereafter GWP)[20], which covers the effect on single issue (global warming), was used for contribution analysis for comparison.

Even though ReCiPe has strong emphasis on fossil fuel depletion, it considers other issues including human toxicity, eco-toxicity and resource depletion. With its broader coverage of the environmental consequences, the EE for studying the production process adopted ReCiPe which is defined as Eq. (3).

$$(EE) = \frac{R}{(\text{ReCiPe score})} \qquad (3)$$

The software in use to compute the environmental impact was SimaPro 8.04 [21].

Types of Thermal Insulation Materials and Inventory Data. The insulation materials studied for were selected by their market significance [22]. In Fig. 2, the market share of thermal insulation types in the seven largest markets are shown. The materials for investigating contribution factors for environmental performance from production process were selected based on current market share and future potential. In addition, materials were selected due to the availability of inventory data. The selected materials were: cellulose fibre, fibreboard, foam glass, stone wool, VIP and polyurethane (PUR).

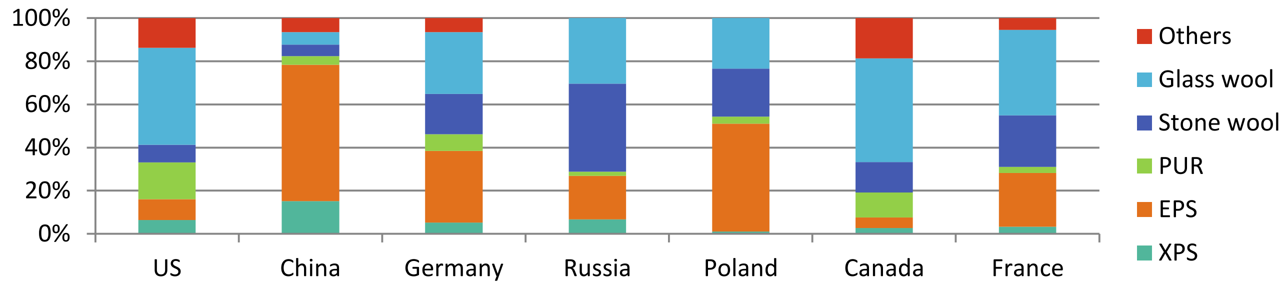

Fig. 2. Market share of 7 largest markets for thermal insulation materials

The main source of life cycle inventory data for analyzing the inventories was ecoinvent data v2.2 [23]. Life cycle inventory data of VIP referred to [24]. The properties and functional units used for LCA and data sources of the materials for investigating the improvement potential are shown in Table 1. All of these materials were considered to be applicable to various parts of buildings such as floors or roofs. For simplicity, the thermal conductivity does not take variance due to temperature or relative humidity of the surrounding environment into account.

Table 1: List of thermal insulation materials and its thermal conductivity and sources of inventory data

Material	Material category	Thermal conductivity [W/mK]	Density [kg/m^3]	Inventory data source
Cellulose fibre	Bio	0.040	50	[25]
Fibreboard	Bio	0.040	140	[25]
Foam glass	Mineral	0.038	110	[25]
Stone wool	Mineral	0.036	32	[25]
VIP	Other	0.003	190	[24]
Polyurethane (PUR)	Polymer	0.025	35	[12, 25]

As the study investigated the influence and feasible improvement on environmental impact of the production process, Table 2 briefly describes the process related to heating for each studied thermal insulation material.

Table 2: Required heating temperature during the production process of each thermal insulation material

Material	Required heating temperature for production [°C]	Purpose	Reference
Cellulose fibre	none	none	[26]
Fibreboard	130-180	Pre-heating, flash drying	[11, 26]
Foam glass	850-1250	Melting, foaming	[26]
Stone wool	1300-1650	Melting, strengthening	[11, 26]
VIP	N.A.	N.A.	[24]
PUR	N.A.	N.A.	[27]

Analysis on Relevance of Thermal Performance on eco-efficiency. For improving the EE of thermal insulation materials, increasing the value created from the materials is another approach. By defining the created value as thermal performance of the material, which was set at thermal resistance with 1 [m^{2}K/W] of material in 1 [m^2] for 40 years, thermal conductivity is typically gaining the focus for increasing the performance. However, when transforming Eq. (2),

$$R = \frac{\text{F.U.}}{\lambda \cdot \rho \cdot A} \tag{4}$$

density (ρ) can also be seen as a property that interacts with the thermal resistance as shown in Eq. (4). Therefore, the study investigated the relevance of the two thermo-physical properties that defines the thermal performance of the material. The analysis on relevance of thermo-physical properties to EE were made based on existing product data.

In order to investigate the relation between the EE and the thermo-physical properties, the number of samples with adequate information was increased from inventory analysis. For this reason, the number of assessed material types (EPS and XPS) was increased. Moreover, data on environmental impact from other LCI databases such as, Inventory of Carbon & Energy (ICE) version 2 [28] from the UK, Inventory Database for Lifecycle Analysis (IDEA) version 1.1.0 [29], and AIJ-LCA&LCW [30] from Japan, have been investigated as reference despite the variation of the representativeness of data. For example the AIJ database relies on input-output based data, while others are average product data. Moreover, geological variation of the material dataset exists on every database.

In addition to LCI databases, product specific data from 23 Environment Product Declarations (EPD) were used. The list of EPD used is given in Table A in the Appendix. End of life phase of each dataset took scenarios from ecoinvent data which aligned the disposal scenario.

For the LCIA indicator, GWP was selected to assess the relation of the thermo-physical properties which allowed better access to data. Thus, the EE for the analysis on thermo-physical property was defined as Eq. (5):

$$(EE) = \frac{R}{(GWP)} \qquad (5)$$

Results and Discussion on Eco-Efficiency of Insulation Materials

In this section, the two approaches to improve the eco-efficiency of the thermal insulation materials were investigated, which were the reduction of environmental impact and the improvement on created value. First, the improvement potential on the production process were analyzed by conducting contribution analysis in two environmental indicators. The sensitivity analysis was made on inventory categories with significance to quantify the improvement potential in ReCiPe that covers more holistic environmental issues. This was followed by the analysis on the relevance of thermo-physical properties on eco-efficiency. Due to the availability of data, the analysis between thermo-physical properties and the efficiency was made by having GWP as the LCIA indicator.

Eco-efficiency and Production Process of Insulation Materials - Contribution of Electricity, Heat and Transportation on Environmental Impact. The result of contribution analysis on inventories of thermal insulation materials are shown in the following which the results in ReCiPe are given in Fig. 3 and emission of CO_2 equivalent in GWP are given in Fig. 4.

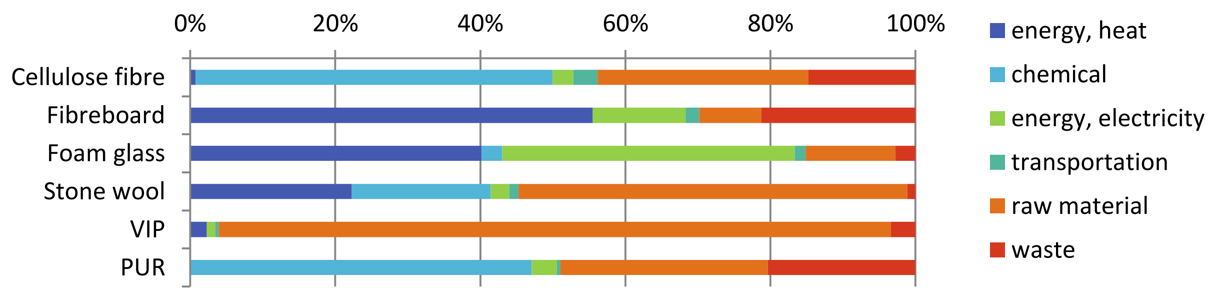

Fig. 3. Composition of raw material, transportation, energy on environmental impact of each thermal insulation material on ReCiPe in cradle-to-grave scope

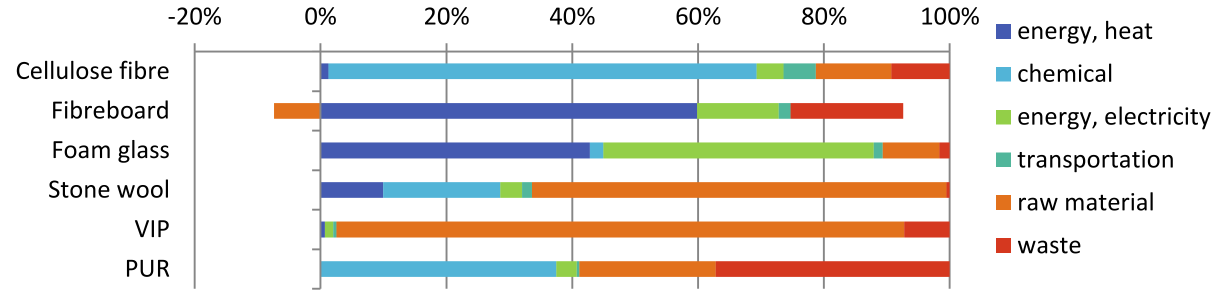

Fig. 4. Composition of raw material, transportation, energy on environmental impact of each thermal insulation material on GWP in cradle-to-grave scope

The obtained result shows significant variation of contributing categories among the investigated materials in both of the graphs. Meanwhile, the share of the inventory categories for each material between the two methodologies shows differences to a certain extent. For instance, cellulose fibre had larger impact from chemicals in GWP (62%) than that of ReCiPe (49%), while heat in stone wool had higher contribution in ReCiPe (22%) than in GWP (10%). The result illustrated the influence of the selected LCIA method, either with multiple or single issue being covered, for assessing the impact of the materials. However, the category of the most significant contribution remained the same on both methodologies for every material despite the difference in coverage.

As the study focuses on the improvement potential within the production process without intervening material properties, transportation, heat and electricity were focused. In

Table **3**, the summary of the results from Fig. 3 on share of environmental impacts from electricity, heat and transportation is shown.

Table 3: Total contribution of electricity, heat and transportation of thermal insulation materials analyzed in ReCiPe and GWP in cradle-to-grave scope

Unit: [%]	Cellulose fibre		Fibreboard		Foam glass		Stone wool		VIP		PUR	
	ReCiPe	GWP	ReCiPe	GWP	ReCiPe	GWP	ReCiPe	GWP	ReCiPe	GWP	ReCiPe	GWP
Electricity	2.8	3.9	12.8	12.6	40.3	42.3	2.6	3.4	1.1	1.3	3.5	3.3
Heat	0.8	1.2	55.5	58.0	40.2	42.1	22.3	9.9	2.3	0.7	0.0	0.0
Transport	3.4	4.7	1.9	1.8	1.5	1.4	1.3	1.6	0.5	0.5	0.5	0.4

From the result in

Table **3**, the share of the transportation on the entire environmental impacts from material production can be concluded as marginal which limits the potential for improvement. On the other hand, certain share of impacts from electricity consumption can be seen for materials such as foam glass and fibreboard which were more than 40% and 12% respectively. Heat energy was also responsible for non-negligible share of impacts of fibreboard (over 55%), foam glass (over 40%) and stone wool (over 10%) production. The fact indicates the improvement potential of EE for foam glass, fibreboard and stone wool by considering alternative heat sources.

Improvement of Eco-efficiency via Consumed Electricity. In order to decrease the impact caused from electricity consumption through average grid mix, changing the electricity source to renewable ones, such as PV or wind, may be one solution. As the purchasing of electricity generated from renewable energies are becoming available for manufacturers through products such as Renewable Energy Certificates (REC) or Renewable Energy Services (RES), case studies for improved EE by utilizing such products were made. In Fig. 5, different EE with four LCIA cases are shown, where all required electricity were supplied by average European grid (former Union for the Co-ordination of Transmission of Electricity (UCTE)), wind, photovoltaic and hydro power for defined functional unit of insulation materials.

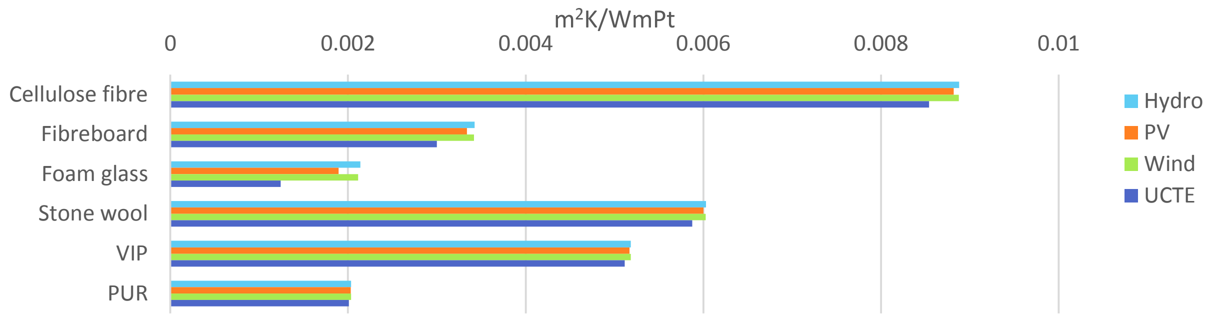

Fig. 5. Eco-efficiency of each case scenario on electricity consumed during the production process in ReCiPe

As foam glass had high domination of impact from electricity consumption, it benefited the most from the option of purchasing electricity from renewable energies. For foam glass, the best scenario was when adopting hydro power which would allow the material to improve by factor 1.72 of its EE. In scenarios with purchasing electricity from wind and hydro energy, foam glass would outperform the environmental performance of PUR. Fibreboard also showed the potential to improve its efficiency by factor 1.14.

Improvement of Eco-efficiency via Consumed Heat. As was shown in Fig. 3, products except cellulose fibre, VIP and PUR had large share of energy for heating on their environmental impacts. For fibreboards, wood chips may become an alternative heat source to improve the environmental performance of the product. Indeed, the heat is already partially supplied by them [25]. When calculating the case where the entire heat demand was met by wooden source, it allowed the material to improve its eco-efficiency by factor 1.27 using ReCiPe. This substitution of the heat source can be achieved thanks to the moderate temperature requirement, ranging around 150°C, of the production process. However, the production of inorganic thermal insulation materials requires rather high temperatures which is over 1000°C. In order to meet such heat demand with biomass, the required volume of the fuel will be large due to its relative low energy content against fossil fuels. Therefore, reduction of the impacts by changing the heating source for those products is expected to be rather limited from the economic viewpoint. Moreover, utilization of biomass as an energy source embeds risks of creating competitions on resource use for alternative purposes such as food supply, which is one of the common theme discussed for biofuels[31-33].

Relevance of Thermo-physical Properties to Eco-efficiency of the Material. As the increase of created value allows better eco-efficiency, this section investigated the relevance of two thermo-physical properties and EE of thermal insulation materials to observe the tendency for effective approach to improve the efficiency. This was made by investigating the correlation between materials' EE and each of the thermo-physical properties from empirical data. Due to the availability of data, GWP was used as the only LCIA indicator for the environmental impact. In Fig. 6, correlation between the thermal conductivity and the EE, in Fig. 7, correlation between the density and the EE are shown.

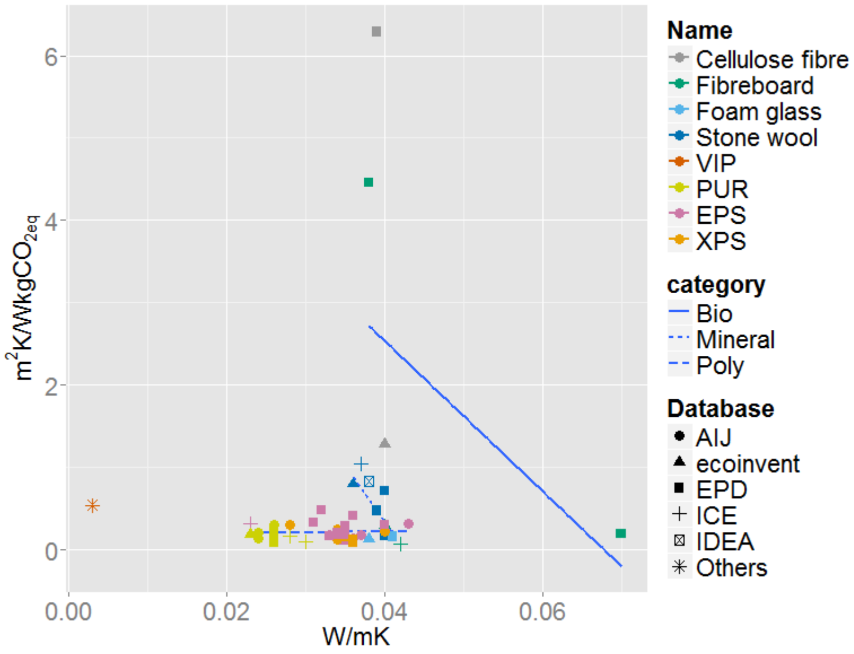

Fig. 6. Correlation between material thermal conductivity and eco-efficiency of materials in GWP from multiple data sources

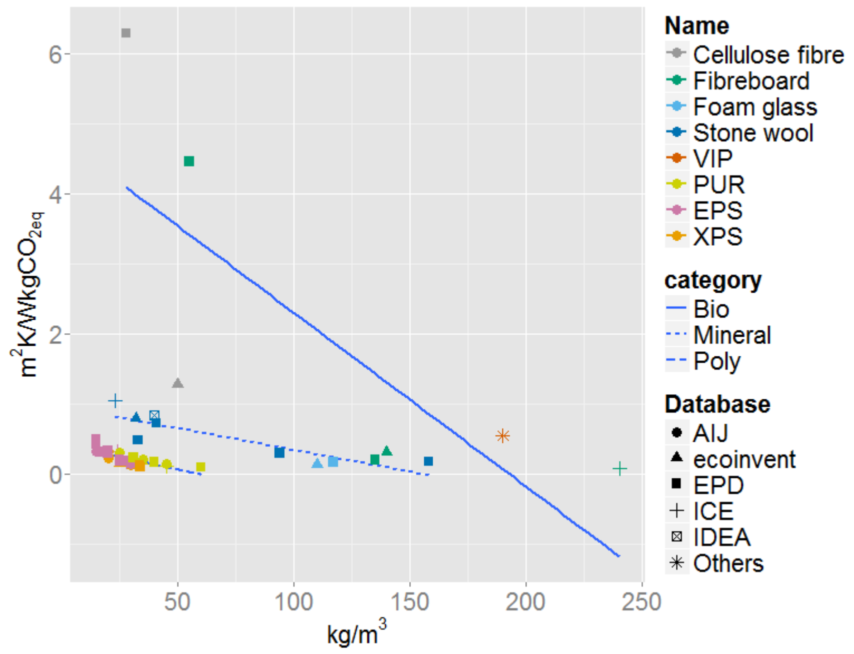

Fig. 7. Correlation between material density and eco-efficiency of materials in GWP from multiple data sources

By comparing Fig. 6 and Fig. 7, density showed clearer relation between the EE of thermal insulation materials than that of thermal conductivity. A general tendency observed from Fig. 7 was that the lower the density of a particular material is, the higher the EE are. In Table 4, the result of linear regression analysis of density and EE in Fig. 6 and Fig. 7 are shown. The obtained correlation coefficients confirmed the observed tendency, which were close to 0.80 in absolute value indicating high correlation for all material types. On the other hand, regression analysis of thermal conductivity and EE for each material category resulted with less correlation except mineral based materials with correlation coefficient with -0.60.

Table 4: Summary of linear regression analysis between thermo-physical properties and eco-efficiency of materials in GWP

Material category	EE – thermal conductivity		EE - density	
	Equation	Correlation coefficient	Equation	Correlation coefficient
Bio (Cellulose fibre, fibreboard)	y = -91.2x + 6.2	-0.43	y = -0.025x + 4.781	-0.75
Mineral (Foam glass, Stone wool)	y = -134.8x + 5.7	-0.64	y = -0.006x + 0.959	-0.88
Polymer (PUR, EPS, XPS)	y = 1.08x + 0.18	0.06	y = -0.007x + 0.418	-0.74

Today, lower thermal conductivity is the material property for thermal insulation materials that gains more attention in relation to environmental concerns among building designers upon selection. The same is true for the material manufacturers. However, the result illustrated the relevance and effectiveness of the development and use of materials with lower density that provides the same value it creates with better EE. Moreover, the fact suggests that achieving resource efficiency, which is one of the important environmental policy implemented currently in EU such as Roadmap to a Resource-Efficient Society [34], can promote materials with effective reduction of environmental impact per provided service.

Limitation of the Defined Eco-Efficiency of the Material. Another aspect related to a material's environmental impact and the thermal performance is on its service life. The service life determines the frequency of replacement and the maintenance of the material during its operation phase which was defined as 40 years with consistent thermal performance for the study. Among the data investigated in the study, there were variances of service life of materials. The range of service life stated in those documents is given in Table 5.

Table 5: Service life of insulation materials

	Service life (years)	Reference
Cellulose fibre	50	[35]
Fibreboard	50 / Building life time	[36, 37]
Foam glass	Unlimited	[38]
Stone wool	Building life time / Unlimited	[39, 40]
VIP	40	[24]
PUR	50	[41]
EPS	35-50	[42, 43]
XPS	Building life time	[44]

As it can be seen from Table 5, the service life of each material differed. When materials are implemented, the service life as described in the table may differ according to the surrounding environment of the buildings. Moreover, the length will be affected by the appropriateness of the implementation of the material. This appropriateness might be more of an issue for some materials. Furthermore, there is no standardized methodology to examine the service life or declaration of the decay of thermal performance over the operation phase of the material within EPD framework. As the defined EE took the thermal performance as the created value, the inclusion of performance decay will affect the EE of the materials. Therefore, illustrating the comparative advantage of EE between the materials that takes the environmental impact of full life cycle remains a challenge.

