Reducing the carbon footprint through reusing building materials

A case study of the Framtiden Byggutveckling residential building project Selma 2 Block 10

Master's thesis in Industrial Ecology

ELIN ISRAELSSON

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
DIVISION OF BUILDING TECHNOLOGY

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
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MASTER’S THESIS ACEX30

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Examensarbete ACEX30
Institutionen för arkitektur och samhällsbyggnadsteknik
Chalmers tekniska högskola, 2022

Department of Architecture and Civil Engineering
Division of Building Technology
Sustainable building
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Department of Architecture and Civil Engineering

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ABSTRACT

The world is facing large scale climate and environmental challenges where the building sector accounts for a large share of the environmental impacts caused by material extraction, production, and use. In spite the fact that the built environment has major climate impact, a growing society demands an even more extensive building industry which in turn requires a radical development of sustainable building processes. Reuse of building materials can contribute to lowering the carbon footprints from buildings by using products several times in a closed loop. This thesis explores the possibilities and climate benefits from reusing building materials. Furthermore, it identifies possible trade-offs and challenges connected to the practice.

The research process consists of a literature review and a case study of the residential building project Selma 2 Block 10. The case study includes interviews on reusable materials in Selma 2 Block 10 and LCA calculations comparing the carbon footprint from a reference case with the carbon footprints from three types of reuse cases.

The findings suggest that there are possibilities to reuse building materials but also that there are several trade-offs and challenges connected to the practice, such as traditions, quality, and logistics. Moreover, the results from the LCA calculations in the case study suggest that the carbon footprint of Selma 2 Block 10 can be reduced by 76%.

Key words: Reuse of building materials, LCA, environmental assessment, climate impact, carbon footprint, residential, sustainable architecture

Reducering av Koldioxidavtryck Genom Återbrukande av Byggmaterial

En Fallstudie av Framtiden Byggutvecklings Bostadsbyggnadsprojekt Selma 2 Block 10

Examensarbete inom mastersprogrammet Industriell Ekologi

ELIN ISRAELSSON

Institutionen för arkitektur och samhällsbyggnadsteknik
Avdelningen för Byggnadsteknologi
Hållbart byggande
Chalmers tekniska högskola

SAMMANFATTNING

Världen står inför stora klimat- och miljöutmaningar där byggsektorn står för en stor del av miljöpåverkan från utvinning, produktion och användning av material. Trots att den byggda miljön har stor klimatpåverkan kräver ett växande samhälle en ännu mer omfattande byggindustri som i sin tur kräver en radikal utveckling av hållbara byggprocesser. Återbruk av byggmaterial kan bidra till att minska koldioxidavtrycken från byggnader genom att återanvända produkter gång på gång i cirkulära kretslopp. Detta examensarbete undersöker möjligheterna och klimatfördelarna med att återbruka byggmaterial. Dessutom identifierar det möjliga kompromisser och utmaningar kopplade till praktiken.

Processen består av en litteraturstudie och en fallstudie av bostadsprojektet Selma 2 Block 10. Fallstudien består av intervjuer om återbrukbara material i Selma 2 Block 10 och LCA-beräkningar som jämför koldioxidavtrycket från ett referensfall med koldioxidavtrycken från tre typer av återbruksfall.

Resultaten tyder på att det finns möjligheter att återbruka byggmaterial men också att det finns flera kompromisser och utmaningar kopplade till praktiken så som traditioner, kvalitet och logistik. Dessutom tyder resultaten från LCA-beräkningarna i fallstudien på att koldioxidavtrycket från Selma 2 Block 10 kan minskas med 76%.

Nyckelord: Återbruk av byggmaterial, LCA, miljöpåverkan, klimatpåverkan, koldioxidavtryck, bostäder, hållbar arkitektur

CONTENTS

ABSTRACT I

SAMMANFATTNING II

CONTENTS III

PREFACE V

ABBREVIATIONS AND DEFINITIONS VI

FIGURES AND TABLES VII

1 INTRODUCTION 1

- 1.1 Background 1
- 1.2 Aim 1
- 1.3 Research questions 2
- 1.4 Limitations 2
- 1.5 Audience 2
- 1.6 Report structure 2

2 THEORETHICAL BACKGROUND 3

- 2.1 Sustainability 3
- 2.2 Environmental systems analysis tools 5
- 2.3 Circular economy 5
- 2.4 Sustainability in the built environment 6
- 2.5 The residential building project Selma 2 Block 10 12

3 METHODOLOGY 15

- 3.1 Literature review 15
- 3.2 LCA of the case study Selma 2 Block 10 16

4 RESULTS: LITERATURE REVIEW 19

- 4.1 Building materials and parts with the highest climate impact 19
- 4.2 Degree of reusability and recyclability 20
- 4.3 Trade-offs and challenges 22
- 4.4 Reference values for buildings in Sweden 24