Conclusion and Outlook

This study investigated the contributing factors of two approaches for improving eco-efficiency of thermal insulation materials: factors of production process and thermal performance. From the contribution analysis on production process which was made by categorizing the inventories into six, the improvement potential of the materials' impact was studied. Sensitivity analysis was made to elaborate potential influence on its impacts by changing electricity and heat sources. The relevance of thermo-physical properties on materials' eco-efficiency was investigated by analyzing existing product data that were accessible with adequate information.

For the improvement on production process, energy sources were key factors for some materials. Fibreboard was capable to obtain higher EE by factor 1.41 in total by fully utilizing renewable energy sources, both for heat and electricity. Foam glass also possessed the potential efficiency increase by factor 1.72. As other materials showed marginal potential for improvement, increasing the EE by improving the production process was less effective for those.

The analysis on thermo-physical properties of materials against its EE highlighted the role density can play for all types of thermal insulation materials. Even with the limitation on variation of data quality due to multiple sources, the result from regression analysis illustrated the importance of having a lower density of the material when determining its EE. The fact also suggested the effectiveness of resource efficiency policy for achieving reducing environmental impact without compensating the performance of the material.

Although having lower density may allow materials to have higher thermal performance per caused impact, there are other aspects that are related to materials. A material's strength is another important property which was not covered in the study. By taking such properties into account, which is one of engineering parameters, the importance of density may change. Further research opportunities can be seen for the inclusion of other material properties. Moreover, not just the created value but the caused environmental impact may also be expanded, such as assessing the impact on water use.

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Annex

Table A shows the data used to create Fig. 6 and Fig. 7.

Table A: List of all inventories used for the analysis between eco-efficiency and thermo-physical properties

Material	Thermal conductivity	Density	Reference
PUR	0.028	30	[28]
PUR	0.03	45	[28]
Fibreboard	0.042	240	[28]
Stone wool	0.037	23	[28]
PUR	0.023	24	[28]
Cellulose fibre	0.04	50	[25]
Foam glass	0.038	110	[25]
EPS	0.035	30	[25]
XPS	0.035	25	[25]
Stone wool	0.036	32	[25]
Fibreboard	0.04	140	[25]
VIP	0.003	190	[24]
PUR	0.023	35	[25]

Stone wool	0.038	40	[29]
XPS	0.034	30	[30]
stone wool	0.046	25	[30]
stone wool	0.051	35	[30]
stone wool	0.036	40	[30]
EPS	0.033	27	[30]
EPS	0.036	30	[30]
EPS	0.037	25	[30]
EPS	0.04	20	[30]
EPS	0.043	15	[30]
XPS	0.04	20	[30]
XPS	0.034	20	[30]
XPS	0.028	20	[30]
PUR	0.024	45	[30]
PUR	0.024	35	[30]
PUR	0.026	25	[30]
Cellulose fibre	0.039	28	[35]
Fibreboard	0.038	55	[36]
Fibreboard	0.07	135	[45]
Foam glass	0.041	117	[38]
Stone wool	0.039	33	[39]
Stone wool	0.04	158	[40]
Stone wool	0.04	41	[46]
Stone wool	0.04	94	[47]
PUR	0.026	31	[41]
PUR	0.026	40	[48]
PUR	0.026	60	[49]
EPS	0.035	20	[50]
EPS	0.034	25	[42]
EPS	0.033	30	[51]
EPS	0.036	15	[52]
EPS	0.034	25	[53]
EPS	0.032	15	[54]
EPS	0.031	20	[55]
EPS	0.035	26.9	[43]
EPS	0.04	17.5	[43]
XPS	0.036	33.7	[44]
XPS	0.036	34	[56]
XPS	0.036	33.7	[57]

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Paper 2

The trends of hourly carbon emission factors in Germany and investigation on relevant consumption patterns for its application

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LCA FOR ENERGY SYSTEMS AND FOOD PRODUCTS

The trends of hourly carbon emission factors in Germany and investigation on relevant consumption patterns for its application

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Abstract
Purpose The share of variable renewable energy sources (vRES) in the German electricity grid has increased over the past few decades. Due to the nature of the generation pattern of vRES, the increase of vRES causes the emission factor (EF) to fluctuate on an hourly basis. This fluctuation raises concerns about the accuracy of quantifying emissions with the current metric of the annual average EF as the respective EF may change depending on the time at which it is consumed.
Methods The study calculated the hourly EF of Germany from 2011 to 2015 and investigated the effect of an increase of vRES on the EF. The calculated hourly EF was clustered based on three aspects of time: the period of time, the time of a day, and the day of the week.
Results and discussion The study showed a higher proportion of vRES on weekend daytimes while the weekday nighttimes resulted in a lower share than the annual average. The study highlighted potential underestimation and overestimation of emissions by using annual average EF which ranged from +22% (2015 weekday nighttime of October) to −34% (2015 weekend daytime of May).
Conclusions The study suggested that the application of hourly EF may be necessary to quantify the respective emission from the consumers that use electricity during the weekend daytime and weekend nighttime. For consumer use at other times, the emissions could be quantified appropriately by using the conventional annual average EF.

Keywords Climate change · Consumption pattern · Dynamic LCI · Emission factor · Environment

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1 Introduction

Electricity is one of the key inventories in a life cycle assessment (LCA); it is frequently used to describe the life cycle inventory (LCI) of various products (Mendoza et al. 2012; Torrellas et al. 2012; Treyer and Bauer 2016). The prevalence of the electricity inventory's use in LCA studies suggests that the accuracy of the inventory may significantly impact the result of an LCA. There exists a tremendous variety of electricity inventories in ecoinvent, with 71 geographical regions being represented (Weidema et al. 2013). Currently, the inventory of electricity is based on the annual share of energy sources in the electricity grid mix of a country. Based on this mix, the annual average carbon emission factor (EF) of electricity is calculated and used to quantify the emission from consumed electricity.

However, the electricity mix has changed rapidly over the last few decades in response to the emission reduction goals set by many countries to combat climate change. For example, the EU set the emission reduction target of 20% by 2020 through the Climate and Energy Package (Commission of the European Communities 2008). In keeping with the commitments outlined, the share of renewable energy sources in the electricity grids increased in several countries. Germany is one of the countries that has successfully increased their share of renewables in the grid. As a result, the grid mix of Germany has transformed over the previous few decades.

The share of renewable energy increased from 3% in 1990 to 30% in 2015 (BDEW 2016; BMU 2013; Morris and Pehnt 2015). In other words, the share of renewable energy in the German electricity grid increased tenfold in 25 years (BDEW

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2016; BMU 2013). Within the increased share of overall renewable energy, the contribution of variable renewable energy sources (vRES), such as solar and wind, was significant. The electricity generation from vRES is dependent on the time when the energy sources are available, which restricts the ability to plan electricity generation in the same manner as is possible with conventional power plants. As a consequence of the increased share of such renewables in the grid, a variation of the electricity grid mix could be expected depending on the time of day. In fact, the study by Paraschiv et al. (2014) offers that the renewable energies in the electricity spot market enhances the deviation in price in Germany.

With the energy mix varying with increased vRES, the corresponding carbon emission by consuming 1 kWh of electricity may change depending on the time. This indicates the weakness of the current usage of annual average EF for quantifying emission from electricity consumption, depending on when the electricity is consumed. Indeed, previous studies state the lack of temporal information in LCA as an important limitation of LCA (Levasseur et al. 2010; Pinsonnault et al. 2014; Reap et al. 2008). To better quantify the respective emission for a specific consumer, higher resolutions of EFs may become relevant. Moreover, with the increase of vRES in Germany as well as various European countries such as Denmark, Italy, and Spain (Eurostat 2016), the importance of yielding a higher resolution of EF of electricity may become relevant for other countries as well. With the adoption of the Paris Agreement in COP21 (UNFCCC 2016), the uptrend in share of vRES can likely be expected in other nations and continents as well.

Recent studies have generated a higher resolution of carbon EFs of electricity for Belgium (Messagie et al. 2014) and Canada (Cubi et al. 2015). However, the German grid system is somewhat unique in its sizeable share of vRES and the size of the power market, which renders the country an interesting case study for assessing the effect of the higher resolution on EF on quantifying carbon emissions. Therefore, this study calculated an hourly resolution of the carbon EF of the German electricity grid mix to assess the relevance of the time of day when the electricity is consumed. To quantify the EF, a life cycle impact assessment (LCIA) was made for each power source. The hourly EF of 5 years (2011–2015) was clustered in various time resolutions based on the period of time, the day of the week, and the time of day. With the clustering, the study intended to highlight that the use of hourly EF grows in significance depending on the consumption patterns of a consumer.

2 Methods

The hourly electricity generation data for Germany was used to calculate the hourly EFs. Based on the energy mix of the generation data, the hourly EF was calculated. The following section introduces the source and method for calculating the averaged EFs.

2.1 Data sources for generation

The hourly electricity generation data for the German electricity grid was sourced from the EEX (European Energy Exchange AG 2015). The data represents the net electricity generation of a specific hour from companies participating in the wholesale electricity market of EEX. In Table 1, the German national statistics of the gross electricity generation and the share of generation data covered by the study are depicted. Due partly to the fact that not all electricity generation facilities are represented in the EEX market, and partly to the differing representations of generation data, the data in the study represented about 65% of the gross German electricity generation (BDEW 2016). For the studied years, the representation of the electricity generated from renewables covered in the study amounted to about 60% of the gross electricity generation of renewables in Germany, which was slightly lower than that of the overall generation. Therefore, the study can be considered to draw conservative rather than optimistic results regarding the EFs. The study did not consider the import and the export of the electricity between the neighboring countries.

2.2 Data sources for emission

The LCI datasets for each energy source from ecoinvent v3.1 were used to quantify the hourly EF of electricity (Weidema et al. 2013), and the global warming potential (GWP) based on IPCC (2013) was calculated via SimaPro (PRé Consultants 2015). The LCIA was based on a cradle-to-factory gate system boundary. The LCI datasets of electricity from ecoinvent and calculated LCIA is shown in Table 2.

For the electricity from nuclear energy, hourly generation data from EEX was only available as an aggregated value comprising data from pressurized water reactors (PWR) and boiling water reactors (BWR). Thus, the ratio of annual generation volume of PWR (78%) and BWR (21%) (Deutsches Atomforum e. V. 2015) was applied to quantify the hourly emission from nuclear energy. For the electricity classified in the "Other" category, the study chose biogas based on the description from EEX which mentioned the biomass as part of the category, while the category "Biomass" was represented by state-of-the-art biomass LCI dataset.

2.3 Emission factors in various resolutions

Since the share of energy source may vary in the electricity grid with the increased capacity of vRES, the study

Table 1 Gross electricity generation in Germany and rate of representation in the EEX market data from 2011 to 2015

	Annual generation		Generation from renewables		
	TWh	Covered rate in the study from EEX data (%)	TWh	Share of renewable in the grid mix (%)	Covered rate in the study from EEX data (%)
2011	613	65.19	137	22.35	63.85
2012	630	63.44	144	22.84	60.78
2013	639	65.17	152	23.86	59.38
2014	628	66.90	163	25.88	62.70
2015	652	74.05	196	30.04	67.65

investigated the variation of the EF in several time resolutions. In the study, carbon EFs were calculated as Eq. (1).

$$EF_t = \frac{\sum GWP_t}{\sum G_t} \quad (1)$$

where *EF* represents the carbon *EF*, *GWP* represents the emitted global warming potential from the entire electricity grid, and *G* represents the total electricity generation of the grid at a given time *t*. The highest resolution of time *t* was hourly.

The EFs were clustered based on three aspects: the length of the time period, the time of day, and the day of the week. Each of the clustered EF was calculated based on Eq. (1). Thus, rather than averaging the hourly EF over the respective period, the clustered EF represents corresponding emission and generation that took place during the represented period. Regarding the length of the time period, the study calculated EF for annual, monthly, and hourly resolution. The influence of the time of day was isolated by defining "daytime" and "nighttime". For the study, 6:00–18:00 was defined as the "daytime", while the rest of the hours were regarded as "nighttime". The EF of weekdays (Monday to Friday) and weekends (Saturday and Sunday) were also calculated with Eq. (1). Thus, the study investigated the potential deviation of clustered average EFs from the annual average to assess the accuracy of quantifying the emission using annual average EFs.

In order to consider the electricity measures from the consumer perspective, the losses that occurred in the grid were included. In ecoinvent, the losses along the transmission and infrastructure for the grid were accounted for in the transformation from high voltage to low voltage. The transmission loss was considered to be 2.6% for the German data. The difference between the high voltage and low voltage electricity mix for German electricity EF was 2.7%, which demonstrates the limited relevance of grid infrastructure compared to the losses occurring in the grid. According to the World Bank

Table 2 Energy sources for German electricity grid mix and GWP of each LCI

Energy source in EEX	LCI in ecoinvent	GWP [gCO_2eq/kWh]
Coal	Electricity, high voltage {DE}| electricity production, hard coal | Alloc Def, U	1112.06
Coal derived gas	Electricity, high voltage {DE}| electricity production, hard coal | Alloc Def, U	1112.06
Gas	Electricity, high voltage {DE}| electricity production, natural gas, at conventional power plant | Alloc Def, U	588.52
Lignite	Electricity, high voltage {DE}| electricity production, lignite | Alloc Def, U	1234.70
Oil	Electricity, high voltage {DE}| electricity production, oil | Alloc Def, U	1150.68
Pumped-storage	Electricity, high voltage {DE}| electricity production, hydro, pumped storage | Alloc Def, U	951.52
Run-of-the-river	Electricity, high voltage {DE}| electricity production, hydro, run-of-river | Alloc Def, U	4.50
Seasonal-store	Electricity, high voltage {DE}| electricity production, hydro, reservoir, non-alpine region | Alloc Def, U	14.37
Nuclear	Electricity, high voltage {DE}| electricity production, nuclear, boiling water reactor | Alloc Def, U; Electricity, high voltage {DE}| electricity production, nuclear, pressure water reactor | Alloc Def, U	13.75
Other	Electricity, high voltage {DE}| heat and power co-generation, biogas, gas engine | Alloc Def, U	313.08
Garbage	Electricity, high voltage {DE}| treatment of blast furnace gas, in power plant | Alloc Def, U	819.47
Biomass	Electricity, high voltage {DE}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Alloc Def, U	38.80
PV	Electricity, low voltage {DE}| electricity production, photovoltaic, 3 kWp slanted-roof installation, single-Si, panel, mounted | Alloc Def, U	93.25
Wind	Electricity, high voltage {DE}| electricity production, wind, >3 MW turbine, onshore | Alloc Def, U	32.98
Offshore wind	Electricity, high voltage {DE}| electricity production, wind, 1–3 MW turbine, offshore | Alloc Def, U	17.09

Table 3 Annual average EF, minimum and maximum hourly EF of each year for German electricity grid mix for 2011 to 2015 in gCO_{2eq}/kWh. Minimum and maximum EF are recorded in gCO_{2eq}/kWh and normalized values that take the annual average EF of respective year as the reference

Year	2011		2012		2013		2014		2015	
Annual average EF	675	100%	686	100%	708	100%	681	100%	676	100%
Min hourly EF	328	49%	351	51%	278	39%	250	37%	278	41%
Max hourly EF	928	138%	920	135%	980	138%	901	133%	951	141%

(World Bank 2016), the losses along the transmission and distribution grid in Germany from 2011 to 2013 totaled around 4.0%. In this study, the transmission loss of 4% was homogeneously applied to all energy sources for all of the investigated years when computing the EF.

3 Results and discussion of averaged emission factors

3.1 Analysis of annual average and hourly emission factors

With the data obtained from EEX and the use of Eq. (1), the hourly EF of 2011 to 2015 was derived. The annual average EF for each year was also calculated, and is displayed in Table 3. The table also includes the minimum and maximum hourly EF of each year, which is presented in both absolute value and normalized value based on the annual average EF of each respective year. In Fig. 1, the share of energy sources at the time when the minimum and maximum hourly EF occurred is depicted.

For the minimum hourly EF, the share of the vRES steadily increased each year from 43% in 2011 to 65% in 2015. Nevertheless, over the five investigated years, the lowest hourly EF took place in 2014 instead of 2015, although 2015 experienced the highest annual share of vRES. Moreover, the minimum hourly EF of 2015 was marginally higher than that of 2013, where 2015 had 9% less share of vRES. This was due to the increased share of coal and gas, with the reduction of nuclear power. However, since the data from EEX does not cover the entire generation volume in Germany, further study may be necessary for a higher accuracy and precision. Yet, the result demonstrated that the variation of the hourly EF over the years can deviate substantially from the annual average EF.

3.2 Monthly emission factors

Figure 2 illustrates the monthly average EF and the share of renewable energy in the grid from 2011 to 2015. Although the monthly average EF within a year fluctuated by nearly 30% between the minimum and maximum value, the month of the year appears not to be a reliable indication for a high or low EF. For instance, a relatively high monthly average EF was recorded during February 2012, 2013, and 2015, while this result was absent in 2011 and 2014. For the minimum monthly

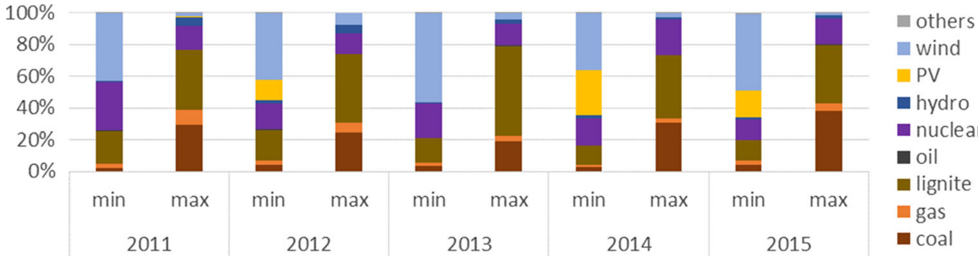

Fig. 1 The share of energy sources at the time when the minimum and maximum hourly EF took place in 2011 to 2015

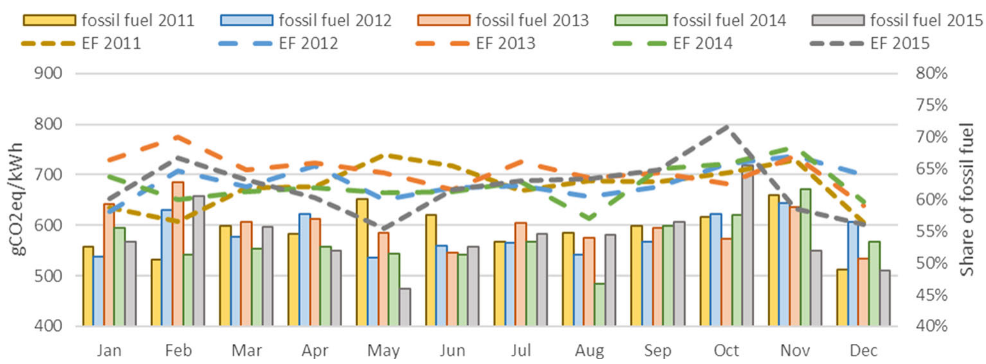

Fig. 2 Monthly average EF and the monthly average share of renewable energy in the German electricity grid mix for 2011 to 2015

Table 4 Annual average EFs subdivided into weekdays and weekends from 2011 to 2015. Annual average EF of each year was taken as a reference

Year	2011		2012		2013		2014		2015	
Unit	[gCO_{2eq}/kWh]	(%)	[gCO_{2eq}/kWh]	(%)	[gCO_{2eq}/kWh]	(%)	[gCO_{2eq}/kWh]	(%)	[gCO_{2eq}/kWh]	(%)
Weekly	675	100	686	100	708	100	681	100	676	100
Weekday	689	102	699	102	725	103	701	103	697	103
Weekend	635	94	647	94	656	93	623	91	615	91

average EF, January was the lowest in 2012, while December was the lowest in 2011 and 2013. In 2014, August was the lowest, and May in 2015 which were in completely different seasons of the year compared to the former 3 years.

However, the deviation of the monthly average EF between the best and the worst month over the years tended to increase. In 2012, the difference of monthly average EF between January and November was 17% against the annual average EF. The difference between the best and worst monthly average EF increased to 20% in 2013, 21% in 2014, and 31% in 2015. These results indicated that with the increased share of renewable energy, in which vRES was the major contributor, the consideration of the month of electricity consumption becomes more important to the accuracy of quantifying the emission.

In Table 5, the monthly average EF subdivided into weekdays and weekends is presented from 2011 to 2015. The values were normalized by the annual average EF of each year.

The results revealed the increasing deviation of some cleaner monthly average EF of the weekend against the annual average EF over the years. In addition to the values from the weekend, some of the "dirtier" monthly average EF of the weekdays also experienced a greater deviation from the annual average EF. It is therefore possible that an increasing variation of the "cleanliness" of the grid mix depends on the day of the week and increased share of vRES. With some months experiencing a nearly 20% underestimation on weekdays and 25% of overestimation on weekends, the use of annual average EF for consumers with specific consumption patterns on the day of the week may be considered as inappropriate.

3.3 Difference between weekdays and weekends

In order to investigate the influence of the time of consumption from a different viewpoint, the relevance of the day of the week was studied. Table 4 illustrates the annual average EF, clustered based on the day of a week. In Fig. 3, the share of energy sources and the average daily volume of electricity generation for weekdays and weekends are presented.

The result showed that the annual average EF of the weekend was becoming "cleaner" than the overall average, by having a lower proportion of fossil fuel in the grid mix with a lower volume of generated electricity than the weekday. It is therefore clear that electricity consumed on the weekends was cleaner than the emission calculated using the annual average EF for the last 5 years. The finding suggests the overestimation of the quantified GHG emission of the weekend by nearly 10% when the annual average EF is used.

3.4 Difference between the daytime and nighttime

The last scope of investigation in relation to the time of consumption was the time of day. In Table 6, the annual average EF was clustered based on the time of day and the day of the week, which were normalized by the annual average EF. In Fig. 4, the share of energy sources and the average daily volume of electricity generation were clustered into four groups of daytimes and nighttimes of weekdays and weekends.

Demonstrably, the electricity user who consumes only during the daytime on the weekend would have their GHG emission overestimated by nearly 15% when the annual average EF was used to calculate the emissions in 2013 to 2015. This overestimation was due to the increased proportion of non-fossil fuel in the energy mix of the electricity through increased available volume of such energy sources, especially from both vRES. While the decrease of the total volume of

Fig. 3 Share of energy sources and average daily electricity generation volume for weekdays and weekends from 2011 to 2015

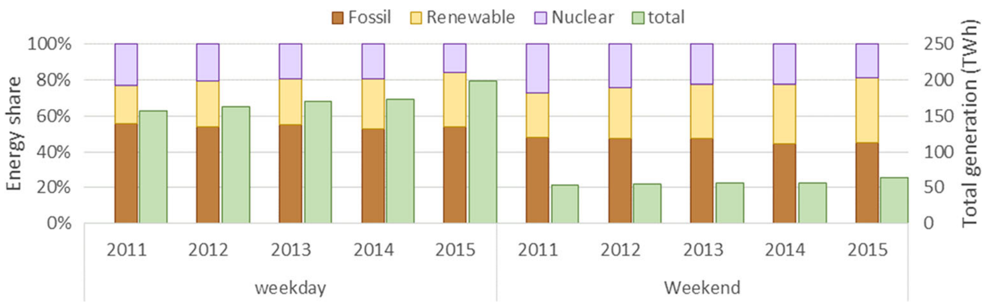

Table 5 Monthly average EF clustered based on day of the week, normalized by annual average EF

		Jan (%)	Feb (%)	Mar (%)	Apr (%)	May (%)	Jun (%)	Jul (%)	Aug (%)	Sep (%)	Oct (%)	Nov (%)	Dec (%)
2011	Weekly	94.00**	90.10**	100.00	100.30	109.40*	106.20*	98.90	102.00	101.70	104.20	108.10*	89.80**
	Weekday	97.70	93.30**	100.40	101.50	112.60*	108.90*	103.80	102.70	101.80	104.10	111.00*	91.60**
	Weekend	85.40**	80.90**	98.70	96.90	100.40	97.80	87.40**	99.50	101.50	104.20	99.50	84.70**
2012	Weekly	91.60**	103.10	98.70	104.60	94.80**	98.30	98.80	95.80	98.60	105.30*	107.60*	102.00
	Weekday	92.80**	103.60	101.90	107.70*	96.40	102.20	100.80	98.10	100.10	106.80*	108.70*	104.20
	Weekend	87.90**	101.90	89.10**	95.80	89.40**	87.90**	93.00**	88.30**	95.00	100.20	104.10	97.00
2013	Weekly	103.10	109.50*	100.20	102.10	99.40	94.70**	102.50	98.10	99.50	96.40	104.10	90.40**
	Weekday	103.10	110.10*	105.30*	102.90	102.10	100.90	104.90	101.60	101.70	97.50	106.70*	93.60**
	Weekend	103.10	107.90*	88.00**	99.60	90.20**	79.00**	94.20**	88.30**	93.50**	92.40**	97.40	81.60**
2014	Weekly	102.30	95.70	97.90	98.90	97.70	98.00	100.60	90.00**	104.70	106.00*	110.90*	95.10
	Weekday	105.00	101.40	102.00	100.90	100.70	100.60	102.50	93.90**	105.40*	108.50*	115.20*	96.40
	Weekend	93.40**	79.90**	87.90**	92.40**	88.90**	90.80**	94.30**	80.70**	102.30	97.10	100.40	91.00**
2015	Weekly	96.30	108.40*	101.90	96.70	87.90**	99.10	101.80	102.40	104.90	117.40*	93.60**	88.80**
	Weekday	99.00	112.20*	104.10	98.70	92.50**	101.90	103.40	105.00	108.00*	119.00*	97.70	93.70**
	Weekend	88.90**	97.30	95.30	89.80**	76.20**	89.50**	96.50	95.60	94.70**	112.80*	82.70**	73.30**

*The values higher than 105%

**The values lower than 95%

Table 6 Normalized annual average EF of the time of a day and the day of the week for 2011 to 2015

	2011		2012		2013		2014		2015	
	Day (%)	Night (%)	Day (%)	Night (%)	Day (%)	Night (%)	Day (%)	Night (%)	Day (%)	Night (%)
Weekly	98.2	102.1	96.2	104.6	95.8	105.0	95.5	105.5	96.0	104.8
Weekday	100.8	103.7	98.8	105.9	98.8	107.0	98.9	107.8	99.4	107.4
Weekend	90.5	97.9	88.5	101.0	86.8	99.4	84.9	99.1	85.3	97.3

produced electricity more significantly affected the proportion of the non-fossil fuel between weekdays and weekends, the increase of volume of non-fossil fuel energy sources exerted more influence in the daytime than the nighttime. On the weekend, the difference in generated electricity volume between the daytime and nighttime over the year was around 5%, whereas the difference in the share of fossil fuel in the mix was nearly 10%. Thus, the inaccuracy of using the annual average EF to calculate the emission of daytime electricity consumers on weekends in a grid where the share of vRES, mainly from solar energy, is expected to increase.

On the other hand, the individuals who consumed electricity during the nighttime on weekdays experienced emission underestimation of nearly 7% when calculating emissions through

Fig. 4 Share of energy sources and average daily electricity generation volume for the daytime and the nighttime of weekdays and weekends from 2011 to 2015

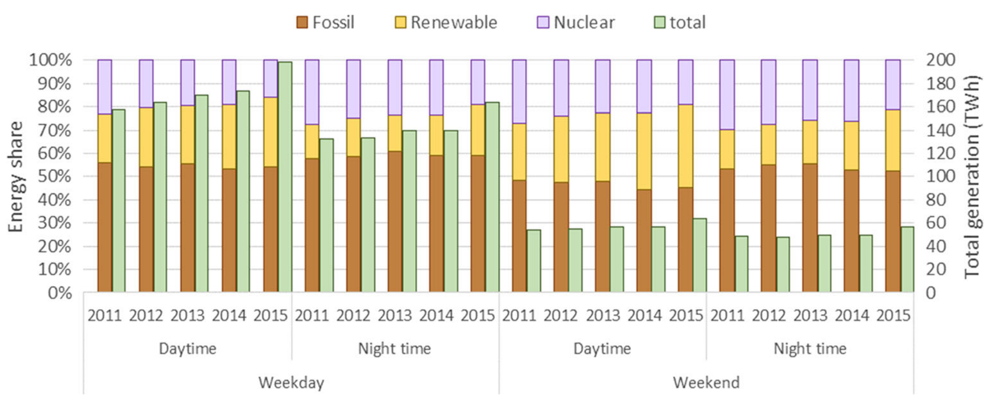

Table 7 Monthly EF clustered in weekday, weekend, daytime and nighttime normalized by annual EF for 2011 to 2015

			Jan (%)	Feb (%)	Mar (%)	Apr (%)	May (%)	Jun (%)	Jul (%)	Aug (%)	Sep (%)	Oct (%)	Nov (%)	Dec (%)
2011	Weekly	Daily	94.00**	90.10**	100.00	100.30	109.40*	106.20*	98.90	102.00	101.70	104.20	108.10*	89.80**
		Day	95.80	91.00**	97.70	96.40	103.70	102.20	95.10	97.70	98.20	102.50	108.50*	91.30**
		Night	92.00**	89.00**	102.60	105.00	116.70*	111.10*	103.50	107.10*	106.00*	106.10*	107.80*	88.00**
	Weekday	Daily	97.70	93.30**	100.40	101.50	112.60*	108.90*	103.80	102.70	101.80	104.10	111.00*	91.60**
		Day	95.80	91.00**	97.70	96.40	103.70	102.20	95.10	97.70	98.20	102.50	108.50*	91.30**
		Night	94.60**	91.60**	102.40	105.50*	119.30*	113.00*	108.20*	107.50*	105.70*	105.20*	110.20*	89.30**
	Weekend	Daily	85.40**	80.90**	98.70	96.90	100.40	97.80	87.40**	99.50	101.50	104.20	99.50	84.70**
		Day	84.50**	79.90**	94.60**	91.20**	92.70**	91.70**	82.40**	93.90**	97.00	100.60	98.40	84.70**
		Night	86.20**	82.00**	103.10	103.40	109.60*	105.00	93.10**	105.90*	106.70*	108.30*	100.70	84.60**
2012	Weekly	Daily	91.60**	103.10	98.70	104.60	94.80**	98.30	98.80	95.80	98.60	105.30*	107.60*	102.00
		Day	92.30**	102.00	94.50**	99.00	87.70**	91.50**	91.40**	88.80**	92.60**	102.60	108.10*	102.80
		Night	90.80**	104.40	103.70	111.50*	104.40	107.40*	108.70*	104.80	106.10*	108.40*	107.10*	101.20
	Weekday	Daily	92.80**	103.60	101.90	107.70*	96.40	102.20	100.80	98.10	100.10	106.80*	108.70*	104.20
		Day	92.30**	102.00	94.50**	99.00	87.70**	91.50**	91.40**	88.80**	92.60**	102.60	108.10*	102.80
		Night	91.10**	103.90	106.50*	113.80*	105.60*	109.90*	110.20*	106.40*	106.60*	109.50*	108.00*	102.60
	Weekend	Daily	87.90**	101.90	89.10**	95.80	89.40**	87.90**	93.00**	88.30**	95.00	100.20	104.10	97.00
		Day	86.20**	98.30	83.30**	87.90**	81.00**	77.90**	83.90**	79.00**	86.70**	95.80	104.00	96.20
		Night	89.70**	105.80*	95.80	105.10*	100.10	100.80	104.40	99.80	104.90	105.10*	104.20	97.90
2013	Weekly	Daily	103.10	109.50*	100.20	102.10	99.40	94.70**	102.50	98.10	99.50	96.40	104.10	90.40**
		Day	103.80	108.30*	95.90	95.50	92.90**	87.60**	92.80**	89.90**	94.60**	94.40**	103.80	90.20**
		Night	102.40	110.90*	105.10*	110.40*	107.90*	104.20	115.50*	108.70*	105.40*	98.70	104.50	90.60**
	Weekday	Daily	103.10	110.10*	105.30*	102.90	102.10	100.90	104.90	101.60	101.70	97.50	106.70*	93.60**
		Day	103.80	108.30*	95.90	95.50	92.90**	87.60**	92.80**	89.90**	94.60**	94.40**	103.80	90.20**
		Night	102.10	111.20*	109.80*	110.70*	109.60*	109.30*	116.90*	111.50*	107.00*	99.70	106.80*	93.70**
	Weekend	Daily	103.10	107.90*	88.00**	99.60	90.20**	79.00**	94.20**	88.30**	93.50**	92.40**	97.40	81.60**
		Day	102.60	105.70*	82.50**	91.30**	80.50**	68.70**	81.20**	78.10**	86.80**	89.50**	96.20	80.80**
		Night	103.70	110.10*	94.10**	109.30*	102.10	91.90**	110.80*	100.90	101.30	95.50	98.60	82.60**
2014	Weekly	Daily	102.30	95.70	97.90	98.90	97.70	98.00	100.60	90.00**	104.70	106.00*	110.90*	95.10
		Day	102.90	93.90**	92.30**	91.20**	89.30**	88.20**	91.80**	81.60**	99.00	103.90	111.20*	96.00
		Night	101.70	97.60	104.60	108.80*	108.80*	111.20*	112.40*	101.20	111.80*	108.40*	110.50*	94.10**
	Weekday	Daily	105.00	101.40	102.00	100.90	100.70	100.60	102.50	93.90**	105.40*	108.50*	115.20*	96.40
		Day	102.90	93.90**	92.30**	91.20**	89.30**	88.20**	91.80**	81.60**	99.00	103.90	111.20*	96.00
		Night	104.70	102.10	108.50*	110.00*	110.50*	112.90*	113.40*	104.20	111.70*	110.40*	114.00*	95.50
	Weekend	Daily	93.40**	79.90**	87.90**	92.40**	88.90**	90.80**	94.30**	80.70**	102.30	97.10	100.40	91.00**
		Day	94.60**	74.70**	81.20**	82.00**	77.40**	78.40**	82.70**	70.00**	93.90**	93.00**	98.40	92.20**
		Night	92.30**	85.70**	95.40	105.00	103.80	106.70*	109.10*	94.40**	112.20*	101.70	102.50	89.80**
2015	Weekly	Daily	96.30	108.40*	101.90	96.70	87.90**	99.10	101.80	102.40	104.90	117.40*	93.60**	88.80**
		Day	96.50	106.70*	97.70	88.50**	80.70**	92.20**	93.00**	94.80**	100.30	114.30	94.90**	90.30**
		Night	96.20	110.20*	106.90*	106.90*	97.20	108.10*	113.00*	111.70*	110.40*	120.90*	92.30**	87.20**
	Weekday	Daily	99.00	112.20*	104.10	98.70	92.50**	101.90	103.40	105.00	108.00*	119.00**	97.70	93.70**
		Day	96.50	106.70*	97.70	88.50**	80.70**	92.20**	93.00**	94.80**	100.30	114.30*	94.90**	90.30**
		Night	98.40	114.10*	109.40*	108.60*	101.00	110.10*	114.00*	113.00*	112.70*	122.00*	96.40	91.20**
	Weekend	Daily	88.90**	97.30	95.30	89.80**	76.20**	89.50**	96.50	95.60	94.70**	112.80*	82.70**	73.30**
		Day	87.70**	95.30	91.30**	80.30**	66.60**	79.40**	85.50**	84.70**	87.30**	108.10*	83.70**	71.70**
		Night	90.20**	99.40	99.60	101.00	87.90**	101.40	109.40*	108.50*	103.10	117.80*	81.70**	75.10**

*The values higher than 105%

**The values lower than 95%

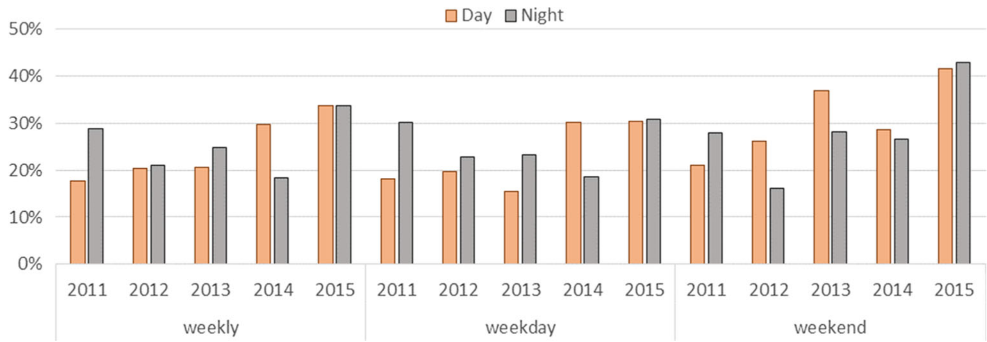

Fig. 5 Difference between maximum and minimum monthly average EF for each cluster of time resolution for 2011 to 2015

annual average EF in 2012 to 2015. The decreased share of renewable energy, primarily from solar, in the grid mix clearly affected the "cleanliness" of the consumed electricity.

Table 7 depicts the results further broken down into months. In Fig. 5, the maximum differences among the monthly average EFs for each cluster are given.

The results of clustering the monthly average EF into the time of day and the day of the week depicted that the range of underestimation and overestimation varied from 22% (2015 weekday nighttime of October) and 34% (2015 weekend daytime of May), respectively. The result did not exhibit clear trends for specific months, as noted in Chapter 3.2. Nonetheless, from March to September, the EF of weekday daytime was generally less than the annual average EF (up to 15%), and weekend daytime was around 20% less. Another clear tendency demonstrated in Fig. 5 was the increasing deviation of minimum and maximum monthly average EF for each cluster of time, especially the decrease of EF during the daytime. The increasing EF difference suggests the increasing inaccuracy of quantifying GHG emission with the annual average EF for electricity consumers with varying demands over the months during the daytime with the higher grid share of vRES.

3.5 Uncertainty in the result

The study is possibly affected by several aspects of uncertainty that might influence the obtained results. The first aspect of uncertainty was the exclusion of the import and export of electricity between the neighboring grids. According to BDEW (2016), the amount of export that took place between 2011 and 2015 was around 55 to 85 TWh, where the amount of import was around 30 to 50 TWh. While the share of export increased from 9 to 13% of the gross electricity generation for the respective years, the share of import decreased from 8 to 5%. Since the inflow of electricity from neighboring grids involves its own mixes and corresponding EFs, the decreasing share of the import implies the decreasing uncertainty of the calculated EF.

Another factor of uncertainty was the sample size of the weekends of each month, which is less than 10 days in Chapter 3.4. With such a limited sample size, the effect of extreme weather events, for instance, may play a significant role in the corresponding EF, especially for vRES.

4 Conclusions

In light of the recent increase of vRES in the German electricity grid, the study calculated the higher temporal resolution of the grid mix from 2011 to 2015. The study assessed the accuracy of the quantified emissions by using the annual average EF through different clusters of time. In the study, the increase of vRES, which was the main source for the increase of renewable energy as a whole, was demonstrated. This affected the variation of the "cleanliness" of hourly EF over the years. This observation suggested the increasing importance of applying the hourly EF over annual average EF with the increase of vRES in the grid for accurate quantification of emission.

Moreover, the study revealed that weekend daytime consumers may have their emissions overestimated by the annual average EF, while the weekday nighttime consumers may have been underestimated. The difference in EF between the days of the week increased over the years. The increase of vRES may have played an important role in this increase. Furthermore, the accuracy of calculating the emission of daytime and nighttime was also affected by the increase of the vRES, where the deviation of these two EFs from the annual average EF was generally increasing. This implies the weakness of applying the annual average EF on consumers who typically use the electricity during the weekday nighttime or weekend daytime. The study also found that when the consumption volume differs from month to month, the inaccuracy of quantified emission may rise, which was evident from the monthly average EF results.

On the other hand, the weekday daytime EF recorded very similar values to the annual average EF, suggesting the appropriateness of the use of the annual average EF for quantifying the emission of the consumer who typically consumes electricity during the weekday daytime.

For future research, the influence of the increased vRES on the EFs may require further investigation. The influence may be investigated by taking other countries such as Denmark, Italy, or Spain—which record high levels of penetration of vRES in the grid recently (Eurostat 2016)—as a case study. However, access to hourly generation data in the grid would be a challenge. The limitation of the study regarding the coverage of generation data may also be strengthened in the future. Furthermore, the limitation regarding the exchange of electricity between the neighboring countries may influence the cleanliness of the electricity. However, in order to account for the influence of taking inflow of electricity from neighboring grids into account, the EF of the inflow electricity will need to be included in the hourly resolution. Furthermore, the inclusion of neighboring grid electricity of Germany will call for further inclusion of grids surrounding the German neighboring grids as electricity in Europe is traded on a continental scale. This calls for the further investigation of the hourly EF of other grids to allow the inclusion of electricity from other grids.

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Paper 3

Abatement cost of embodied emissions of a residential building in Sweden

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ABSTRACT

In 2010, the world's buildings accounted for approximately 19% of all greenhouse gas emissions. These emissions stem from both the construction and operation of buildings. In recent years the carbon efficiency of energy sources and energy efficiency of new buildings has been improved in Sweden. Therefore, embodied emissions accounts for an increasing share of the life cycle emissions of new buildings. This study aims to asses the cost effectiveness in abatement of embodied emissions. This was done by assessing the embodied emissions of a case building and several conventional design measures along with the implication on production cost. It was found that many of the measures enabled cost effective carbon abatement. Embodied emissions could be reduced by 15% using cost neutral or nearly cost neutral measures. Abatements up to 18% were found cost effective in relation to abatement of carbon dioxide emissions in other sectors. Abatements up to 24% were possible with minor increases in total production cost (0.22%) even though some of the individual measures were found expensive in relation to abatement of carbon dioxide emissions in other sectors. Some measures entailed increased floor area that could potentially lead to economic gain where exterior area is a limiting factor. Acoustic requirements were found to be a limiting factor in abatement of embodied emissions.

1. Background

The building sector is generally agreed to be of key relevance for mitigating manmade emissions in order to limit climate change. In 2010, the world's buildings accounted for 32% of global final energy use and 19% of all greenhouse gas emissions [53]. The 5th IPCC report [1] lists the built environment to be responsible for 6.4% of the global energy consumption by building material production and 12% by energy consumption during the usage phase. In the EU, buildings are responsible for 40% of energy consumption and 36% of CO_2eq emissions [2]. The relative importance of the building sector for the EU results mainly from the usage phase, heating, cooling, domestic hot water and domestic electricity usage.