5 RESULTS: LCA OF THE CASE STUDY SELMA 2 BLOCK 10 27

- 5.1 Goal of the case study 27
- 5.2 Scope of the case study 27
- 5.3 Expert interviews regarding reusability of the building materials in Selma 2 Block 10 31
- 5.4 Inventory analysis of the case study 33
- 5.5 Climate impact assessment of the case study 40
- 5.6 Interpretation of the case study 45

6 ANALYSIS AND DISCUSSION 51

- 6.1 Discussion of the results from the literature review 51

6.2 Discussion of the results from the case study 52
6.3 Discussion of the methods and applied assumptions...53
6.4 Limitations and consequences of chosen methods 55
6.5 Future studies 56
7 CONCLUSIONS...58
REFERENCES..61
APPENDIX I – Inventory: pre-existing data on Selma 2 Block 10...65
APPENDIX II – Inventory: transportation data..68
APPENDIX III – Inventory: ecoinvent input data..70
APPENDIX IV – Climate impact assessment results...73
APPENDIX V – Modelling in openLCA 74

PREFACE

This report is the result of a Master´s thesis of 30 ECTS in the Master´s programme of Industrial Ecology. The work has been conducted at the department of Architecture and Civil engineering, division of Building Technology, at Chalmers University of Technology, Sweden with external supervision from Framtiden Byggutveckling, Gothenburg, Sweden. The work has been carried out from January to June 2022 with Cecilia Johannison and Teres Stenholm at Framtiden Byggutveckling as supervisors and Professor Holger Wallbaum as examiner.

I would thereby like to thank Cecilia Johannison and Teres Stenholm at Framtiden Byggutveckling for valuable support, knowledge and rewarding discussions. I would also like to thank Anna Wöhler for helpful guidance in openLCA. I would further like to send my gratitude to Holger Wallbaum for valuable feedback and support throughout the entire process.

Lastly, I would like to bring a special thanks to my friends and family. Thank you for your endless support and encouragement throughout my educational years at Chalmers University of Technology.

Gothenburg, June 2022
Elin Israelsson

ABBREVIATIONS AND DEFINITIONS

BOA	Building area for residential use
BTA	Building area including external walls
Boverket	The Swedish National Board of Housing, Building and Planning
CO_2 eq.	CO_2 equivalents
Cradle to gate	Resource extraction to finished product A1-A3
Cradle to site	Resource extraction to transport to site A1-A4
Cradle to handover	Resource extraction to construction and installation A1-A5
Cradle to grave	Resource extraction to end of life A1-C4
ecoinvent	LCA database
EPD	Environmental product declaration
Functional unit	Measure of function. Also provides reference flow in LCA
GHG	Greenhouse Gases
GWP	Global warming potential
IVL	Swedish Environmental Research Institute
LCA	Life cycle assessment
LCIA	Life cycle impact assessment. The third step in the LCA procedure
LCC	Life cycle cost
openLCA	LCA calculation software

Life cycle phases for buildings

A1-A3	Production
A4	Transportation
A5	Construction
B1-B7	Use
C1-C4	End of life
D	Benefits and loads

FIGURES AND TABLES

Figures and tables stated without source are made by the author of the thesis.

Figure 1 Sustainable development goals from Agenda 2030. 3

Figure 2 The lighthouse model. Adapted from Holmberg & Larsson (2018). 4

Figure 3 The triangular approach of sustainability. Adopted from Meadows (1998). 5

Figure 4 Circular economy phases. Adopted from Ghosh (2020). 6

Figure 5 Emissions and waste from the Swedish building and real estate sector in 2018 and 2019. Adopted from Boverket (2019e). 7

Figure 6 Stages for LCA in the building industry. Adopted from SIS (2011). 9

Figure 7 Example of life cycle assessment results for a residential building. Adapted from Boverket (2021f). 9

Figure 8 A circular building- and deconstruction process. Adapted from Göteborgs Stad (2020). ..11

Figure 9 Site plan of Litteraturgatan. Provided by Framtiden Byggutveckling (n.d.). 12

Figure 10 Preliminary plan of Selma 2 Block 10. Provided by Framtiden Byggutveckling (n.d.). ..13

Figure 11 The methods of conducting the thesis. 15

Figure 12 The LCA procedure. Adapted from SIS (2006). 16

Figure 13 Example of stepwise aggregation of information in LCA. Adapted from Baumann & Tillman (2004). 18

Figure 14 Building materials with the highest climate impact for three different types of buildings analysed by Malmqvist et al. (2021). 25

Figure 15 Building parts with the highest climate impact for the residential buildings, offices and small houses analysed in the research report by Malmqvist et al. (2021). 25

Figure 16 Climate impact in kg CO_2 eq./m^2 BTA for three different types of buildings analysed by Malmqvist et al. (2021). The climate impact considers phases A1-A5. 26

Figure 17 Flowchart of scenario 1 and 2 illustrating the systems to be studied. 28

Figure 18 Flowchart of scenario 3 and 4 illustrating the systems to be studied. 29

Figure 19 LCA stages included in the case study. 30

Figure 20 Total impact from Selma 2 Block 10 for the four different scenarios presented in kg CO_2 eq./m^2 BTA. 41

Figure 21 The relative results of the total impact from Selma 2 Block 10 for scenario 1, 2, 3 and 4. 41

Figure 22 Total impact from the foundation for the four different scenarios presented in kg CO_2 eq./m^2 BTA to the left and the relative results from the foundation for scenario 1, 2, 3 and 4 to the right. 42

Figure 23 Total impact from the frame for the four different scenarios presented in kg CO_2 eq./m^2 BTA to the left and the relative results from the frame for scenario 1, 2, 3 and 4 to the right. 42

Figure 24 Total impact from the roof for the four different scenarios presented in kg CO_2 eq./m^2 BTA to the left and the relative results from the roof for scenario 1, 2, 3 and 4 to the right. 43

Figure 25 Total impact from the facade for the four different scenarios presented in kg CO_2 eq./m^2 BTA to the left and the relative results from the facade for scenario 1, 2, 3 and 4 to the right. 43

Figure 26 Total impact from the windows and doors for the four different scenarios presented in kg CO_2 eq./m^2 BTA to the left and the relative results from the windows and doors for scenario 1, 2, 3 and 4 to the right. 44

Figure 27 Total impact from the inner walls for the four different scenarios presented in kg CO_2 eq./m^2 BTA to the left and the relative results from the windows and doors for scenario 1, 2, 3 and 4 to the right. 44

Figure 28 Total impact from Selma 2 Block 10 for the four different scenarios presented in kg CO_2 eq./m^2 BTA. S1, S2, S3 and S4 represent the original results while (S1), (S2), (S3) and (S4) represent the results from the sensitivity analysis. 46

Figure 29 The relative results of the total impact from Selma 2 Block 10 for scenario 1, 2, 3 and 4. S1, S2, S3 and S4 represent the original results while (S1), (S2), (S3) and (S4) represent the results from the sensitivity analysis. 47

Figure 30 The total impact and relative results of the total impact from Selma 2 Block 10 for the different building parts. S1, S2, S3 and S4 represent the original results while (S1), (S2), (S3) and (S4) represent the results from the sensitivity analysis. 48

Figure 31 Comparison of climate impact in kg CO_2 eq./m^2 BTA for three different types of buildings analysed by Malmqvist et al. (2021) and Selma 2 Block 10. The climate impact considers phases A1-A5 for the residential buildings, office buildings and small houses 49

Figure 32 Climate impact in percentage from the different building parts for the residential buildings analysed in the research report by Malmqvist et al. (2021) and for Selma 2 Block 10 scenario 1. 50

Figure 33 Example of a modelled product system in openLCA. 74

Table 1 Description of Selma 2 Block 10 (Framtiden Byggutveckling, personal communication, April 29, 2022). 13

Table 2 Included building parts and materials based on pre-existing calculations on the building project. 14

Table 3 Embodied energy for 23 commonly used building materials in the Netherlands. Adopted from (Koezjakov et al., 2018). 19

Table 4 Answers from the interviewees on what building materials in Selma 2 Block 10 that can be reused from other deconstructed buildings (personal communication, May 2, 2022). 32

Table 5 Building materials included in the foundation and the chosen process from the database ecoinvent as well as the location. 33

Table 6 Explanation of building materials in the foundation that are modelled as reused in openLCA for scenario 1, 2, 3 and 4. 34

Table 7 Building materials included in the frame and the chosen process from the database ecoinvent as well as the location. 35

Table 8 Explanation of building materials in the frame that are modelled as reused in openLCA for scenario 1, 2, 3 and 4. 35

Table 9 Building materials included in the roof and the chosen process from the database ecoinvent as well as the location. 36

Table 10 Explanation of building materials in the roof that are modelled as reused in openLCA for scenario 1, 2, 3 and 4. 37

Table 11 Building materials included in the facade and the chosen process from the database ecoinvent as well as the location. 37

Table 12 Explanation of building materials in the facade that are modelled as reused in openLCA for scenario 1, 2, 3 and 4. 38

Table 13 Building materials included in the windows and doors and the chosen process from the database ecoinvent as well as the location. 39

Table 14 Explanation of building materials in the windows and doors that are modelled as reused in openLCA for scenario 1, 2, 3 and 4 39

Table 15 Building materials included in the inner walls and the chosen process from the database ecoinvent as well as the location. 40

Table 16 Explanation of building materials in the inner walls that are modelled as reused in openLCA for scenario 1, 2, 3 and 4. 40