With the usage phase having been identified as the main contributor to emissions in the building sector in the EU, the European Parliament consequently reacted by establishing energy efficiency standards for buildings. The main legislation in order to ensure the reduction of energy consumption in buildings are the 2010 Energy Performance of Buildings Directive (EPBD) [3] and the 2012 Energy Efficiency Directive (EED) [4]. These frameworks demand establishing financial incentives and subsidy schemes and aim to build up awareness via energy audits. They also step by step increase the energy efficiency standards. Depending on country, building typology and owner, new buildings in the EU have to be Near Zero Energy Buildings (NZEB) from 2018 to 2021.

The exact definition of NZEB standards is up to the individual member countries and varies significantly from very ambitious standards to rather conservative ones. With the climate agreement in Paris [5] however it is likely that the more unambitious standards will be refined. Therefore, the relevance of the usage phase will continue to decrease significantly in the coming years.

While this does not take away the need to dramatically increase refurbishment rates in the existing building stock [6] the foreseeable development generates a new relevance for material usage and embodied impact in new buildings. For all components of buildings numerous alternatives exist. These range from very general options such as a wooden structural system as alternative to a concrete or steel frame solution to minor variations such as the choice of the insulation material or plaster. Extensive research has been conducted concerning the comparison of different construction systems with no clear conclusion on which system is preferable from an environmental viewpoint [7–9]. The main reason for this is the diversity of buildings and therefore the difficulty in defining the functional unit at the core of any Life Cycle Assessment (LCA). At the same time studies have found rather diverse results of individ-

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ual solutions for components of buildings in terms of performance, costs and environmental impact. [10–12].

Market surveys indicate that environmental impact anyway is not a key reason for developers or house owners to decide on the construction system of a building. Rather culture, available competence and regional building habits most often define the basic outline of a building. Therefore, while efforts to change general building habits might face great difficulties, assessing alternative solutions within the same construction system does make sense.

2. Aim and research question

As any effort to change key parameter of a building, such as the construction system of a building via an environmental argumentation, is unlikely to be successful, the study focuses on alternative solutions for exchangeable components rather than alternative construction systems.

This paper does so by identifying the environmental optimization potential for a given building. The basic outline of the building, a concrete based structure, was not questioned. Also frame conditions such as the floor plans were not varied. Rather the study looks at alternative make ups for the different components that have less environmental impact and were cost-neutral or nearly cost-neutral in relation to the base house.

The paper aims to address three questions:

- How much can the embodied carbon emissions of a residential building be reduced using conventional building methods?
- How cost effective are these methods?
- What legal framework is the most limiting barrier in regards to build more environmental friendly

3. Literature review

LCA methodology has been widely used to assess primary energy use and carbon emissions from buildings with the aim to survey where in a building's life cycle emissions occurs. Studies have shown that in many cases, a majority of the energy use and emissions stem from the operational phase of buildings [13–17]. A Swedish study on buildings constructed during the mid 90's supports this, showing that a majority (70–90%) of emissions stem from the operational phase of a building. It was concluded that embodied emissions of buildings is of little importance and focus should be to limit the operational energy use in order to decrease environmental impact [18].

However, since the studied buildings were constructed, the average use of energy for heating and hot water of newly produced multi-dwelling buildings have decreased by 26% (121–89 kWh/m2 [19]). Additionally, the use of public heating has increased from 68% to 91% of total constructed area between 1995 and 2015 along with a shift towards the use of renewable fuels for public heating production. As of 2013, 60 percent of the added energy came from bio-fuels and 8% from excess heat, compared to 30% and 5% in 1995 [20].

The perception that as operational energy emissions decreases due to less demand and cleaner energy production, the relative part of embodied emissions increases is intuitive and supported by literature [17,21,22,14]. It was shown that a low-energy building is more energy-efficient than a conventional building over its life-cycle, but also have a higher level of embodied energy. Additionally, several authors argue that depending on energy scenario, the embodied emissions of a building may be of greater importance if operational energy is clean [23,22].

Reviewing recent development in the Swedish energy market along with articles [24–28,21] it seems that newly produced energy-efficient buildings might have reached a stage where embodied emissions need to be considered in order to limit total environmental impact further.

3.1. Limiting embodied emissions

Several studies have been made regarding embodied emissions of construction materials, showing that it is possible to limit embodied emissions by using less carbon intensive materials [29,30,14,13]. Typical suggestions presented are the replacement of traditional materials such as concrete or steel with a wooden structure, eps insulation with different natural materials or using natural rock instead of ceramics. While these reports show that major reductions of embodied emissions can be made, the suggested solutions are not representable for a majority of the Swedish construction market, an issue identified on a global level by Cabeza et al. [31]. As of 2012, 88% of the newly constructed multi-family dwellings in Sweden are built with a framework of concrete [32]. It is therefore of interest to study possible design measures that introduce less deviation to common practise in order to make reductions of embodied carbon more easily achieved. If the aim is to identify easily accessible alterations to current practise, the study should also include cost estimates of the alterations in order to ensure their cost effectiveness.

3.2. Cost of carbon emission abatement

In order to assess the cost effectiveness of abatement of embodied emissions on a general level, comparative figures are required.

Cost of carbon abatement vary widely depending on sector. In energy renovation of existing building stock the cost is often negative, i.e. economic gain, and ranges between −20 to −255 /tonne CO_2eq [54]. The Stern review [33] investigates cost of carbon abatement on a global level and concludes that reducing carbon emissions will likely entail costs, the cost will depend on how and when emissions are reduced, some examples were given. Negative costs in improvement of energy efficiency in transportation, buildings, technology, behaviour among others. Costs associated with changes in forestry, agriculture and changes in land use ranges from 5 to 24 /tonne CO_2eq. Use of CCS technologies were estimated to 17–44 /tonne CO_2eq. Reducing fossil fuel emissions were estimated at 55 /tonne CO_2eq. Ackerman et al. [34] describe how the marginal cost of carbon abatement on a global level depends on the target concentration of carbon dioxide, averaging on 72 /tonne CO_2eq for the 550 ppm scenarios and 55 /tonne CO_2eq for the 650 ppm scenarios. van Vuuren et al. [35] and IEA [36] describe a global marginal abatement cost to stay on a two degree trajectory. Their scenarios predict progressive marginal abatement costs, the scenario by van Vuuren et al. [35] ranging from 6 /tonne CO_2eq in 2010–144 $/tonne CO_2eq by 2050, the scenario by IVA [24] ranging from 27 /tonne CO_2eq in 2010–153 /tonne CO_2eq by 2050.

Investigation of costs related to reduction of embodied emissions in buildings is highly interesting. These figures could help clarify the responsibilities and possibilities of the actors involved in the design and construction process, and where efforts should be put in order to limit total carbon emissions. Methods and assumptions used to obtain abatement costs of carbon dioxide emissions vary in the reviewed literature. Figures are therefore not directly comparable and should rather be used as an indication on a general level rather than direct comparisons with specific measures in different sectors.

4. Methodology

The methodology encompasses an evaluation of embodied emissions and construction cost of a state of the art building constructed in Sweden. The building was realized by Skanska which is one of the major construction companies in Sweden. Second largest in 2014 with a market share of approximately *6,4%* [37]. The building was selected to represent the production methods, building materials and format of a common, newly produced, residential building in Sweden.

A set of design measures, developed in accordance with Skanska's standardized building methods, was evaluated in terms of cost and embodied emissions in order to calculate the possible reduction of the carbon footprint. The studied measures were designed to be equivalent in terms of technical performance during the operational phase of the building. Design measures were compared both as individual measures and as combinations of individual measures to assess the overall possibilities of a reduction of carbon emissions related to their implications on construction cost. As a final step, building regulations that prevent further reduction of carbon emissions were identified.

4.1. LCA approach

An LCA was made to calculate embodied emissions of the building and the studied design measures. The calculation considers the initial stages of the life cycle, from raw material extraction to finished building (A1-A5 according to *EN 15804*). The LCA focused on GWP (CO_2 equivalents) as being the key environmental indicator addressed by the legal building frameworks on a EU scale. Modules in the life cycle that were not affected by the individual measures (B1-B7 according to *EN 15804*) were omitted from the analysis. End of life modules (C1-C4 according to *EN 15804*) were not included due to their negligible impact on the total emissions. Less than 1% of total life cycle energy according to Sartori and Hestnes [17]. Module D allows accounting for potential benefits from recycling of materials. It should however be considered to be outside of the system boundary and thus calculated and reported independently (EN 15804). Including module D in the analysis would introduce uncertainties such as actual degree of recycled input and output materials making the results less general and harder to interpret. Recycling potential will therefore be disregarded (Fig. 1).

The embodied emissions of the base house were assessed using the LCA Software *Anavitor* with environmental data from *IVL (Swedish Environmental Institute)*. Inconsistency among environmental data in LCA studies is an issue that needs to be addressed [38]. Dixit et al. [38] identifies a set of parameters that often cause inconsistencies in embodied energy figures in LCA studies. Specific standards for buildings (EN 15978), environmental product declarations for building materials (EN 15804) and product category rules aim to address many of the parameters identified by Dixit et al. [38]. These standards are incorporated in IVL's database. Some sources of inconsistency remain, most notably geographical location, feedstock energy and technology of the manufacturing process. The IVL database is focused on generic data for material used on the Swedish market and its production processes [39] Erlandsson, M., Communication, November 11, 2016).

While this may decrease the ability to compare results with studies from other regions of the world, it makes the study more valid on the intended market. Results from two additional databases, Eco Invent and KBOB [40] were obtained to assess the applicability of the study in other markets.

4.2. Cost assessment and economic impact

Cost assessments for the base house and the design measures were assessed in collaboration with calculation engineers at Skanska using Skanska's tools and framework agreements. Skanska's framework agreements with suppliers and subcontractors are confidential, specific prices can therefore not be published. Being one of the major actors on the Swedish construction market, it is however reasonable to assume that Skanska's prices for material and labour are equivalent to those of other large actors and slightly lower compared to those of medium sized and small actors on the Swedish market.

The economic impact were calculated as the alternative cost of a design measure in relation to the original production cost. Economic impact was calculated both including and excluding effects from differences in floor area. Some of the measures were minor and comprised only minor changes in material while others were more extensive changes including interchanged building parts. The cost assessments included costs for both building material, labour and material transportation.

4.3. Comparison of design measures

A base house constructed by Skanska was modified with 14 design measures. Design measures encompassed five versions of intermediate floor slabs, three versions of exterior walls, three versions of interior walls, two changes in insulation material and one alternative roof design. All studied design measures are frequently used by Skanska and are established designs in the Swedish construction sector. The measures were based on Skanska's documentation of standardized designs and developed in dialogue with structural engineers at Skanska [41] (Nilsson, personal interview, January 27 2016). Material amounts were verified using blueprints and a design model.

The design measures were studied in order to evaluate potential reduction of embodied emissions within the studied project. They were designed to be interchangeable without major changes of the base house in terms of layout, structural system, maintenance need or shape. This allows for design measures in roof, exterior walls, interior walls, intermediate slabs and insulation.

All design measures were designed to meet the requirements of Swedish building standards. These requirements includes fire safety, structural stability, energy performance and acoustic performance. In some cases the acoustic performance was lowered from class B to class C, both classes are however sufficient for residential buildings [42].

The measures were designed to be equivalent to the original design in terms of operational energy efficiency. The U-value of the insulation layer was unchanged in the design measures. The changes in thermal resistance deriving from changes in concrete thickness was omitted due to its negligible contribution (approximately *0.5%* deviation). The same HVAC system was used in all of the design measures.

4.4. Base house description

A typical Swedish residential building in terms of design, energy performance, size and localization was selected as a base house for the case study. The base house is located in Solna, Sweden, and was constructed between 2012 and 2013. It is a four floor residential building with 15 apartments, ranging from 50 to 100 m^2 resulting in a total apartment net floor area of 1090 m^2. Drawings of the base house are given in Fig. 2.

The total heated floor area (Atemp) of the house is 1343 m^2 including apartments, public areas and equipment room. The structure consists of outer walls of pre-fabricated half-sandwich elements with a plastered façade, interior walls of prefabricated concrete and solid concrete floor decks made up of flat slab bases and cast-in-situ concrete. The roof structure consists of wooden trusses that rests on the uppermost slab. Detailed description of essential building elements of the base house are given in Table 1.

The total calculated energy consumption of the building is *64 kWh/m2·Atemp·year.* This is approximately 60% of the maximum

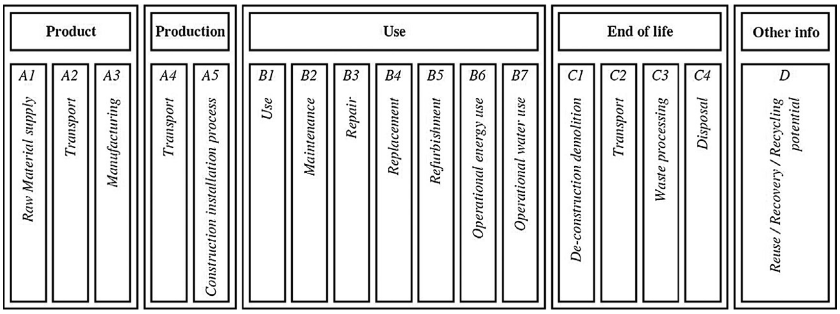


Fig. 1. Overview of the life cycle modules of a building (EN 15804).

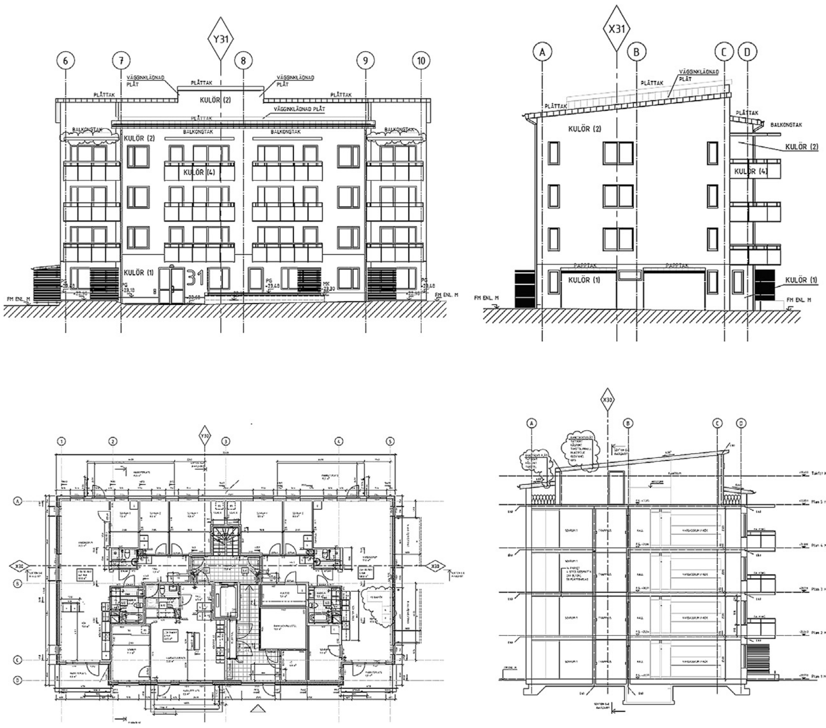


Fig. 2. Drawings of the base house (Skanska).

allowed energy consumption (*110 kWh/m2·Atemp·year*) of a building only complying with the minimum regulations of the National Board of Housing, Building and Planning [43] BFS, 2011:6). The base house does however not fulfil the requirements of a passive house regarding energy efficiency.

5. Results

5.1. Embodied emissions of base house

The embodied emissions from the construction of the base house, module A1-A5, were calculated to be *525 000 kg CO_2-equivalents* translating into *391 kg CO_2-equivalents per m^2* Atemp.

Concrete structures including reinforcement steel account for the largest impact, in total *67.0%*. Other resources which account for major parts of the emissions during the building process are: EPS and XPS insulation (*6.5%*), household appliances (*2.8%*), heating of site cabins and drying of concrete (*2.2%*), electricity, sewage and water (*2.1%*) and propane (*2.0%*). See Fig. 3 for graphical representation of emission distribution. A list of the 20 most significant materials are given in Table 2, note that transportation and processes on site are not included in this table.

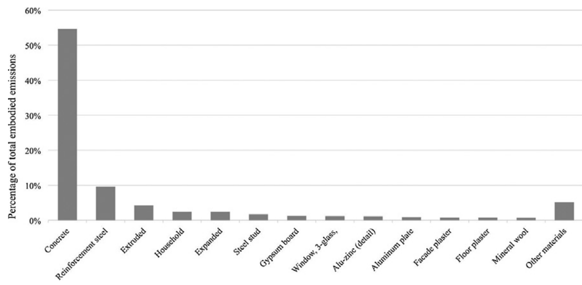


Fig. 3. The ten most significant materials. Materials that, summarized, accounts for less than 5% of total emissions are represented as "Other materials". Transportation to site and processes on site not included.

The results were used to select structural parts for the comparison of design measures: prefabricated walls, floor slabs, insulation and roof structure. These were parts of the building that contributed significantly to the total embodied emissions of the building.

A comparison of the ten most significant material contributors using two additional databases, KBOB [40] and Eco Invent v3.0 [44] verified that inconsistencies among databases exist. Eco Invent, considering the global market, resulted in higher overall emis-

Table 1
Description of building components of base house.

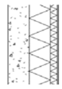
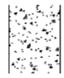
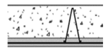
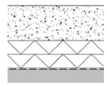
External walls (from outside to inside)		
10 mm mortar plaster, 200 mm EPS insulation, 150 mm prefabricated concrete, Reinforcement steel	Prefabricated, load bearing half-sandwich element. Façade is plastered at site.	
Interior walls		
200 Prefabricated concrete, Reinforcement steel	Load bearing internal walls. Painted at site.	
Floor		
50 mm prefabricated concrete, 200 mm cast in-situ concrete	Prefabricated flat slab bases. Site cast concrete on top. Allows piping in floor.	
Foundation		
250–300 mm cast in situ concrete, 100 – 200 mm EPS insulation, 270 × 270 × 9000 mm concrete piles, Reinforcement steel	In situ cast concrete. Varying thickness depending on load. Founded on prefabricated concrete piles.	
Roof		
Wooden trusses, Steel sheets	Prefabricated wooden trusses.	

Table 2
List of life cycle inventory, materials, transports and processes and their embodied emissions. Resources that, summarized, accounts for less than 1% of total emissions are omitted.

Material (A1–A3 and material waste)	Quantity		Emissions	
Concrete	1 921 135	kg	278 565	kg CO_2 eq
Reinforcement steel	59 480	kg	48 773	kg CO_2 eq
Extruded polystyrene (EPS)	5 614	kg	21 556	kg CO_2 eq
Household appliances	4 194	kg	12 371	kg CO_2 eq
Expanded polystyrenbe (XPS)	3 263	kg	12 302	kg CO_2 eq
Steel stud	3 523	kg	8 561	kg CO_2 eq
Gypsum board	23 411	kg	6 321	kg CO_2 eq
Window, 3-glass, wood	7 144	kg	5 787	kg CO_2 eq
Alu-zinc (detail)	2 281	kg	5 543	kg CO_2 eq
Aluminum plate	338	kg	4 466	kg CO_2 eq
Facade plaster	19 660	kg	3 932	kg CO_2 eq
Floor plaster	18 825	kg	3 765	kg CO_2 eq
Mineral wool	4 990	kg	3 443	kg CO_2 eq
Tiles and clinker	10 840	kg	2 276	kg CO_2 eq
Cabinets	7 113	kg	2 276	kg CO_2 eq
Ventilation equipment (metal)	993	kg	2 075	kg CO_2 eq
Radiators	1 337	kg	1 991	kg CO_2 eq
Paint	760	kg	1 620	kg CO_2 eq
Parquet floor	7 470	kg	1 494	kg CO_2 eq
Wood	12 428	kg	1 367	kg CO_2 eq
Bitumen board	748	kg	1 354	kg CO_2 eq
Wooden door	4 358	kg	1 351	kg CO_2 eq
Plastic (PP/PE)	798	kg	1 317	kg CO_2 eq
Polycarbonate plastic	161	kg	1 249	kg CO_2 eq
Stainless steel (sink)	559	kg	1 169	kg CO_2 eq
Electroplated fasteners	218	kg	1 060	kg CO_2 eq
Gravel	199 547	kg	998	kg CO_2 eq
Steel doors	387	kg	809	kg CO_2 eq
Material transport (A4)				
Transports 20–70 km	158 402	ton km	20 751	kg CO_2 eq
Transports >70 km	40 123	ton km	3 491	kg CO_2 eq
Building processes (A5 – material waste)				
Site vehicles	23 605	kWh	8 957	kg CO_2 eq
Site truck	15 180	kWh	5 760	kg CO_2 eq
District heating (during construction)	93 212	kWh	11 812	kg CO_2 eq
Electricity (during construction)	72 289	kWh	10 956	kg CO_2 eq
Propane	42 607	kWh	10 430	kg CO_2 eq

sions (by a factor 1,50). KBOB, considering the European market, resulted in equivalent overall emissions (by a factor 0,98). Both databases showed some differences in internal weights compared to the results from the IVL database. Most notably, Eco Invent gave the reinforcement a higher weight while KBOB gave concrete a lower weight and insulation a higher weight. The overall relevance of the study is verified by the comparison since the materials of significance calculated using the IVL database also were the most significant materials using KBOB or Eco Invent.

5.2. Embodied emissions of design measures

The results of the LCA of the Base House and the studied measures are discussed in this section. Initially, results are presented from isolated measures before combining several measure in order to identify the total potential decrease of CO_2eq-emissions.

Additionally, the economic impact in relation to total production cost for each measure is presented to acknowledge their economic feasibility. In some cases, the design measures entails differences in floor area which in turn affects the project economy. Economic impact is listed both with and without the effects from differences in floor area. The economic impact without these effects only considers differences in production costs. The economic impact with these effects also considers the economic impact from gaining or losing sellable area given the average market prices in Stockholm County 2014 [45].

Limiting factors for further emission reductions were identified for each building part. The effect on CO_2eq-emissions from the individual design measures along with costs are given in Table 3. Combinations of individual measures along with their cost information and effect on CO_2eq-emissions are given in Table 4.

5.2.1. Floors

For the modified floor design measure, a possible reduction of embodied emissions compared to the base house with 7.5% was possible by changing the current solid concrete deck to hollow-core slabs with an acoustic mat in combination with floor screed. The reduction in embodied emissions derives from the reduced amount of concrete in hollow core elements compared to solid concrete decks. A hollow-core slab is a lighter structure leading to less satisfying sound insulation properties. In order to achieve proper sound insulation, the design measure needed to be supplemented with additional measures. Three such measures were evaluated: an additional layer of concrete, installing a joisted floor and application of an acoustic mat. It was found that an acoustic mat was the most feasible measure both cost-wise and form an emission perspective. This solution only implied negligible cost increases.

5.2.2. Outer walls

By decreasing the concrete thickness to 120 mm it was possible to reduce the embodied emissions by 1.6%. The concrete thickness could not be reduced further since it was needed in order to give room for two layers of reinforcement and at the same time provide sufficient cover thickness to prevent corrosion. The amount of reinforcement remains unchanged in this measure. In total, there was no significant difference in cost between a 120 and a 150 mm thick wall. However, a thinner exterior wall entailed a minor increase in the total floor area, approximately 9 m^2 overall. Using data on mean prices for newly produced dwellings in Stockholm County [45], this increased the sales price by an equivalent to *1.7%* of the production costs. The excess capacity of the original wall was explained by a standardized design process in combination with minimal economic gain of an optimized design. The design process of residential buildings is often initiated by preliminary blueprints from an architect, thicknesses of structural parts are estimated based on previous projects and handbooks [46,47]; [41] (Nilsson, personal interview, January 27 2016). Optimization potential in later stages of the design is often neglected due to minimal economic gain [41] (Nilsson, personal interview, January 27 2016).

5.2.3. Interior walls

Similar results were retrieved for the interior walls. While they serve as load bearers, the concrete thickness was possible to reduce without jeopardizing the structural stability of the building [41] (Nilsson, personal interview, January 27 2016). This was possible as acoustic performance, not structural stability, was the limiting factor. A reduction in concrete thickness from 200 to 160 mm entailed a 1.7% reduction of total embodied emissions. This measure did not introduce any additional costs during manufacturing, instead a minor decrease due to less transportation need and material use could be identified. This measure also entailed a minor increase in the total floor area, approximately *10m2*. Using data on mean prices for newly produced dwellings in Stockholm County [45], this increased the sales price by an equivalent to *1.9%* of the production costs. Due to the lighter construction this wall does not hold the same acoustic qualities as the original wall of the base house. 160 mm of concrete is sufficient to reach sound class C, which is an acceptable sound class in Swedish residential buildings, without additional sound dampening measures. Also, an interior wall design measure comprising 120 mm of concrete and an additional sound dampening layer was studied. The additional sound dampening layer allows reduction of concrete thickness to a level where the structural properties of the wall is the limiting factor. It was found that this design measure would decrease the total embodied emissions by 2.3%. While it required less concrete, the additional materials and increased labour cost resulted in increased production costs, approximately 0.3%.

5.2.4. Alternative materials

Additional reductions of carbon emissions could be achieved by alternating the material used in the base house. Studied measures included the use of graphite-EPS instead of ordinary EPS and low-impact concrete instead of ordinary concrete.

Low-impact concrete means that some of the cement is replaced by additives that yield less environmental impact. The amount of cement that can be replaced depends on the exposure class of the structure. A common additive in Sweden is fly-ash. Changes in structural properties are often negligible according to Johansson [48]. If regular concrete was exchanged with low-impact concrete in interior and exterior walls and floors a total reduction of 6.1% of carbon emissions was possible to achieve. The change in production cost depends on fly-ash supply. Between *0%* and *0.14%* is common [48,49].

Graphite-EPS is similar to ordinary EPS but have slightly better thermal characteristics, enabling a thinner insulation layer with unchanged thermal resistance. If ordinary XPS and EPS was exchanged with graphite EPS, total reductions of approximately 4.1% of carbon emissions could be achieved. Graphite EPS is more expensive than ordinary EPS and XPS, accordingly overall production costs rose approximately by 1.8%. The higher thermal resistance of graphite EPS allowed thinner walls, which increased the sellable floor area of the base house, approximately 10 *m2*. Using data on mean prices for newly produced dwellings in Stockholm County [45], this increased the sales price by an equivalent to *1.7%* of the production costs.

5.3. Combination of design measures

The analysis suggested that embodied carbon could be reduced in specific building parts. Measures presented above may be combined in order to reduce the overall environmental impact. Different combinations are presented in Table 4.

Table 3
Compilation of individual design measures.

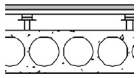
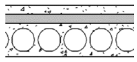
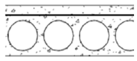
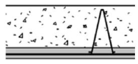
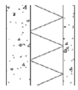
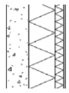
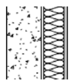
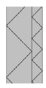
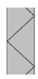
	GWP difference Percentage of total emissions and kg CO2-eq per Atemp	Economic impact related to original production costs. (excluding effect from differences in sellable area)	Economic impact related to original production costs. (including effect from differences in sellable area)	Picture of reviewed design
Floors				
1. Exchanged floor slab: HD/F 190 with Joisted distances	−7.2% (−28.2 kg CO2-eq)	−0.6%	−0.6% (no difference in saleable area)	
2. Exchanged floor slab: HD/F 190 with acoustic mat and floor screed	−7.5% (−29.4 kg CO2-eq)	∼0%	∼0% (no difference in saleable area)	
3. Exchanged floor slab: HD/F 270 and 65 mm of cast concrete	−2.8% (−10.9 kg CO2-eq)	−0.01%	−0.01% (no difference in saleable area)	
4. Modified floor slab: 50 mm prefabricated concrete 180 mm cast concrete	−1.7% (−6.5 kg CO2-eq)	+0.02%	+0.02% (no difference in saleable area)	
5. Modified material: Low-impact concrete	−3.4% (−13.2 kg CO2-eq)	−0.08%	−0.08% (no difference in saleable area)	–
Exterior walls				
6. Exchanged wall: "Sandwich wall" 70 mm prefabricated concrete, 200 mm EPS insulation, 150 mm prefabricated concrete, reinforcement steel	+4.1% (+16.1 kg CO2-eq)	−0.6%	−4,7%	
7. Modified wall: 120 mm prefabricated concrete	−1.6% (−6.0 kg CO2-eq)	0% to +0.2%	+1,7% to +1,9%	
8. Modified material: Low impact concrete	−1.3% (−4.9 kg CO2-eq)	−0.03%	−0.03% (no difference in saleable area)	–
Interior walls				
9. Modified wall: 160 mm prefabricated concrete	−1.7% (−6.6 kg CO2-eq)	+0.2%	+2,1	
10. Modified wall: 120 mm prefabricated concrete, 10 mm air gap, 70 mm Steel studs, mineral wool, 13 mm Gypsum board.	−2.3% (−8.7 kg CO2-eq)	−0.3%	−0,8%	
11. Modified material: Low impact concrete	−1.4% (−5.5 kg CO2-eq)	−0.03%	−0,03% (no difference in saleable area)	–
Roof structure				
12. Exchanged structure: Wooden roof trusses (in place of uppermost floor slab)	−5.8% (−22.7 kg CO2-eq)	0% to +0,08%	0% to +0,08% (no difference in saleable area)	
Insulation				
13. Modified material: Graphite-EPS in exterior walls (170 mm of graphite EPS in place of 200 mm EPS)	−1.2% (−4.7 kg CO2-eq)	−0.04%	+1,7%	
14. Modified material: Graphite-EPS in basements and groundwork (85 mm of graphite EPS in place of 100 mm XPS)	−2.9% (−11.3 kg CO2-eq)	−0.03%	+0,06%	

Table 4
Different measures combined to present the potential GWP difference in combination with difference in production cost and effects from increased saleable area.

Description of combinations (relation to individual measures given in Table 3 stated within parentheses)	GWP difference Percentage of total embodied emissions and kg CO_2-eq per A_{temp}	Economic impact related to original production costs. (excluding effect from differences in sellable area)	Economic impact related to original production costs. (including effect from differences in sellable area)
Combination 1 Low impact concrete in floor slabs (5) and interior/exterior walls (11 & 8) Sound Class B maintained	−6.0% (−23.6 kg CO2-eq)	−0.14%	−0.14%
Combination 2 Reduction of material in exterior walls, 120 mm (7). Reduction of material in interior walls, 160 mm (9). Floor slab exchanged with HDF 190 and acoustic mat (2). Wooden roof trusses (12). Graphite EPS insulation instead of EPS/XPS in exterior walls and ground works (13 & 14). Reduction to sound class C	−24.1% (−94.2 kg CO2-eq)	−0.22%	+3.45%
Combination 3 Reduction of material in exterior walls, 120 mm (7). Floor slab exchanged with HDF 270 with a layer of cast concrete (3). Graphite EPS insulation instead of EPS/XPS in exterior walls and ground works (13 & 14). Sound class B maintained	−13.4% (−52.4 kg CO2-eq)	−0.23%	+3.34%
Combination 4 Sandwich elements instead of half sandwich elements in exterior walls (6). (Increase in carbon emissions, sometimes preferred due to higher level of prefabrication) Sound class B maintained	+4.1% (−16.0 kg CO2-eq)	−0.6%	−4.60%

If several of the measures were combined, a reduction of embodied emissions by approximately 24% was possible to achieve with a minor increase of production costs (0.22%). Higher sales prices due to increased floor area would however counter these costs and lead to considerable economic gains, assuming Stockholm's prices on dwellings 2014 and that the exterior area is a limiting factor in many urban areas. In some combinations, the combined measures are dependent on each other. For instance, in the reduction of material amount in exterior walls and exchange of concrete with low-impact concrete. This reduced material amount has been considered when calculating the reduction potential from the changed materials.

5.4. Summary of results

The cost of carbon dioxide mitigation of the case building is represented in Fig. 4 along with comparative figures discussed in the literature review. Cost of carbon mitigation are assessed by Stern [33] and Ackerman et al. [34]. The Swedish tax on fossil fuels are given by the wedish Transport Administration [50]. Each combination is represented as a series of individual alternations ordered in accordance with their cost per reduction (per ton CO_2eq), forming a marginal cost graph. For instance, by utilizing the measures in Combination 1, the cost of reducing the overall emissions by 9% is cost neutral. Reducing the emissions further, from 9% to 15%, cost approximately 5 per tonne of CO_2eq avoided. Note that the graph only includes the marginal cost of the studied measures, unexplored measure could potentially alter the shape of the graph.

In Fig. 5 the overall annual reduction potential in Sweden is assessed, assuming combination 2 is used. The total reduction potential was estimated to 230 000 t CO_2eq each year assuming 2015 figures on newly produced multifamily dwellings and average apartment sizes [51]. The total annual emissions from production of multifamily dwellings was estimated to 958 000 t CO_2eq which can be compared to the total annual emissions of Sweden, 55 800 000 t CO_2eq [52]. Production of multifamily dwellings accounted for approximately 10.5% of the total revenue of the Swedish construction sector in 2014 [37].

6. Discussion

A number of design measures were evaluated and compared to the overall embodied emissions of the base house. It was found that embodied carbon emissions could be significantly reduced by altering certain aspects of the building using conventional and available design measures. Up to 15% reduction of the embodied emissions was possible using practically cost neutral measures. Up to 18% reduction of the embodied emissions was possible at abatement costs of 59 /tonne CO_2eq. These measures can be considered cost effective since they are below the marginal cost of carbon mitigation on a 550 ppm trajectory given by Ackerman et al. [34] (72 /tonne CO_2eq), partly below the marginal cost of carbon abatements given by IVA [24] (27–153 /tonne CO_2eq) and well below the Swedish carbon tax on fossil fuels [50] (128 /tonne CO_2eq). Note that referenced cost of carbon abatements should mainly be used as an indication on a general level rather than direct comparisons with specific measures in other sectors.

Some measures entailed changes in total floor area. When the economic effect from the additional floor area was added, the measures even lead to economic gain in some cases. The main reasons that these design measures were not used was found to be low awareness of embodied emissions in combination with an inflexible design process. Embodied emissions of buildings have previously been regarded as less important than emissions from operational energy [13–17], which may be a cause for this situation. Judging by the cost of carbon mitigation, there should however be

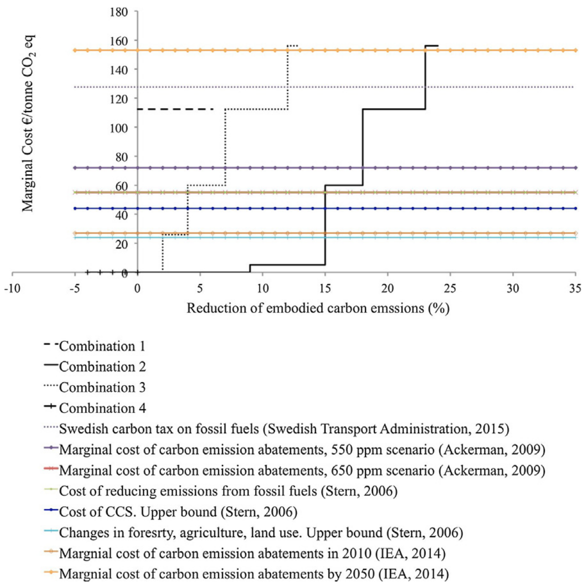


Fig. 4. Marginal cost of emission abatement for the different combinations.

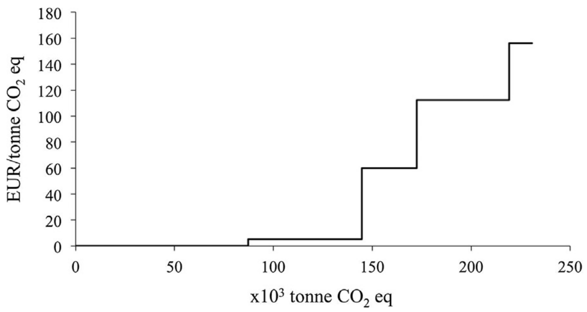


Fig. 5. Annual reduction potential.

an intrinsic economic interest on part of construction companies, developers and the government to address this aspect in upcoming projects and policies.

While the LCA framework can provide a comprehensive view of a building's environmental impact it lacks the ability to compare individual measures from a cost-effectiveness point of view. The approach used in this study was aimed to isolate exchangeable building parts and identify improvement measures while locking certain key features such as operational energy use and maintenance. Also the environmental and economic impact of the improvement measures were assessed. This way the cost-effectiveness could be compared, both between design measures and with other sectors. There may be limits to this method since it only allows for design measures within the default framework of the building. The advantage it brings is that it limits the complexity of the comparison to the extent that it excludes every option that does not fit into the studied building framework. It does however allows for design measures for the contractor and not only in early stages of the design process or even in the conceptual stage.

The most prominent barrier for reducing embodied carbon emissions was found to be the current use of mass (i.e concrete) in order to fulfil sound regulations. Sound regulations were the limiting factor in interior walls and intermediate floor slabs (these two building parts represent 34% of the embodied emissions). Findings suggest that by using alternative soundproofing methods such as damping layers, lighter structures can be used with similar results. In some cases, even after applying sound dampening measures, the acoustic performance was still the limiting factor preventing further reduction of embodied emissions. The case study revealed that the structural elements of the building were designed with excess capacity. Due to lacking incentives to create optimized designs, this is often the case in residential building design according to Nilsson [41] (Nilsson, personal interview, January 27 2016).

The results demonstrates a number of potential reductions in green house gas emissions that are low-cost and achievable using established methods. The applicability of the results are mainly limited to the Sweden and other Nordic countries. The method however, can be applied to other markets as well. It is possible that similar measures of reducing embodied emissions exist in other markets as well. This is an interesting topic for further research.

7. Conclusions

It was found that abatement of embodied emissions were cost effective in relation to carbon dioxide abatement in other sectors. Up to 15% of embodied emissions could be reduced using cost neutral or nearly cost neutral measures. Another 3% could be reduced at a cost of approximately 59 /tonne CO_2eq reduced. Another 7% could be reduced at cost approximately ranging from 112 to 156 /tonne CO_2eq reduced.

Many of these measures to reduce carbon dioxide emissions were found cost effective. However, there is no universal benchmark of cost-effectiveness. A literature review indicate that measures in the range 24–72 /tonne CO_2eq reduced is feasible short term allowing cost of carbon dioxide abatements to gradually increase over time. This comparison considers cost effectiveness on a general level, it should not be used to compare specific measures in different sectors.

Acoustic requirements were found to be a limiting factor in abatement of embodied emissions. Results are not directly applicable to other markets due to known and unknown variations in construction methods, energy scenarios and material production. The method, however, could be useful when conducting similar studies in other markets.

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Paper 4

Investigation of Regional Conditions and Sustainability Indicators for Sustainable Product Development of Building Materials

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Investigation of Regional Conditions and Sustainability Indicators for Sustainable Product Development of Building Materials

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Keyword: LCA, LCT, Sustainable Product Development, Sustainability Indicators, Building Materials, Construction Industry

Abstract

With the increasing importance of the sustainable product development of the building materials for the sustainable building and its industries, this study structured the existing sustainability assessment methods based on a common information structure, which was classified by its categories, aspects, and indicators. Sustainability indicator lists were structured into 25 categories, 88 aspects which 25% of those were product or product and regional related ones. Most of the sorted indicators related to products were difficult to be applied at the early phase of product development due to the lack of required level of information. Meanwhile, the indicators could be a supportive tool for the later phase of product development, for the production planning step as an example. Since the regional conditions showed the link between the sustainability performance during the building's operational phase, the conditions may serve as a proxy information to guide during the earlier product development phase.

1. Background

1.1. Challenge of the sustainability of construction industry

Traditionally, the life cycle environmental impact of buildings was dominated by the energy consumption of the use phase (Dean et al., 2006). Even with the state-of-the-art energy efficient buildings, the impact from the use phase energy consumption was around 50% of the entire impact (Blengini and Carlo, 2010; Mosteiro-Romero et al., 2014; Ostermeyer et al., 2013). With the Energy Performance Directive (European Parliament, 2010) requiring the energy consumption of new buildings in Europe to be nearly-zero from 2020 however, the importance of the impacts associated to the material production will increase. Furthermore, sustainable use of natural resources is one of the basic requirements stated in the Construction Product Regulation (CPR) (European Parliament, 2011).The fact calls for building material manufacturers to further improve the environmental performance of their products. Due to the significance of the construction industry on the socio-economic (European Comission, 2012) and environmental (European Commission, 2011; Herczeg et al., 2014; IPCC, 2014; UNEP, 2003) sustainability, not just the environmental issues but also socio-economic aspects need to be better taken into account.

1.2. Review on Sustainability and Products

Given the importance of the manufacturing activities for transitioning the society towards sustainability (Gaziulusoy et al., 2013; Hallstedt et al., 2013), various attempts had been made to support the decision making of companies. Those attempts to embed sustainability into businesses could be seen based on the three scopes of implementation: Business model; product design; and product development. In the following section, the three approaches are briefly explained, leading to a description of why focusing on the scope the paper is contributing.

1.2.1. Sustainable Business Model

Since business models conceptually describe how a company does business (Magretta, 2002), the study from (Bocken et al., 2014) focused on the scope of sustainable business models. The study introduced the archetypes of sustainable business models to speed up the development of the business models for both research and practice, where (Ritala et al., 2018) investigated the adoption of sustainable business models among the existing largest global companies in the last decades while (Yip and Bocken, 2018) tailored the business model specifically for the baking sector. A research from (Boons and Lüdeke-Freund, 2013) viewed business model innovation as the key for creating sustainable value, which builds upon the view of (Lovins et al., 1999) and (Hart and Milstein, 1999) to achieve sustainable development. The characteristics of a sustainable business model could be described as rather a top-down approach for embedding sustainability concepts in the products, which the management level of the firm creates the sustainability vision of the company and aligns the corporate activities to the vision.

1.2.2. Sustainable Product Design

Design principles for achieving sustainability oriented goals have received high attention over the years. Design for X (DfX) is one of the well-recognized design guideline, which is “an umbrella term for many design philosophies and methodologies that help to raise designers' awareness of the characteristics that are most important in the finished product" (Ijomah et al., 2007). The "X" in the term may represent any aim for a design, for instance, environment or disassembly. Design for Multiple Life-Cycles (Go et al., 2015) is one of such DfX guidelines which aims for a more sustainable design and development of products through combining several DfX strategies for multiple life-cycles. Other studies have looked into applying quality function deployment (QFD) to DfX (Masui et al., 2003) and created a design framework out of it (Sakao, 2007). The sustainable design could be described as rather a bottom-up approach for a company to achieve sustainability targets as the idea comes from where the detailed work for realization is being made.