Table 17 Summary of the percentage reduction of CO_2 eq. emissions for both the total impact from Selma 2 Block 10 and the different building parts included in the case study. 45

Table 18 Changed inputs of transportation distances for the sensitivity analysis. 46

Table 19 Overview of the reduction in carbon footprint for both the total impact from Selma 2 Block 10 and the different building parts included in the case study. 60

Table 20 Materials and quantities preliminary set in Selma 2 Block 10 used as the basis for the LCA calculations 65

Table 21 Selection of transportation data from Boverkets klimatdatabas, retrieved (2022). 68

Table 22 Selection of transportation data from the EPD library (International EPD system), retrieved (2022). 69

Table 23 Input data explaining the chosen processes, quantities, transportation types and distances. 70

Table 24 Summarized results from openLCA in kg CO_2 eq. and kg CO_2 eq./m^2 BTA for the four different scenarios. 73

1 INTRODUCTION

This section presents the background, aim, research questions, limitations, targeted audience, and overall structure of the thesis.

1.1 Background

Research and scientific reports continue to confirm that we are in a climate crisis (Brady et al., 2021). Human activities are stressing the natural systems on Earth, resulting in climate change and extreme weather. The world is facing large scale climate and environmental challenges that up until today mainly have been addressed by focusing on energy applications such as heating, electricity and transportation (Göteborgs Stad, 2021a). Although an efficient and low carbon energy use is important, it is not the single and final solution. The energy sector is merely responsible for 55% of the global emissions. The remaining 45% comes from materials and products, material extraction, production and land use. The building sector accounts for a large share of the environmental impacts caused by material extraction, production, and use. In Sweden, the building sector entails 20% of the greenhouse gas emissions from consumption, mainly caused by the production of building materials and the energy consumptions in the buildings. Furthermore, the sector generates large amount of both waste and hazardous waste. In 2018, the building sector in Sweden generated 12 400 000 tons of waste which is equal to 1/3 of the total waste generated in the country that year. All the same, the reuse of building materials is today imperfect with only around 5% of the waste being recycled in a high-quality way.

In spite the fact that the built environment has a major impact on the environment, a growing society demands new buildings and an even more extensive building industry (Göteborgs Stad, 2021a). Within the coming 40 years, 230 billion square meters of new buildings will be constructed in the world (Brady et al., 2021). In perspective, that is the size of Paris every week. This growth requires a radical development of sustainable building processes (Göteborgs Stad, 2021a).

Pilot studies provide opportunities to evaluate and exemplify new methods and strategies (Hughes et al., 2018). They reduce the risk of new approaches by working in a smaller scale and have been studied in everything from more sustainable transportation models to air pollution management. In 2021, Framtiden Byggutveckling (FBU) started to develop a climate pilot on the building project Selma 2 block 10 located at Litteraturgatan in Gothenburg. The goal with the climate pilot was and is to investigate the possibility to reduce carbon dioxide emissions with a minimum of 50%, from a life cycle perspective on the entire building project. This thesis report intends to contribute to this climate pilot by investigating the impact from reuse of building materials in the project.

1.2 Aim

The aim of the thesis is to investigate the possibilities and climate benefits of reusing building materials, but also to identify possible trade-offs and challenges connected to the practice. The investigation will be performed through a literature review and a case study of the residential building project Selma 2 Block 10 located in Gothenburg, Sweden. The results aim to guide the entrepreneurs within the project towards informed decisions related to material choices that will contribute to the overall goal of the building project: to reduce the CO_2-equivalent emissions with a minimum of 50% over its whole life cycle. Furthermore, the results are meant to contribute to a dialogue on the climate benefits of reusing building materials, but also contribute to a discussion on how trade-offs and challenges can be managed.

1.3 Research questions

The research questions (RQ) that will be addressed in the thesis are:

RQ1: Which building materials (e.g., wood, steel and concrete) and parts (e.g., foundation, facade and roof), generally have the highest climate impact in residential building projects?

RQ2: Which building materials are possible to reuse, and to what extent can they be reused?

RQ3: What possible trade-offs and challenges needs to be taken into consideration when reusing building materials?

RQ4: With how many percentages can the carbon footprint be reduced by reusing building materials in comparison to using only new materials in the residential building project Selma 2 Block 10?

1.4 Limitations

Since the thesis will investigate the difference in CO_2 eq. emissions, the focus will be on the ecological dimension of sustainable development while economic and social sustainability will not be discussed. Further, the thesis will focus on reuse of building materials and the case study will only consider taking old building materials directly from a deconstructed building without further treatment. A preliminary design and construction of Selma 2 Block 10 will already be set at the beginning of the thesis start and will not be influenced. Further limitations specifically connected to the case study are presented in Section 5.2.6.

1.5 Audience

Given that the aim of the thesis is to give guidance towards informed decisions related to material choices, the targeted audience of the thesis are the entrepreneurs within the building project Selma 2 Block 10. Furthermore, the work is directed towards sustainability and building technology engineers, architects, and real estate developers. The audience is also the research field of LCA and sustainable building design as well as actors working in a broader perspective, such as policy makers.

1.6 Report structure

The thesis contains 7 chapters. It begins with an introduction of the background, aim, research questions, delimitations and intended audience. Chapter 2 provides a theoretical background of sustainability, environmental systems analysis tools, circular economy, sustainability in the built environment and the building project Selma 2 Block 10. Chapter 3 introduces the method for the literature review and case study. In chapter 4, the result from the literature review is presented while chapter 5 provides the results from the case study. In chapter 6, a discussion on the method and results are presented together with suggestions of future studies. Lastly, the conclusions with a revisitation of the research questions are presented in chapter 7.

2 THEORETHICAL BACKGROUND

In this section the theory is presented to give a foundation for the caste study, results, and discussion. More exactly, sustainability as a concept is described to provide an understanding of the different perspectives and definitions of the subject. Furthermore, some environmental systems analysis tools are presented together with a description of the concept circular economy. Moreover, a brief description of sustainability in the built environment is presented to introduce the more specific topic of the thesis further. Lastly, a description of the building project Selma 2 Block 10 is presented.

2.1 Sustainability

Sustainability can be interpreted and approached in various ways and the concept sustainable development is generally used to frame and discuss desirable futures (Holmberg & Larsson, 2018). Sustainable development is most commonly defined by the Brundtland definition from the report Our Common Future (1987) as *“a development that meets the needs of the present without compromising the ability of future generations to meet their own needs*” (Hedenus et al., 2018). While this definition of the concept increased in popularity, three sustainability dimensions emerged: the ecological, the economic and the social (Holmberg & Larsson, 2018). The ecological part involves everything from renewable natural resources such as forests, cropland, and clean water to management of pollutants and other environmental impacts (Hedenus et al., 2018). The economic dimension is about managing the economy and financial resources in an efficient way. The social dimension investigates which social structures that is required for people to meet their needs and how to maintain these structures. The Brundtland definition and the three dimensions is commonly used in international agreements and sustainability initiatives (Holmberg & Larsson, 2018). Agenda 2030 for sustainable development is one example of an international agreement that refers to the environmental, economic, and social dimensions of sustainable development. The agenda is centred around 17 sustainable development goals and 169 associated targets that engage and encourage all nations in the world to act towards a more sustainable future (Hedenus et al., 2018). The goals cover everything from zero hunger to sustainable cities and communities (Omer & Noguchi, 2020) illustrated in Figure 1 below.

Figure 1 Sustainable development goals from Agenda 2030.

Another interpretation of sustainable development is the so-called lighthouse model (Holmberg & Larsson, 2018). This definition considers four dimensions of sustainability: ecological, economic, social, and human needs & wellbeing. The added dimension *human needs & wellbeing* is considered important for two reasons. On one hand, since a clarification on desirability can provide motivation, purpose, and guidance in adaptions and, on the other, since human needs and fulfilment have implications on the ecological, economic and social sustainability dimensions. The model is visualized as a lighthouse as shown in Figure 2 with the human needs and wellbeing illustrated as the light at the top of the model and answers the question *"What is a good life?"*. These needs influence the other three dimensions and provides direction and purpose. The ecological dimension is described as the fundamental basis for all human activities and is therefore placed at the bottom of the model answering the question *"How can society´s activities fit within nature´s carrying capacity?"*. The social and economic dimensions are located in between the ecological and human needs and wellbeing. They are explained to combine the other dimensions and answers the questions *"How can we live together"* and *"How can capital be managed for the future?"*

Figure 2 The lighthouse model. Adapted from Holmberg & Larsson (2018).

Further research has presented sustainability in additional ways. Herman Daly introduced a triangular approach in 1973 with four components: nature, economy, society, and human wellbeing (Holmberg & Larsson, 2018). This approach was later evolved by Donella Meadows (Meadows, 1998). The basis of the triangle consists of the natural capital as the ultimate means. The built, human and social capital is considered as the intermediate means and ends in the middle of the triangle and finally, well-being is considered the ultimate end at the top as shown in Figure 3.