1.2.3. Sustainable Product Development

Sustainable product development (SPD) functions as something in between the former two scopes for the businesses to become more sustainable. SPD is considered as an effective approach to make products more sustainable as the life cycle socio-ecological impact of a product is largely dependent on early product development phases (McAloone and Tan, 2005). Within this scope, several tools are available, such as Method for Sustainable Product Development (MSPD) and Template for Sustainable Product Development (TSPD) (Hallstedt et al., 2013; Ny et al., 2008). A study from (Aschehoug and Boks, 2013) investigated how sustainability information could support the product development and sorted the related stakeholders and life cycle stages. Furthermore, a framework was created to define sustainability criteria and matrix, which had been applied in companies (Hallstedt, 2017; Hallstedt and Isaksson, 2017). Nonetheless, even with the advantage of affecting the leverage point for making products more sustainable, the field of SPD seems to have received less attention compared to that of sustainable design in terms of the availability of tools (Byggeth et al., 2007). Moreover, poor practical applicability is often identified as an issue for SPD to be used more widely (Zetterlund et al., 2016). This study intends to contribute to addressing this gap, specifically for the case of building materials. In Figure 1, the illustration of how the three scopes for embedding sustainability on a product scale fits together is shown.

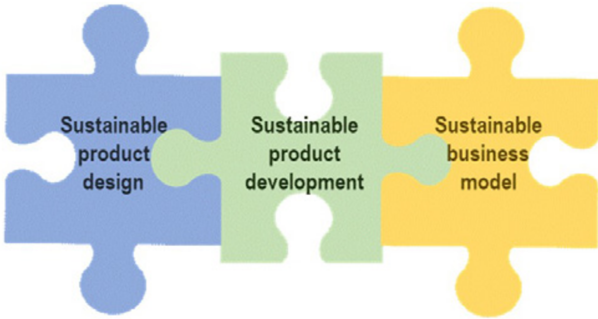

Figure 1. An illustration of the relation of three scopes for implementing sustainability issues on products by the industries

1.3. Influence of regional conditions on buildings

While the sustainability requirement of a building is increasing, the core function of it remains as a shelter against the external environment to keep human safe and comfortable. Such external environments which buildings are exposed to differ depending on the regions. This may pose stresses on buildings. Such stresses can be hygrothermal due to the climatic conditions (Goto et al., 2012b; Pakkala et al., 2014), or can be mechanical due to natural disasters such as typhoons or earthquakes. Not just the condition of the natural environment but also socio-economic conditions, such as market demands or indoor habits, may differ depending on the location. This functional demand of the building indicates the importance of taking these regional conditions into account to meet not just the technical but also the environmental as well as socio-economic challenges that materials are facing for the sustainable development of the building industry. In fact, meeting the functional and technical needs are the two prerequisites for the sustainability according to CPR (European Parliament, 2011). To reflect on the practicality issues that were pointed as a bottleneck for SPD methodologies, literature that considered the relation between regional conditions and the sustainability performance were investigated.

1.4. Aim of the study

The previous studies have shown the effectiveness of the sustainable product development for improving the sustainability performance of products as well as its bottleneck as practical applicability. Concerning buildings, regional conditions reveal to be an important aspect related to the practical aspects. Given the circumstances, the study contributes to the field of sustainable product development through assembling and structuring the existing sustainability assessment methods to examine how manufacturers can address the relevant indicators during the product development phase. This was made through the analysis of the collected indicators considering the operational boundaries of manufacturers and the applicability of the indicators during the product development phase by them.

2. Methods

2.1. Literature review

In the study, two literature reviews were conducted: one for the relation between the regional conditions and the building's sustainability performance; and the other for sorting the indicators from the exiting sustainability assessments.

To understand the relation of the regional conditions and the sustainability performance, the investigation on literature regarding regionality and life cycle assessment (LCA), one of the established environmental sustainability assessment methods, was made. Further, investigation on climate, building, and sustainability was made to understand the influence of the conditions on the sustainability performance of the building sector.

For covering the existing sustainability assessment schemes and indicators holistically, the study investigated the international initiatives on sustainability, such as global reporting initiative (GRI) (Global Reporting Initiative, 2014), product environmental footprint (PEF) (Manfredi et al., 2012) and sustainable development indicators (Eurostat, 2015). Due to the importance of the life cycle thinking (LCT) for the sustainability performance of products (Hallstedt et al., 2013), the study looked into literatures related to LCA not only for the regional related ones but also in general, including environmental product declaration (EPD) (European Committee for Standardization, 2013, 2011). Further literature review for the last 10 years was conducted using SCOPUS with keywords being "sustainability; indicator; building" on March 2017. From the resulting literature, studies which were identified as high relevance by reading the title and abstract were investigated further referring to design research methodology (Blessing and Chakrabarti, 2009). The indicators included in the studies related to regional conditions were also included for the sake of holistic coverage of the assessment of the sustainability performance.

2.2. Sustainability Indicator Structuring

Among the collected previous studies with different intentions and motivations, various types of indicators were identified. These indicators were structured based on a common information hierarchy which was inspired by the Global Reporting Initiative (GRI) (Global Reporting Initiative, 2014). As such the structure was organized in three tiers: category; aspect; and indicator. The identified indicators and aspects were merged and sorted to avoid redundancy. From the sorted aspects, categories were introduced to structure them based on the characteristics of the aspects. Since most of the collected indicators had a hierarchical relationship within the respective schemes, most of the links were kept as much as possible when applying the three tiers introduced in this study.

2.2.1. Classifying the Aspects

In order to understand how the sorted indicators can support the manufacturers to improve the sustainability performance, the indicators were further assessed based on the viewpoint of how a company could respond. At the tier of aspects, three classifications were introduced based on this viewpoint. Those three were: product; company; and regional conditions. These classifications were chosen to clarify the aspects that companies can address (product and company specific aspects), and the ones given to the companies (regional specific aspects).

Among the ones that companies can manage or affect, two classes were introduced depending on whether it is related to the products or company's organizational issue. For instance, "Effluent and waste emissions" of a product was classified as product specific aspects, while employment-related aspects were classified as company specific ones. For the regional specific aspects, indicators such as policy related ones were assigned in the class.

Aspects concerning two of the classes, regional and product or company, were also introduced for the classification. As an example of a regional and product aspect, biodiversity was one of them. This was classified here since the magnitude and severity of impacts caused by the emission from a product on biodiversity may depend on the carrying capacity of the region. Wage related aspects are the ones which depend on the regional conditions, the living wage, and the effort from the company, thus classified as regional and company specific aspects.

In Table 1, the summary of the introduced class, its definition, and examples are shown.

Classification	Definition	Example
Product specific aspects	Aspects that are dependent on product specs or production	Effluent and waste emission
Company specific aspects	Aspects that are dependent on company's action or structure	Employment relationship
Regional specific aspects	Aspects that are dependent on regional conditions or beyond product/company's action	Public policy

Regional and product	Aspects that concerns both company's action or structure and regional conditions	Biodiversity
Regional and company	Aspects that concerns both product specs or production and regional conditions	Fair salary

Table 1. Summary of the classification of sustainability indicators

2.2.2. Grouping the Product Related Indicators

To assess the applicability of the existing indicators during the product development phase to evaluate the sustainability performance of the products, further clustering was made at the indicator level. The clustering was made on the indicators assigned to the aspects classes in product or product and regional specific ones. Based on the observed characteristics of the indicators, these product specific sustainability indicators were grouped into the following three: product property related indicators, inventory related indicators; and impact related indicators. For instance, property related indicators include the "Ability to accommodate technical change". As an inventory related indicator, "Use of reused materials" is included while "NOx emission" is included as an impact related indicator. In Figure 2, the grouping of sustainability indicators in the information structure is represented.

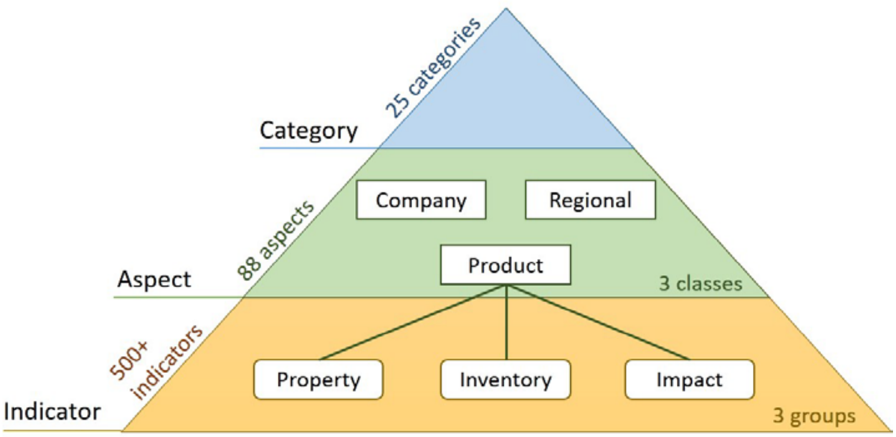

Figure 2. Representation of information hierarchy structure for sorting sustainability indicator and its classes and groups

3. Review of research on regional conditions for sustainability

In this section, the review of studies focusing on the regional conditions and sustainability assessments were made. The relation of the regional conditions and the sustainability assessments were investigated by looking at the study types and the affected life cycles. In Table 2, the summary of reviewed studies with regional conditions is shown.

Based on how the regional influences were considered in the respective studies, the reviewed studies were categorized into four types: 1) evaluation; 2) optimization; 3) adaptation; and 4) impact assessment. Depending on the study types, the life cycle phases of buildings in concern differed. For instance, the evaluation and adaptation type studies looked into the operational phase of buildings (B module in EN 15804 (European Committee for Standardization, 2013)). Studies showed that the regional climatic conditions affected the energy performance of the buildings and the longevity of building components. In the optimization study, which covered all life cycle phases, the regional conditions affected the design of the building and its components based on the given conditions for the optimization problem. Studies that dealt with impact assessments and the influence of the regional viewpoint allowed better decision making over the entire life cycle with better representation of the result. Thus, the result from the literature review suggests the importance of taking regional differences into account for the sustainability of buildings on its performance and assessment accuracy improvement, which implies its importance for the development of building materials.

Types of regional study	**Paper**	**Region in concern**	**Study topic**	**Covered life cycle**
Evaluation	(Li et al., 2012)	Future climate in Northern countries	The change in energy demands of buildings	use phase
	(Wong et al., 2010)	Future climate in Southern region (Hong Kong)	The change in energy demands of buildings	use phase
	(Dirks et al., 2015)	Future climate in the US	The change in the energy peak demands of buildings	use phase
	(Lee and Kung, 2011)	Climate classification in Taiwan	Evaluation of energy performance of buildings	use phase
Optimization	(Saner et al., 2014)	Swiss municipality	Optimization of the environmental performance of buildings	all phases
	(Goto et al., 2012a)	Climate zones in Japan	Optimization of insulation thickness of a	use phase

			building envelope system	
Adaptation	(Hausladen et al., 2012)	Climate zone	Adaptation of building concepts	use phase
	(Lisø, 2006)	Future climate in Norway	Adaptation of building envelopes of wooden and brick structures	use phase
	(Pakkala et al., 2014)	Future climate in Finland	Assessment of concrete durability	use phase
	(Nik et al., 2015)	Future climate in Sweden	The uncertainty on prediction of hygrothermal performance of building facades	use phase
Impact assessment	(O'Keeffe et al., 2016)	A spatial scale below a nation	Review on the regional and spatial information on the goal orientation and LCI.	all phases
	(Kounina et al., 2014)	Continent	Intercontinental variation of toxic emissions	all phases
	(Dressler et al., 2012)		Assessment of regional parameter on biogas production	production phase
	(Rosenbaum et al., 2015)	Continent/economic	Developed an impact assessment method for indoor pollution	all phases

Table 2. Summary of regional studies

4. Results of sustainability indicator sorting

From the literature review, 9 studies from the regional focused studies, 12 LCA related studies, 5 international statistics, initiatives, and standards and 2 generic and building related sustainability studies were used to create a list of holistic sustainability indicator list which resulted in +500 unique indicators. The complete list of references is given in the appendix. These indicators were structured into 88 aspects, in 25 categories, as described in section 2.2. In Table 3, a list of sorted sustainability aspects is shown.

Categories	Aspects 1	Aspects 2	Aspects 3	Aspects 4	Aspects 5	Aspects 6	Aspects 7
Accessibility	Accessibility to public transportation	Accessibility to urban amenities	Access to tangible resources	Access to material resources			
Biodiversity	Biodiversity	Land use					
Climate	Climate change						
Community	Local capacity building						
Costs	Life-cycle costs	Indirect Economic Impacts	maintenance				
Culture	Indigenous Rights						
Development	Contribution to economic development	Socioeconomic development					
Education	Education and awareness of sustainability	Training and education					
Emission	GWP	Effluents and Waste	ODP	Acidification	Eutrophication		
Employment Relation	Employment	Employment relationship	Job satisfaction and engagement	Labor/Management Relations			
Energy	Energy consumption	Energy efficiency	CED				
Forced Labor	Child Labor	Forced or Compulsory Labor	Human rights Assessment				
Governance	Corruption	Fair competition	Good governance	Security Practices			
Health and Safety	Health and comfort	Health and Safety	Public health	safety and security	eco/human-toxicity		
Market Relationship	Market Presence	Marketing Communications	Transparency	Customer Privacy	Product and Service Labeling	Promoting social responsibility	Sustainable consumption and production
Policy	Public Policy	Social benefits, legal issues	Migration	Compliance	Prevention and mitigation of conflicts	Global partnership	
Resource	Materials	Materials and waste management	Natural resources	Water			
Stakeholder Management	Stakeholder Involvement	Social inclusion	Community engagement	Grievance Mechanisms for Impacts on Society	Human Rights Grievance Mechanisms	Environmental Grievance Mechanisms	
Statistics	Economic Performance	Demographic changes					
Supply Chain Management	Supplier Assessment for Labor Practices	Supplier Assessment for Impacts on Society	Supplier Environmental Assessment	Supplier relationships	Sourcing of materials and services	Procurement Practices	
Sustainable Buildings Social	loadings on the neighborhood	Adaptability	Experienced well-being				
Transportation	Sustainable transport						

Waste	closing-loop at the regional level	End of life responsibility				
Worker's Right	Worker's rights	freedom of association and collective bargaining	Fair salary	Equal Remuneration for Women and Men	Labor Practices Grievance Mechanisms	Diversity and Equal Opportunity
Working Conditions	Work-life balance	working hours	wage	Discrimination	Non-discrimination	

Table 3. List of structured sustainability aspects based on the categories

4.1. Classification of sustainability aspects based on the classes

From the collected and sorted indicators assessing the sustainability performance, this section investigated the ones that the companies could take good control or manage well. As was described in section 2.2, the indicators were classified based on three classes, where some of the indicators were assigned in two classes. In Figure 3 the summary of classified aspects is shown.

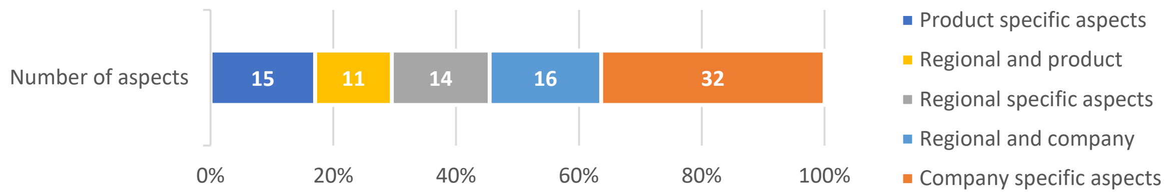

Figure 3. Result of the classified sustainability aspects

Among the sorted aspects, 26 out of 88 aspects was classified as product specific. 11 of those were categorized as aspects related to both product and regional conditions. The indicators classified in these aspects could have a potential to be applied at the product development phase. Thus, the sustainability performance assessed through these indicators can potentially be handled at the level of product development for improving its performance.

62 of the covered aspects turned out to be related to the company and/or regional conditions. The sustainability performance assessed through company specific indicators could be improved via the corporate governance. However, although company specific indicators could be influenced by the decisions and actions that companies take, it could be challenging to be influenced by the product development team. Instead, the indicators in these classes could potentially support the decision making for the sustainable business model.

In Figure 4, an illustration that summarizes the characteristics of each category based on the classes of the included aspects are given, where the horizontal axis represents the regional or generic characteristics and the vertical axis represents the product or company related ones. In the figure, the location of each category is based on the classes of the included aspects.

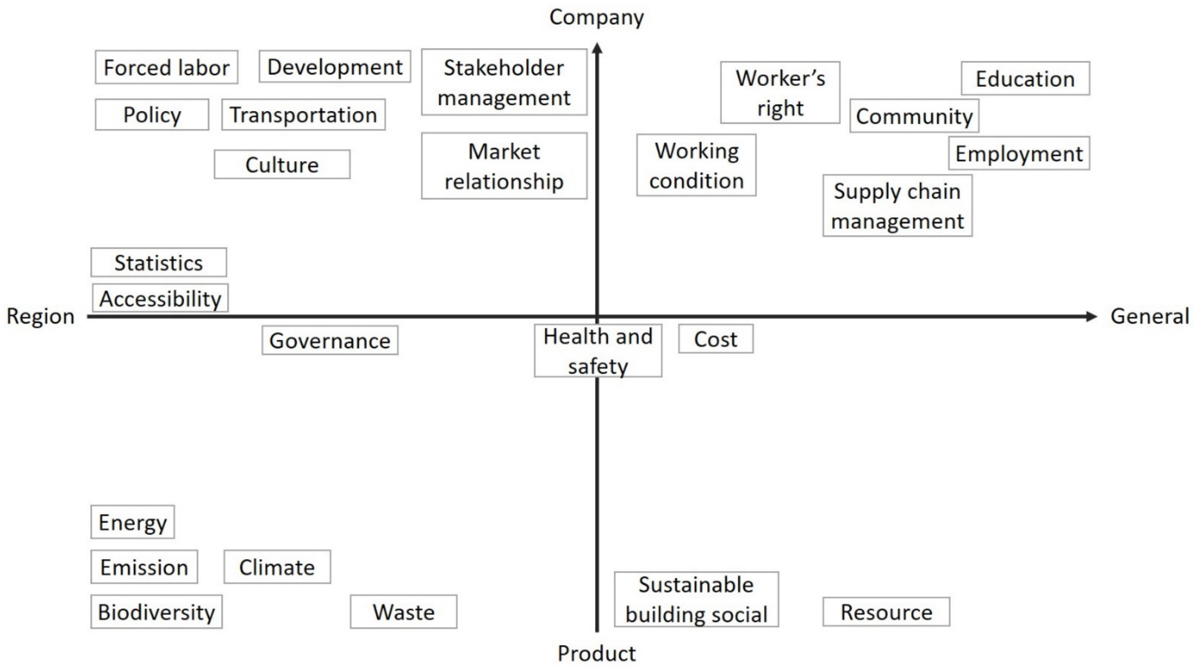

Figure 4. Mapping of the class of categories

4.2. Categorization of product specific sustainability indicators

Among the 26 product specific aspects, further grouping was made to see the applicability of the indicators during the product development phase. The result of grouping at the indicator level was as shown in Table 4. Most of the inventory and impact related indicators were originating from LCA studies, which will generally require a good level of details of the assessed product or service. However, such level of information does not typically exist at the stage of product development phase (Chang et al., 2014). This brings up the question about the practical applicability of the inventory and impact related sustainability indicators for supporting the SPD of building materials.

Groups	Number of indicators
Property related	17
Inventory related	25
Impact related	18

Table 4. Summary of a grouping of indicators classified as the product related aspects

Although the assessment of the impact based on the existing sustainability indicators related to products remained challenging at the product development phase, there was an indication of the usefulness of the regional conditions to be considered for the better sustainability performance of a product. For instance, an indicator like rain hours from studies about regional conditions and the sustainability performance highlighted the importance of the indicator on the energy consumption from the heating ventilation and air conditioning (HVAC) demand in sub-tropical regions (Lee and Kung, 2011). This regional condition can be understood as to affect the product performance of the sustainability aspects on energy and the emission category, shown in Table 4. Not just the rain hours but also other climatic conditions could affect the resource, energy and emission categories. Thus, the regional conditions have the potential to support the SPD of the building materials as a proxy information for the better sustainability performance.

5. Discussion

5.1. Relatedness of sustainability indicators for SPD

According to (Hallstedt et al., 2013; Roozenburg and Eekels, 1995), product development is a phase that includes marketing planning and product designing, as illustrated in Figure 5. The figure was rearranged by reflecting the relevant sustainability indicators at the respective phases and by adding an illustrative drawing representing the development of the available information about a product during the development phases.