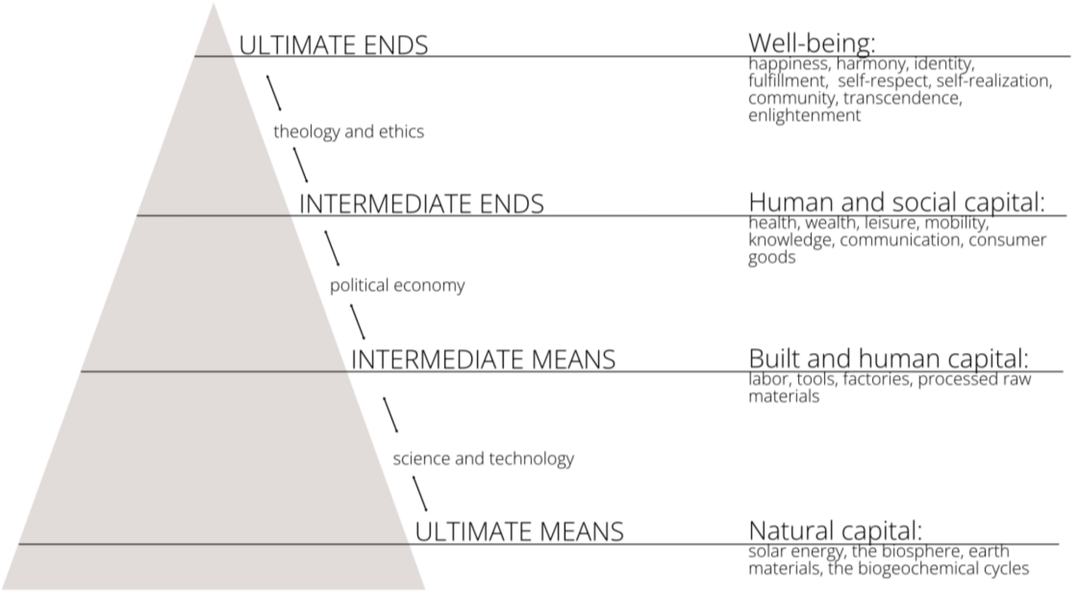


Figure 3 The triangular approach of sustainability. Adopted from Meadows (1998).

2.2 Environmental systems analysis tools

Assessments of environmental impacts can be performed in many ways using different tools (Finnveden & Moberg, 2005). Material Flow Analysis (MFA), Life Cycle Assessment (LCA) and Environmental Impact Assessment (EIA) are three examples of available tools. The different tools can be described in relation to various characteristics such as if the tool is an analytical or a procedural tool, what types of impacts that will be considered, what the object of the study is, and if the study will be descriptive or change oriented. An analytical tool is focused on technical aspects of the analysis while a procedural tool centres around the procedures and connections to the societal and decision context of the analysis. The types of impacts are important since a distinction is made between tools that focus on environmental impacts or resource use. The tools can also be focusing on both and have an economic aspect.

2.3 Circular economy

The dominating model for the world’s production and consumption has over the past 100-150 years been linear (Ghosh, 2020) and it is therefore a familiar cycle (UNCTAD, 2018). However, this one-way approach does not support sustainability and resource efficiency seeing that resources are extracted and used in the production of goods and services (Ghosh, 2020). The goods and services are later sold, used and disposed to landfill or incineration, resulting in major impacts on the environment. Further industrialisation, population growth, urbanisation, negative environmental impacts, and growing demand for resources lead many researchers, companies, and policy makers towards a more circular model. Circular economy is believed to minimize the leakage of resources by reusing, repairing, recycling, sharing, and leasing resources in a closed loop as illustrated in Figure 4.