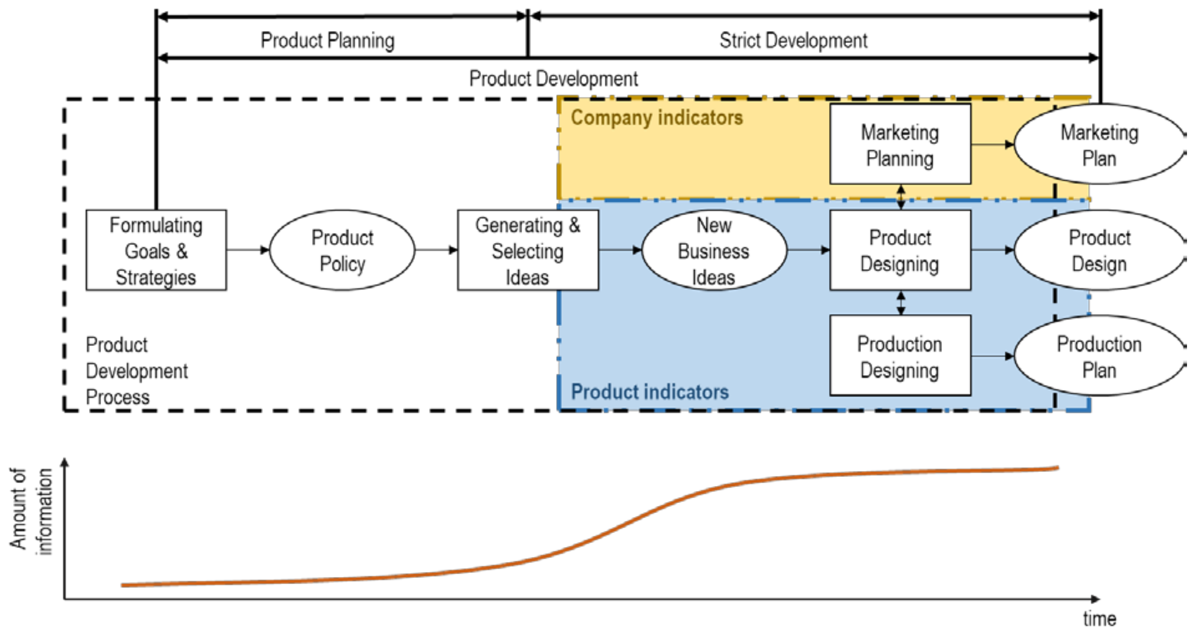

Figure 5. Illustration of a product development and potentially relevant sustainability indicator categories at the respective phases with an illustrative drawing of the progress of the level of available product information

When relating the categorized sustainability indicators to the steps illustrated in Figure 5, the product related indicators could potentially assess the sustainability performance of the implemented sustainable design of products or production. For the company related sustainability indicators, the assessment may support the marketing planning step. Thus, the existing sustainability indicators in those categories may support the designing and the planning phase of the product development, the "Strict Development" phase illustrated in Figure 5. However, due to the lack of information during the early product development phase, the use of the sorted sustainability indicators in the earlier phases remains challenging. For instance, product specific indicators in the group of inventory and impact often require the information on mass and the types of materials used to assess the sustainability performance. At a phase when which materials to be used remains a topic to be decided, such information would not be accessible. With the limitation of the available information for the assessment through the existing product and company specific sustainability indicators at the early product development phase, there is further need for research.

One potential pathway to support the early phase of product development could be the investigation of proxy information to estimate the sustainability impact. For instance, a study from (Huijbregts et al., 2010) states the usefulness of the cumulative energy demand for estimating the different kinds of life cycle environmental impacts of the majority of commodity products. This could guide the product development team to proactively seek for materials that tend to require less energy for its production. A study from (Kono et al., 2016) states the density as a key factor for the eco-efficiency of the building thermal insulation materials, guiding the products to become lighter to achieve optimal embodied carbon emission and thermal performance. Further investigation of proxy information that could be used during the product development phase could be valuable for supporting the early phase of a building material development.

5.2. Relation of the regional conditions and the early PD phase

One of the common approaches for the development of building materials is setting a target value of a technical performance. For instance, it could be a specific thermal conductivity value in the case of developing a new thermal insulation material. Among the technical performance criteria, the longevity of materials could be a potential development criterion. The longevity of materials could be understood as a criterion related to the resource issues in the sorted sustainability category. As was seen from the previous studies, climate change influence the longevity of building materials (Nik et al., 2015; Pakkala et al., 2014), which the degree of climate change may differ depending on the regions.

The effect of climate change is not only seen through the increased global temperature and the sea level rise but also through the increased heat island effect which causes an impact on economic and health care cost (Estrada et al., 2017), aspects included in Table 3. This heat island effect is an example where regional conditions may influence the sustainability performance of a building, which in turn may affect the building material’s performance requirement. For instance, regions expected with increased heat island effect may prefer materials with lower heat capacities to ease the effect. This calls for a potential need to take such regional influence of climate change into account for the optimal sustainability performance of buildings and the development of its materials. The fact suggests the inclusion of regional climate change information in the “Product Planning” phase, shown in Figure 5, could effectively support the building material development for a better sustainability performance. The structured aspects in Table 3 may provide a basis for identifying sustainability aspects affected by the regional conditions.

5.3. Relation of the regional conditions and the later PD phase

Among the sorted 88 aspects, 41 of them were classified as regional related ones. Although some of the indicator performance could not be improved by the company’s effort, such as the corruption occurrence in the regional government, there are indicators that could be used for a company to manage the performance during the later phase of product development. For instance, emission caused from the energy consumption during the manufacturing could be improved by selecting a factory location with a cleaner electricity grid mix (Kannegiesser et al., 2013), or changing the operation hours based on the cleaner grid mixes, as can be seen from the recent German case (Kono et al., 2017). This kind of information on regional conditions could support the “Production Designing” phase, one of the steps shown in Figure 5. Furthermore, managing the supply chain with regional conditions in mind could allow improving the product related sustainability performance on socio-economic issues. (Govindan et al., 2013) included economic and social criteria in their fuzzy multi-criteria approach for sustainable supply chain management, as an example.

6. Conclusion

This paper investigated the relation of the regional conditions on the sustainability performance related to buildings, where the influence of the conditions on the performance was seen on the assessment accuracy and the performance improvement. Furthermore, the paper structured a holistic set of sustainability indicators for clarifying the potential use and pathways to implement those for the sustainable product development of building materials.

For companies to improve the sustainability performance of a product during the product development phase based on the collected indicators, the analysis of the classified indicators showed that the later phase of product development could be supported by the existing indicators. However, due to the nature of inventory and impact assessment related indicators typically requiring a good level of information, the use of such indicators during the early product development phase remained challenging. The analysis regarding the regional conditions hinted the potential link between the conditions and the sustainability indicators, which were related to energy and emission. The influence the conditions on sustainability performance was also seen in the “Product Planning” as well as in the “Production Designing” phase, suggesting the effectiveness of taking the conditions into account for both early and later phase of product development.

Further investigation could be made to support the earlier phases of product development. One potential pathway could be via sorting proxy information, which regional conditions may play a role. Another approach could be made through assessing the associated risks of the product sustainability, a perspective which may allow easier integration during the product development phase. A case study to showcase such an assessment could also be a valuable investigation.

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Appendix

Type of study	References
Regional focused studies	(Dirks et al., 2015; Dressler et al., 2012; Goto et al., 2012a; Hausladen et al., 2012; Lee and Kung, 2011; Mosteiro-Romero et al., 2014; Nik et al., 2015; Pakkala et al., 2014; Wong et al., 2010)
LCA related studies	(Boulay et al., 2018; Chaudhary and Hellweg, 2014; Devika et al., 2014; Fontes et al., 2016; Galan et al., 2013; GreenDelta GmbH, 2016; Henderson et al., 2011; Hiete et al., 2011; Kounina et al., 2014; Pennington et al., 2005; Pishvaee et al., 2012; Steen, 2015)
International statistics, initiatives, and standards	(European Committee for Standardization, 2012a, 2012b; Eurostat, 2015; Global Reporting Initiative, 2014; Manfredi et al., 2012)
Generic and building related sustainability studies	(Kucukvar et al., 2014; Mateus and Bragança, 2011)

Table A.1. Studies covered for creating the sorted list of sustainability indicators

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Paper 5

Trade-off between social and environmental performance of green concrete: case of 6 countries

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Trade-off between social and environmental performance of green concrete: case of 6 countries

Abstract

Introduction

Improving the sustainability performance of construction industry is demanded which, for instance, can be seen from policy initiatives. However, improving the sustainability performance could be financially beneficial for enterprises. Through the investigation of the sustainability hotspots and impacts, concerning social and environmental, of green concrete, the study assessed the factors relevant for its performance and examined how to improve them.

Method

Hotspot analysis and impact assessments were made by social LCA and environmental LCA. Based on the reliability of the inventory data in PSILCA, six social indicators were chosen to assess the concrete from six countries. The environmental impact assessments were assessed by applying CML as the impact assessment method. The assessed concrete represented not just the variety of geographic representation but also the product designs through three different slag contents as well as the potential difference occurring from the company performance, where four classes were introduced based on the results from Monte-Carlo analysis. The related inventory of the hotspots was analyzed in three groups: steel slag; clinker; and energy.

Result

Regarding the social impacts, the majority of the hotspots were related to the steel slag inventory group. The impact assessment showed that the variation of the impacts was less dominant from the introduced company classes but the geographic representation. For social impacts, the product design with lower slag content showed better performance.

Environmental hotspots concerning GWP, ODP, and acidification each had the same inventory group as the hotspots regardless of the geographical representation. The influence of regional conditions on environmental hotspots was mostly seen through the energy sources. Regarding the impact of abiotic depletion for non-fossil fuel, the relevance of the company class was seen over the other aspects. The influence of the product design was seen as the higher the slag content, the better the environmental performance.

Discussion and conclusion

The investigation of the social and environmental hotspots of the green concrete showed the effectiveness of the supply chain management for improving both the social and environmental hotspot analysis. Although the product design may affect the environmental sustainability performance effectively, the impact assessment showed the limitation of the sustainable product design concerning the investigated social sustainability performance. In fact, trade-offs between the social and environmental performance were observed with the change in product design for all the six countries.

To handle the traded-off, the procurement policy of the steel slag and/or steel slag mixed cement from companies producing it with clean energy mix with good governance could be important to improve the sustainability performance of green concrete with high steel slag content. For forced labour related sustainability performance, supply chain management, which may manage the hotspots, could be the most effective way to improve the performance of the green concrete. For other worker-related indicators, corporate governance and management could be considered necessary to improve the categories.

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Keyword: LCA, LCT, SLCA, Building Materials, Construction Industry, alternative cement

1. Introduction

1.1. Improving sustainability performance of products for better financial performance

The construction industry is a significant sector affecting our society: economically, socially (European Comission 2012) and environmentally (European Commission, 2011; Herczeg et al., 2014; IPCC, 2014; UNEP, 2003). The fact created a societal pressure on the industry to become more sustainable. One of such can be seen as a regulatory push, including CEN/TC350 (CEN 2005) that describes how sustainable building should be assessed and achieved, and Construction Product Regulation (CPR) (European Parliament 2011) states the sustainable use of natural resources is one of the basic requirements. Furthermore, Energy Performance Directive (European Parliament 2010) requires the energy consumption of new buildings in Europe to be nearly-zero from 2020.

Meanwhile, various studies have investigated the potential benefits that companies could gain from improving the sustainability performance. For instance, the study from (Alikaj et al. 2017) showed the positive link between both the increase in the corporate social responsibility (CSR) strength and the reduction in the CSR concern, defined in Kinder Lydenburg Domini (KLD) Social Ratings Data, and the corporate financial performance. Former studies such as (Waddock and Graves 1997; Orlitzky et al. 2003) support these findings that the companies with better CSR performance were associated with the higher return on equity (ROE), return on asset (ROA) and return on sales. The study from (Harjoto and Salas 2017) highlighted the improvement of brand value with the CSR strength while the brand reputation was affected negatively by the CSR concerns. Furthermore, a white paper from RobecoSAM (RobecoSAM SI Research & Development 2014) which looked into the corporate sustainability performance from their database, which is used for Dow Jones Sustainability Index, and the financial performance measured by stock return confirmed the positive relationship. These findings imply the value of the sustainability performance improvement of companies in the construction sector not just to meet the requirement from the regulatory bodies but also for their financial benefits.

Concrete is one of the common building materials used around the globe (Petek Gursel et al. 2014; Turk et al. 2015). Meanwhile, it has its consequence on the sustainability issues of the society. For instance, the cement used in concrete is approximately responsible for 5% (IEA and WBCSD 2009) of the global greenhouse gas emission, around 10% when being CO_2 specific (Boden et al. 2016; Scrivener et al. 2016). In order to decrease the impact on the environmental sustainability, various attempts had been made. One of such is the use of steel slag as an alternative binder to cement, which is one of the green concretes (Turk et al. 2015). This study expanded the scope of sustainability by investigating not just the environmental but also social hotspots of the green concrete which uses steel slag as a cement alternative.

Life cycle assessment (LCA) is an established decision-making support tool that accounts for the environmental impact of a product or a service, and social life cycle assessment (SLCA) looks into the social dimension of those. The study took the two approaches to assess the sustainability hotspots and the impacts of the green concrete to understand how the sustainability performance could be improved. To understand the factors affecting the sustainability performance, the differences in product design, regional representation, and the company efforts in sustainability performance were considered.

2. Methodology

This section describes the methodologies applied to conduct the SLCA and LCA. Both assessments were conducted by taking the cradle-to-factory-gate system boundary (module A1-A3 according to the EN 15804 (European Committee for Standardization 2013)).

2.1. SLCA

PSILCA (GreenDelta GmbH 2016) is one of the few databases available that compiles the life cycle inventory (LCI) for social issues, which is defined in the guideline from UNEP-SETAC life cycle initiative (UNEP Setac Life Cycle Initiative 2009). The database is created based on the multi-regional input-output database, which the inventory is expressed as money flows. The database uses worker hours as the activity variables (Norris 2006), which is a necessary term that “reflect the share of a given activity associated with each unit process”(UNEP Setac Life Cycle Initiative 2009).

For each of the 42 indicators in PSILCA, a risk assessment is conducted to identify the social hotspot. The risk assessment is made by classifying each social indicator into six levels, which the criteria for the risk levels are assigned individually. The risks are used as a characterization factor to quantify the social hotspots where worker hours are multiplied by the characterization factors. These risk hours were used to identify the hotspots as well as for the impact assessment. As part of the assessment, the allocation can be made. In this study, no allocation was made. For the details of worker hours, the risk level for individual indicators and the allocation, please refer to (GreenDelta GmbH 2016).

In addition, the database contains information about the data quality of each input data and the quantified indicators. The data quality assessment was made through a pedigree matrix, based on the one from (Weidema and Wesnaes 1996) for LCA, and adapted to the social version. The data quality is assessed based on five aspects, which are the reliability of the source, completeness conformance, temporal conformance, geographical conformance, and further technical conformance. Each aspect has its own criteria for the quality level, which is scored in 1 (the best) to 5 (the worst). In the study, social indicators with low quality, containing any aspect with the worst quality level, were excluded from the assessment. Any indicators that may overlap with environmental indicators were also excluded to avoid the redundancy.

In the study, six datasets were created to represent the green concrete using steel slag for the respective countries. Those six countries were Switzerland (CH), Germany (DE), Japan (JP), Sweden (SE), Thailand (TH) and the United States of America (US). These countries were chosen to examine the influence of regional influence as well as the availability of environmental LCI datasets. Since the inventory was created based on the monetary unit, the cost data from (Andersson et al. 2018) to create the green concrete LCI dataset. The cost of the steel slag was estimated as the same as the fly ash, which was used in the green concrete in the study from (Andersson et al. 2018). In Table 1, the inventory used in PSICLA to create the green concrete dataset is shown. Three product designs regarding the slag contents were also introduced to investigate its effect on the social performance of green concrete: 33%; 70%; and 85%. The study assumed that the price ratio between the slag and the other materials are identical regardless of the region. In Table 2, the defined social inventory of the steel slag mixed concrete is shown. The cut-off criteria were applied when creating the product system of all datasets, which was set at 1E-5.

	CH	DE	JP	SE	TH	US

SLAG	Manufacture of basic metals {CH}	Basic ferrous metals {DE}	Steel scrap {JP}	Manufacture of basic metals {SE}	Iron and Steel{TH}	Iron and steel mills and ferroalloy manufacturing {US}
CEMENT AND AGGREGATES	Construction {CH}	Basic construction {DE}	Ready mixed concrete {JP}	Construction {SE}	Cement and concrete products {TH}	Ready-mix concrete manufacturing {US}

Table 1. LCI of the green concrete for SLCA

SLAG CONTENT	33%	70%	85%
STEEL SLAG	0.35 USD	0.69 USD	0.90 USD
CEMENT AND AGGREGATES	0.65 USD	0.31 USD	0.10 USD

Table 2. Social inventory of the investigated steel slag mixed concrete

2.2. LCA

For the environmental LCA, ecoinvent v3.3 (Wernet et al. 2016) was used as the source of LCI datasets. In the database, the technical representation of the datasets was better compared to that of the PSILCA, which has better geographical representation. Since the majority of the environmental impact of a concrete is due to the use of cement (Turk et al. 2015), the investigation on the environmental hotspots was made through the different mixes between the cement and the steel slag. The investigated slag mixes were in the following three segments: 25-70%; 66-80%; and 70-100%. The available geographic representation of the LCI of the cement mixed with steel slag was Switzerland (CH), Europe without Switzerland (EU), the United States of America (US), and rest of the world (RoW). The study took the recycled content approach as the allocation method.

The life cycle impact assessment (LCIA) was made by using CML-IA baseline (Universiteit Leiden 2015) as the impact assessment methods in SimaPro v8.3 (PRé Consultants 2017). The assessed impact categories were the following: Abiotic resource depletion for non-fossil fuels; Abiotic resource depletion for fossil fuels; global warming potential (GWP); ozone depletion potential (ODP); human toxicity; freshwater toxicity; marine water toxicity; terrestrial toxicity; photochemical ozone formation (PO); acidification and eutrophication.

2.3. Analysis of hotspots

To analyze the hotspots to support the decision making of the manufacturers, three groups were introduced: clinker related inventories; slag related inventories; and energy-related inventories. These groups were applied to assess both the social and environmental hotspots.

2.4. Impact assessment

For the quantitative assessment of the social and environmental impacts of the investigated products, all the indicators were normalized with the worst performing dataset within the respective indicators.

2.5. Company classes

In order to investigate the potential relevance of the manufacturers' variation in efforts made for the sustainability performance, four classes (Class A to D) were introduced. As the basis for the classification, the results from Monte-Carlo analysis of each dataset was used to represent the class. As the top-tier performing companies as Class A, the results representing the 2.5 percentile of the Monte-Carlo analysis was used. The Class B companies, which represents the majority of the companies, the median from the analysis was used to represent the class. For Class C, the mean value was used as average companies. To represent the Class D, the laggards, the result of 97.5 percentile was used.

3. Result

3.1. Social hotspots

Among the 42 assessed indicators, the result from the data quality assessment showed the reliable social indicators of the six datasets as the followings: Public spending on education (Education); Fair salary; Goods produced by the forced labor; Health expenditure; Trafficking in persons (Trafficking); and Weekly hours of work per employee (Worker hours). In Table 2, the relevant stakeholder for each indicator is shown.

STAKEHOLDER	INDICATORS
Society	Education; Health expenditure;
Worker	Fair salary; Goods produced by the forced labor; Trafficking in persons; Worker hours

Table 3. Relevant stakeholder for each social indicator

In Table 3, the summary of the identified social hotspots of the investigated datasets is shown. In the table, the process with the highest risk is shown as the hotspots for each indicator. The hotspots identified abroad are shown in the bold italic font in the table.

When assessing the related inventory groups, as described in section 2.3, all of the hotspots of the assessed countries were classified as slag related inventories, except for the “Goods produced by forced labour” in Thai. Thus, the identified hotspots will remain related to steel slag even when increasing the share of the slags in the binder from 33% beyond, which was assessed in the environmental LCA. Another common aspect among the identified hotspots seen in the indicator “Goods produced by forced labour” was that products from China were the hotspot for all the countries. The fact indicates the origin of the steel slag has a role to play regarding the indicator.

The hotspots for other indicators observed some variety depending on the regions. For instance, the hotspots for the case in Thailand and in the US were mostly identified in the domestic steel industry, while the hotspots of the other four countries were observed abroad, mostly in China or India. The fact suggests that the universal approach to treating the social hotspots does not exist. Thus, there is a need to conduct a region-specific investigation to elaborate the most appropriate measure to address the social hotspots.

	STEEL SLAG CONCRETE 33% {CH}	STEEL SLAG CONCRETE 33% {DE}	STEEL SLAG CONCRETE 33% {JP}	STEEL SLAG CONCRETE 33% {SE}	STEEL SLAG CONCRETE 33% {TH}	STEEL SLAG CONCRETE 33% {US}
EDUCATION	***Manufacturing {IN}***	Basic ferrous metals {DE}	***Construction {CN}***	***Construction {CN}***	Iron and Steel {TH}	Iron and steel mills and ferroalloy manufacturing {US}
FAIR SALARY	Manufacture of basic metals {CH}	***Construction {CN}***	***Construction {CN}***	Manufacture of basic metals {SE}	Iron and Steel {TH}	Iron and steel mills and ferroalloy manufacturing {US}
GOODS PRODUCED BY FORCED LABOUR	***Metal Products {CN}***	***Metal Products {CN}***	***Metal Products {CN}***	***Metal Products {CN}***	***Crop cultivation{CN}***	***Metal Products {CN}***
HEALTH EXPENDITURE	***Manufacturing {IN}***	***Construction {IN}***	***Construction {IN}***	***Construction {IN}***	Iron and Steel {TH}	Iron and steel mills and ferroalloy manufacturing {US}

TRAFFICKING	***Manufacturing {IN}***	***Construction {CN}***	***Engines and Turbines {TH}***	***Machinery and equipment n.e.c. {RU}***	Iron and Steel {TH}	Iron and steel mills and ferroalloy manufacturing {US}
WORKER HOURS	Manufacture of basic metals {CH}	Basic ferrous metals {DE}	***Construction {CN}***	Manufacture of basic metals {SE}	Iron and Steel {TH}	Iron and steel mills and ferroalloy manufacturing {US}

Table 4. The identified social hotspots of the selected social indicators for the investigated inventories

3.2. Characteristics of the social impacts

In Figure 1, the distribution of the normalized social impact assessment results in risk hours by company classes is shown. The normalization is made by taking the maximum value of the respective categories as the reference.