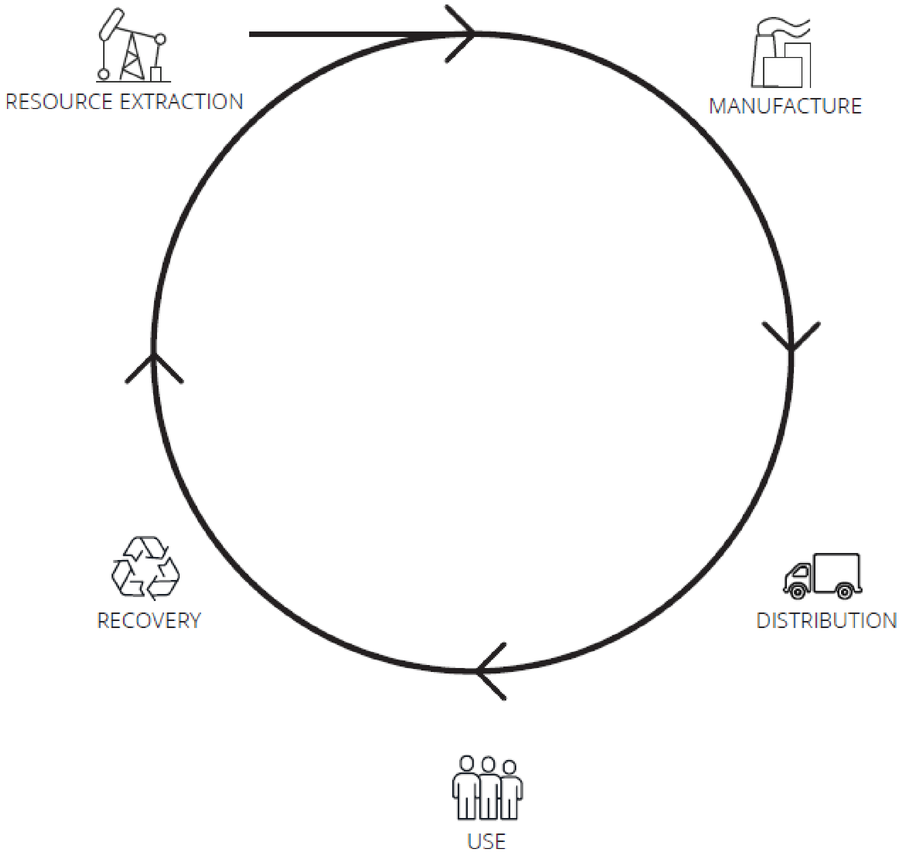


Figure 4 Circular economy phases. Adopted from Ghosh (2020).

The practical applications of circular economy entered economic systems and industrial processes in the late 1970s or early 1980s (Ghosh, 2020). Originally the concept evolved from the cradle-to-cradle framework that focuses on safe lifecycles of products, processes, and materials from an environmental and human health perspective. There is no single universal definition of circular economy and researchers define the concept in different ways. Generally, most definitions mention minimized or zero waste by reuse, long lifetime and closed loops. A common factor is that most definitions agree that circular economy has potential to contribute to economic, environmental and social sustainable development. Circular economy is considered to be closely connected to the 17 sustainable development goals in many aspects. The approach is believed to help achieve several goals but primarily goal number 6, 7, 8, 12 and 15.

2.4 Sustainability in the built environment

Sustainability as a term and concept reached the building industry in the middle of the 1990's when the awareness of the industry's environmental impacts increased (Gundes, 2016). Back then, the sustainability work focused only on the ecological dimension but in recent years the economic and social parts have been incorporated in the assessments as well. The social aspect is however reported to be more challenging than the other two. Yet, it is equally important for the sustainable development.

The building industry has major impacts on the environment (Omer & Noguchi, 2020). It accounts for 40% of the natural resources extracted in the industrialized countries and 45-65% of the waste disposed to landfills. Moreover it is responsible for 39% of the global emissions and 50% of the global material consumption (Malabi Eberhardt, van Stijn, et al., 2021). The expected population and urbanization growth implies a greater need for new constructions and buildings and with that also an increased need for building materials (Omer & Noguchi, 2020). This growth will cause further environmental impacts and a sustainable building industry seems to be an important part of achieving the overall sustainable development goals.

In 2019, the Swedish building and real estate sector emitted a total amount of 19.3 million tons of carbon dioxide equivalents (including both domestic emissions and import) which is equal to 21% of the total emissions in the country from a life cycle perspective (Boverket, 2021e). Further, the sector was responsible for 19% of the total nitrogen oxide emissions, 24% of the total energy use, 4% of the total usage of hazardous chemicals for the environment and 35% of the waste in 2018, as illustrated in Figure 5 below.