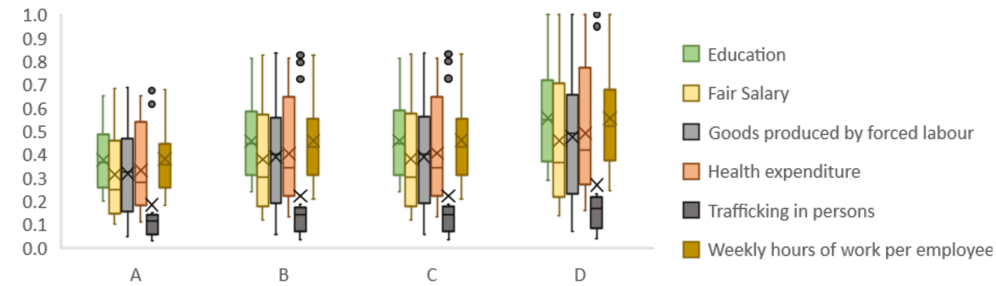

Figure 1. Distribution of the SLCA results

The result showed that the company classes have an influence on the social performance of the investigated product datasets. However, the significance may be limited since most part of each box plots overlaps with each other for all the classes. Thus, the influence of other aspects may be more significant over the company class regarding the social performance of the steel slag mixed cement.

In order to investigate the influence of other aspects on the social sustainability performance of the green concrete, the results of the normalized social impact assessments for each investigated dataset is shown in Figure 2.

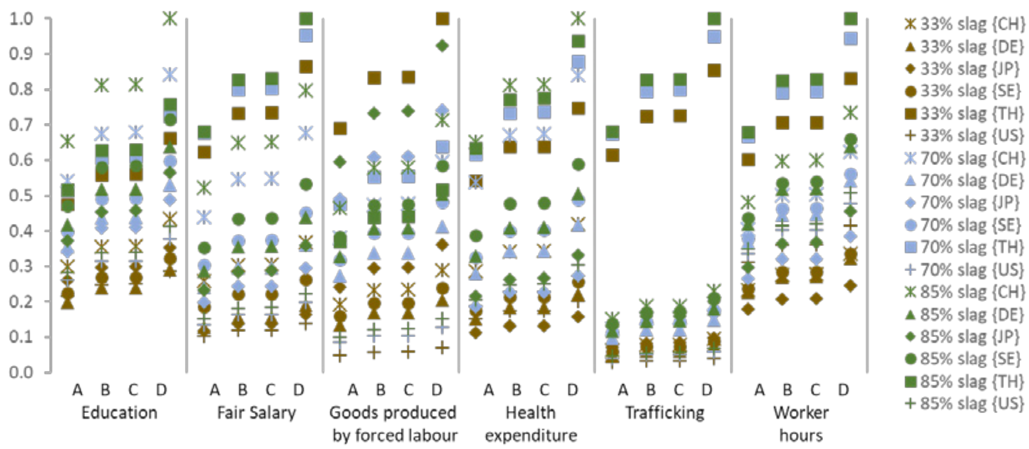

Figure 2. Normalized life cycle social impact in risk hours of green concretes. The shape represents the geographic representation and the color represents the slag content of the green concrete

As an overall characteristic regarding the geographic representation, Thai and Swiss products performed worse for most of the considered indicators. Furthermore, the influence of region was clearly seen for a fair salary, trafficking and worker hours, where the Thai datasets were the worst performing. Regarding the best performer, the products from the US was the best in fair salary, goods produced by forced labour, and trafficking. Concerning the influence of product design, the social performance was worse with the higher steel slag content regardless of the regions, all but the goods produced by the forced labour of the Thai dataset.

3.3. Environmental hotspots

The identified hotspots from the conducted LCIA, given in Table 4, shows that the hotspots of GWP, ODP, and acidification have the same cause indicator groups for each of the slag content independent from the geographical representation. For ODP, the hotspots are related to the energy source of heat and/or electricity being used, which could be regional relevant conditions. For GWP and acidification, either clinker or grounded slag was the hotspot depending on the ratio of the mixed slag.

When analyzing the hotspots in the three groups of inventories as described in section 2.3, the relevant groups differed depending on the ratio of the slag and the geographic representation. For the Swiss green concrete, clinker related inventories were the hotspots regardless of the slag mixture ratio for freshwater toxicity, marine water toxicity, and eutrophication. Thus, complete replacement of the clinker could be an ideal strategy to reduce the water-related impact categories in case of Switzerland. For GWP, abiotic depletion of fossil fuels, human toxicity, and acidification, grounded slag was the hotspots when the mixture ratio of the slag was over 80%.

The result of the hotspot analysis of the EU dataset showed that energy-related inventories were the hotspots of ODP, human toxicity, freshwater toxicity, marine water toxicity and eutrophication, regardless of the slag mixture. Meanwhile, clinker related inventories were the hotspots of all slag mixture datasets for abiotic depletion of fossil fuels and terrestrial toxicity, showing the difference from the Swiss case.

When looking at the RoW dataset, clinker were the hotspots for abiotic depletion of fossil fuels and terrestrial toxicity for all slag mixture, while energy related inventory was the hotspot for ODP. Grounded slag related inventories showed up as hotspots for human toxicity and PO when the steel slag mixture was beyond 65% and became also the hotspots for GWP, PO, and acidification when the mixture was over 80%.

In the case in the US, two datasets were investigated due to the difference in the slag mixture classification. The hotspots of GWP, PO, and acidification differed between the two slag mixture ratio, where clinker were the hotspots for the lower content while the grounded slag was for the higher one. Energy related inventories were the hotspots of ODP, human toxicity, freshwater toxicity, marine water toxicity and eutrophication regardless of the mixture.

SLAG CONTENT	REGION	CLINKER RELATED	SLAG RELATED	ENERGY RELATED
36-65%	CH	Abiotic fos, GWP, Hum tox, Freshwater tox, Marine tox, Terrestrial tox, PO, Acidification, Eutrophication	0	ODP
	EU	Abiotic fos, GWP, Terrestrial tox, PO, Acidification	0	ODP, Hum tox, Freshwater tox, Marine tox, Eutrophication
	RoW	Abiotic fos, GWP, Hum tox, Freshwater tox, Marine tox, Terrestrial tox, PO, Acidification, Eutrophication	0	ODP

20-70%	US	Abiotic fos, GWP, Terrestrial tox, PO, Acidification	0	ODP, Hum tox, Freshwater tox, Marine tox, Eutrophication
66-80%	CH	Abiotic fos, GWP, Hum tox, Freshwater tox, Marine tox, Terrestrial tox, PO, Acidification, Eutrophication	0	ODP
	EU	Abiotic fos, GWP, Terrestrial tox, Acidification	PO	ODP, Hum tox, Freshwater tox, Marine tox, Eutrophication
	RoW	Abiotic fos, GWP, Freshwater tox, Marine tox, Terrestrial tox, Acidification	Hum tox, PO	ODP, Eutrophication
81-95%	CH	Freshwater tox, Marine tox, Eutrophication	Abiotic fos, GWP, Hum tox, PO, Acidification	ODP, Terrestrial tox
	EU	Abiotic fos, Terrestrial tox	GWP, PO, Acidification	ODP, Hum tox, Freshwater tox, Marine tox, Eutrophication
	RoW	Abiotic fos, Terrestrial tox	GWP, Hum tox, PO, Acidification	ODP, Freshwater tox, Marine tox, Eutrophication
70-100%	US	Abiotic fos, Terrestrial tox	GWP, PO, Acidification	ODP, Hum tox, Freshwater tox, Marine tox, Eutrophication

Table 5. Related inventories of the hotspots for respective impact categories and inventories

3.4. Characteristics of the environmental impacts

For examining the influence of the company classes for the environmental performance of the green concrete, the distribution of the impact assessment results for each indicator by the classes is given in Figure 3 and Figure 4.

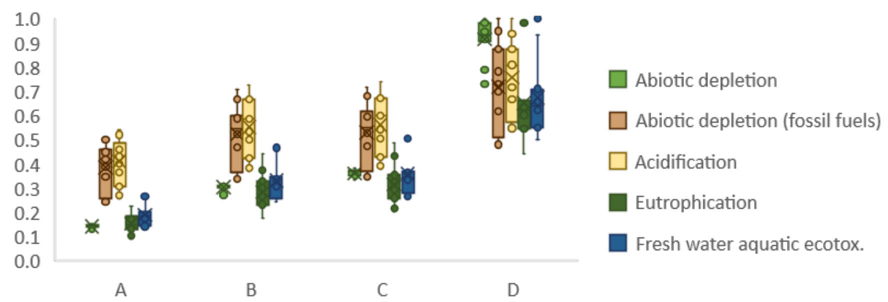

Figure 3. Distribution of the LCIA results by company classes (Abiotic depletion non-fossil and fossil, Acidification, Eutrophication and Freshwater tox)

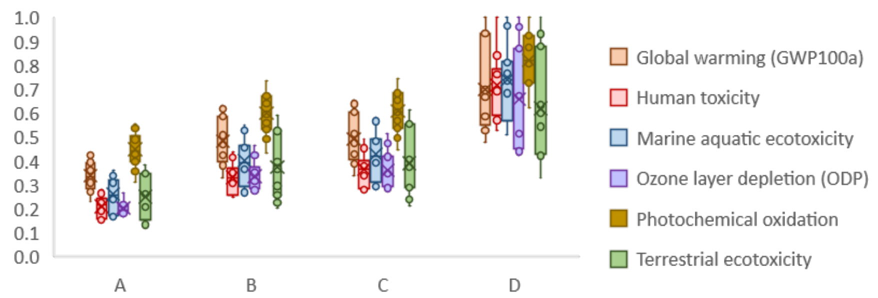

Figure 4. Distribution of the LCIA results by company classes (GWP, Human tox, Marine tox, ODP, PO, Terrestrial tox)

When looking at the difference occurring between the company classes, the impact of abiotic depletion caused by class D companies was substantially worse than the rest of the classes. In addition, the distribution within each class was narrow compared to other impact categories. The fact implies the importance of the company class over product details and regions regarding the impacts on abiotic depletion for non-fossil resources for steel slag mixed concrete.

For other impact categories, the difference between the company classes was not as significant. Moreover, the range of the box plots was rather wide which implied the importance of the product design and the regions concerning the performance of the respective indicators.

In Figure 5, the results of the LCIA of each dataset that investigated the relevance of the product design and the region are shown.

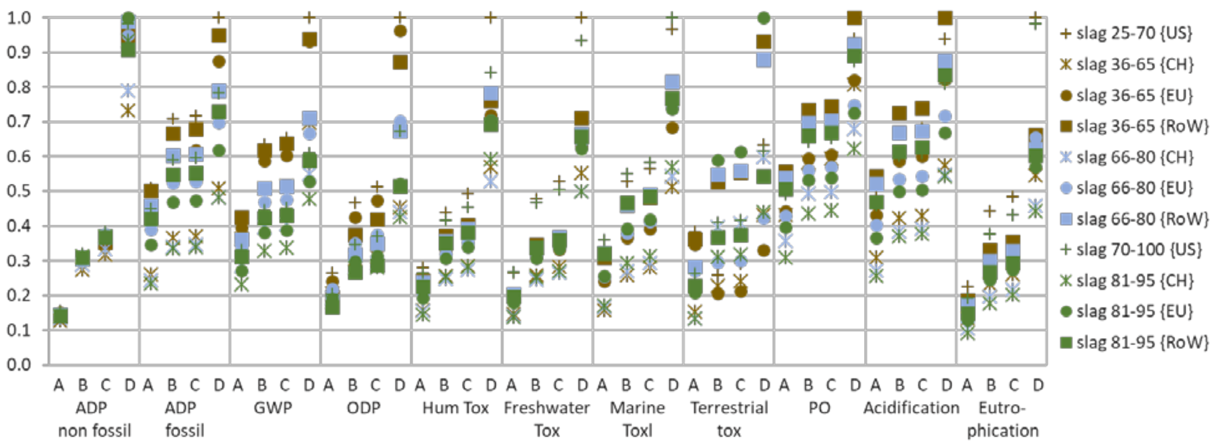

Figure 5. Normalized life cycle environmental impact of green concretes. The shape represents the geographic representation and the color represents the slag content of the green concrete

When looking into details of each company class, the difference of products from companies in class A was rather small while the ones from class D had a large variation for most of the indicators. The fact suggests the importance of other factors, the product design, and the geographical representation, for the environmental performance of green concrete in class D.

Regarding the influence of the geographic representation, general characteristics were observed as Swiss data being the best performing in most of the indicators, where US or Thai data were the worst.

The influence of the product design was seen which the concrete with higher slag content was better performing for the majority of the indicators and regions. The exceptions were RoW datasets for ADP non-fossil, Human toxicity, freshwater toxicity, and marine water toxicity where the influence was marginal.

4. Discussion

4.1. Treatment of the social hotspots

When investigating the social indicators by its related stakeholders, the society related indicators would be difficult to improve through the effort from the manufacturers. For instance, public expenditure on education would be a topic that manufacturers may not have a huge influence on. In order to treat the hotspots related to society as manufacturers, adapting the supply chain could be an approach to take. The supply chain management could also be an effective measure for the worker related indicators, especially concerning the results on the forced labor related indicators: goods produced by forced labour; and trafficking in persons.

On the other hand, working hours and salary level could mostly be handled by the manufacturer's effort, since most of the hotspots were identified within the domestic industry. The hotspots in these indicators could be one of the low-hanging-fruits to improve the social sustainability performance, although the margin of improvement from company efforts may be limited as can be implied by the results in section 3.2.

4.2. Treatment of the environmental hotspots

For environmental issues, the influence of the region on the identified hotspots was seen through the consumed energy. For instance, the hotspots of ODP in all slag mixture ratio was identified as energy related inventories with diversity in its source. The number of hotspots related to energy increased with the higher slag mixture showing certain variety regarding the concerned indicators depending on the region. Since the investigated countries are located on various continents around the globe, the energy system could be considered as a universal key performance indicator (KPI) for improving the environmental performance of the steel slag mixed cement, especially for the higher the slag content is. The energy mix of the system is typically different depending on the region, regarding its energy sources and the mix. As was indicated in (Kono et al. 2018), this regional condition could be a useful proxy information to be considered during the early product development phase when considering the location for manufacturing or the origin of the material.

Thus, theoretically speaking, procuring the steel slag mixed cement from regions with energy system with better sustainability performance could improve the environmental performance. In fact, the import of the steel slag is already taking place in the UK, implying the cost-effectiveness of transporting long distance (Alberici et al. 2017). This implies the potential of sourcing the steel slag mixed cement from a location with clean energy system and improving the worker related social indicators may allow improving not only one but the three pillars of sustainability performance: economic; social; and environmental.

4.3. Comparison of the treatment of the social and environmental hotspots

When analyzing the characteristics of the social and environmental hotspots, several issues from both pillars could be solved by careful determination of the supply chain of the consumed material, regardless of the geographical representation of the green concrete. The fact suggests the supply chain management could be an effective measure to improve the sustainability performance of every green concrete with steel slag.

The influence of the regional representativeness was seen on the identified hotspots from both pillars. For instance, the social hotspots of trafficking varied from the identified industries to the regions. The cause of environmental hotspots of the human toxicity also changed depending on the geographic representation when the mixture of the steel slag was 66% to 80%. Thus, the importance of taking the regional aspects into consideration revealed important in order not to mistreat some of the sustainability hotspots.

In Table 6, the characteristics of each indicator are shown, either being regional or universal regarding its cause.

	SOCIAL	**ENVIRONMENTAL**		
SLAG CONTENT	25-100%	25-70%	66-80%	81-100%
REGIONAL	All others	Human tox, freshwater tox, marine tox, eutrophication	Human tox, freshwater tox, marine tox, PO, eutrophication	All others
UNIVERSAL	Goods produced by forced labour	All others	All others	Abiotic non-fossil, GWP, ODP, PO, acidification

Table 6. The characteristics of the sustainability hotspots of each indicator

4.4. Trade-off between social and environmental performance

From the impact assessments, the tendency of the trade-off between the social and environmental performance and the product design was observed. In Figure 6, the illustration of the social and environmental performance of the green concrete with different steel slag content in the six investigated countries are shown.

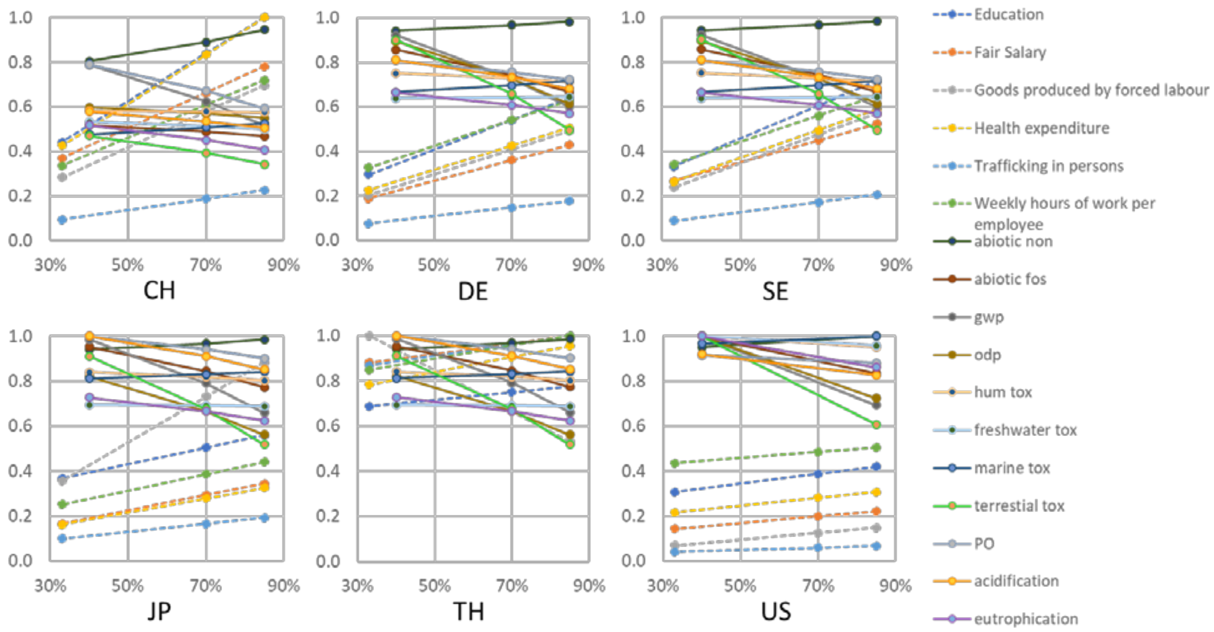

Figure 6. Normalized social and environmental performance of green concretes with different slag content in six countries. For the environmental performance of DE and SE, the LCIA results of EU is shown. For the environmental performance of JP and TH, the LCIA results of RoW is shown.

As can be seen from the figure, the trade-off between the majority of social and environmental performance occurs with the increase of slag content in all the investigated regions. The result shows the limitation of the effectiveness of pursuing the sustainable design of the products, one of the solutions for improving the environmental performance, for improving the social sustainability performance of green concretes. The findings from the hotspot analysis support the trade-off as the majority of the social hotspots were steel slag related. As was also seen from the hotspot analysis, however, most of the investigated social indicators were capable to improve via supply chain management. Thus, it is vital to take social aspects into consideration for improving the sustainability performance of green concrete, not just by its product designs.

4.5. Limitation

In the study, the difference in the level of details between the social and environmental LCI datasets is a limitation to be considered. The representativeness of the data is a challenging issue for the social LCI in PSILCA due to the availability of the data. For instance, most of the construction-related product inventories are represented as “Construction” as a whole. This means the social hotspots of the concrete products and the thermal insulation materials would appear as to be the same, due to the source of inventory data being the input-output database. Therefore, the identified hotspots would require a further scrutiny for the better representativeness when, for instance, quantifying the social impacts.

While the social LCI datasets have a higher level of details regarding the geographic representation thanks to its basis on the input-output database, the environmental LCI datasets in ecoinvent have better representation on the technical specifics. However, since the influence of the energy system were identified as hotspots for a few indicators, higher resolution of the geographical representation may allow improved accuracy of the environmental impact assessment and hotspot analysis.

5. Conclusion

This study investigated the social and environmental hotspots and impacts of green concrete in six countries.

- Regarding the of social hotspots, the assessment showed that the treatment of the employment related indicators may be one of the low-hanging-fruits for improving the social sustainability performance of the material.
- The effectiveness of the supply chain management was seen for improving both the social and environmental hotspot analysis.
- The limitation of improving the sustainability performance of green concrete through product designing is evident through the trade-off between the social and environmental performance.
- Although the one-size-fits-for-all solution may not apply for all the investigated sustainability indicators, the procurement of the steel slag and/or the slag mixed cement produced in countries with good employment condition and production in clean energy mix may improve ranges of the social and environmental performance of green concrete.

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