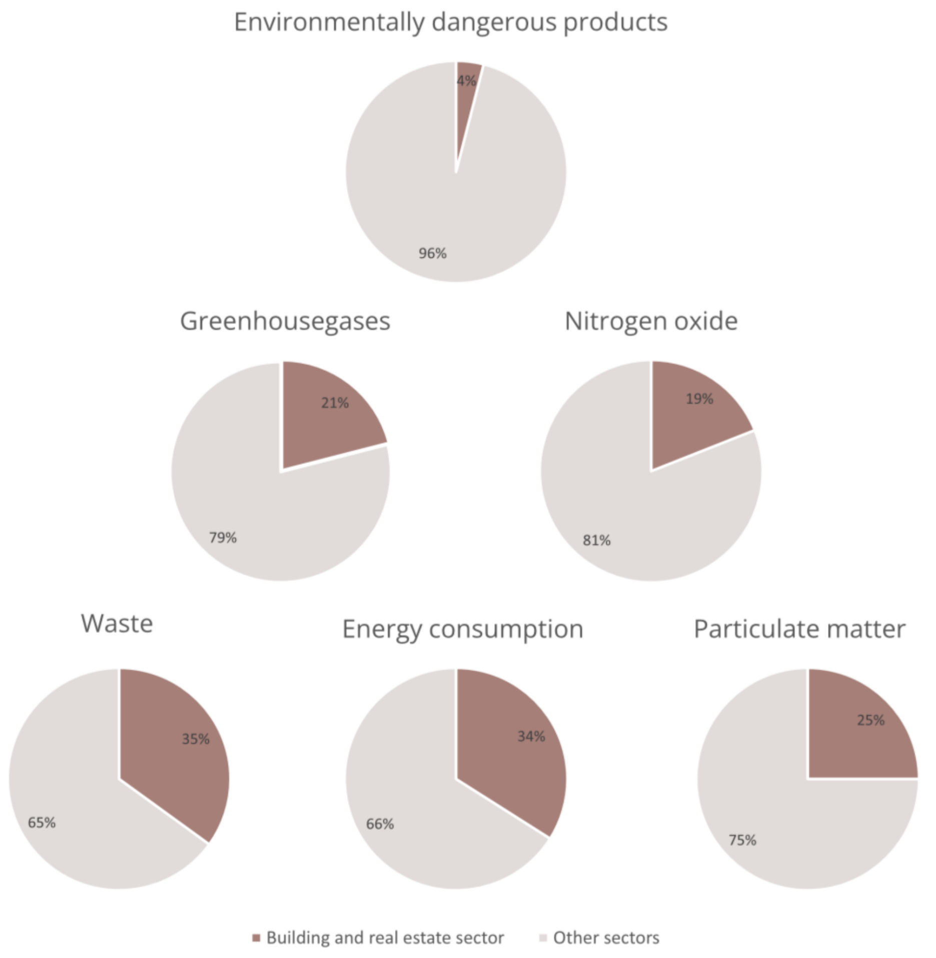


Figure 5 Emissions and waste from the Swedish building and real estate sector in 2018 and 2019. Adopted from Boverket (2019e).

2.4.1 LCA in the built environment

The importance of environmental protection has increased together with an interest in the development of methods to understand and analyse impacts from products manufactured and consumed in society (SIS, 2006). One of the tools developed for this purpose is life cycle assessment (LCA). LCA is a quantitative tool that in a structured way investigates environmental issues (Baumann & Tillman, 2004). It is today an important and widely used method that analyses the environmental impacts of a product throughout its entire life cycle. The tool has different applications such as decision making (e.g., process design and development, and policy instruments), learning and exploration (e.g., identification of improvement possibilities), and communication (e.g., eco-labelling and environmental product declarations). Life cycle assessment is also one of the best methods to calculate the environmental impacts from a building (Boverket, 2019c). Further, it is useful to influence and suggest environmental improvements (Boverket, 2019a). LCA facilitates an identification of the stages in the building life cycle that has the biggest environmental impacts and can guide the design process and material choices.

According to most researchers there are two main types of LCA: change oriented (also called consequential) and accounting (also called attributional) (Baumann & Tillman, 2004). Change oriented (consequential) LCA answers questions like *"What would happen if…"* while accounting (attributional) LCA investigates questions such as *"What environmental impact can this product be held responsible for?"*.

It is rather common to use the results from an LCA as a part of the basis for various environmental certifications (Boverket, 2019c). BREEAM, LEED and Miljöbyggnad (MB) are certification systems that all require some sort of LCA. BREEAM, short for Building Research Establishment Environmental Assessment Method, was developed in Great Britain in 1990 and is one of the oldest environmental certifications. The version BREEAM-SE is developed by the Sweden Green Council and is used on the Swedish market to certificate new buildings and to assess the building's environmental performance (Seweden Green Building Council, 2018). Everything from water and waste management to energy use and choice of building materials is graded and according to Boverket (2019b) an LCA can give extra credit if conducted in roof, windows, walls and beams. LEED is a certification with four levels: certified, silver, gold, and platinum. It was developed by U.S Green Building Council and was launched in 1998 (Council, n.d.). The aim of the certification is to identify, realize and measure the design, construction, usage and maintenance from an environmental perspective. LEED prioritize LCA studies of the frame, foundation and building envelope (Boverket, 2019b). Miljöbyggnad is a Swedish certification with three levels developed by the Sweden Green Building Council (Sweden Green Building Council, 2018). Miljöbyggnad has in total 15 indicators of which one includes an LCA (Boverket, 2019b). The calculations consider the foundation and frame, and the analysis is based on the transportations and building materials.

When applying LCA in the building industry, the life cycle of a building is divided into different building specific stages as illustrated in Figure 6 according to the European standard EN 15978 (SIS, 2011). The standard EN 15978 is prepared by the technical committee CEN/TC 350 *"sustainability of construction works"* and provides calculation rules for the assessment of environmental impacts from existing or new buildings. The building specific stages are important for the interpretation and comparisons of the results (Boverket, 2021d). Modules A1-A3 constitute the product stage (including everything from raw material extraction, transport and refinement to production of building materials), modules A4-A5 constitute the construction process stage (including transportation of building materials to the building site and the completion of the building), modules B1-B7 constitute the use stage (including usage, maintenance, repairs, energy use and water use), modules C1-C4 constitute the end of life stage (including demolition, transportation of the old building materials, recycling and deposition) and lastly, module D constitutes the benefits and loads beyond the system boundary (including reuse, recovery and recycling potential).

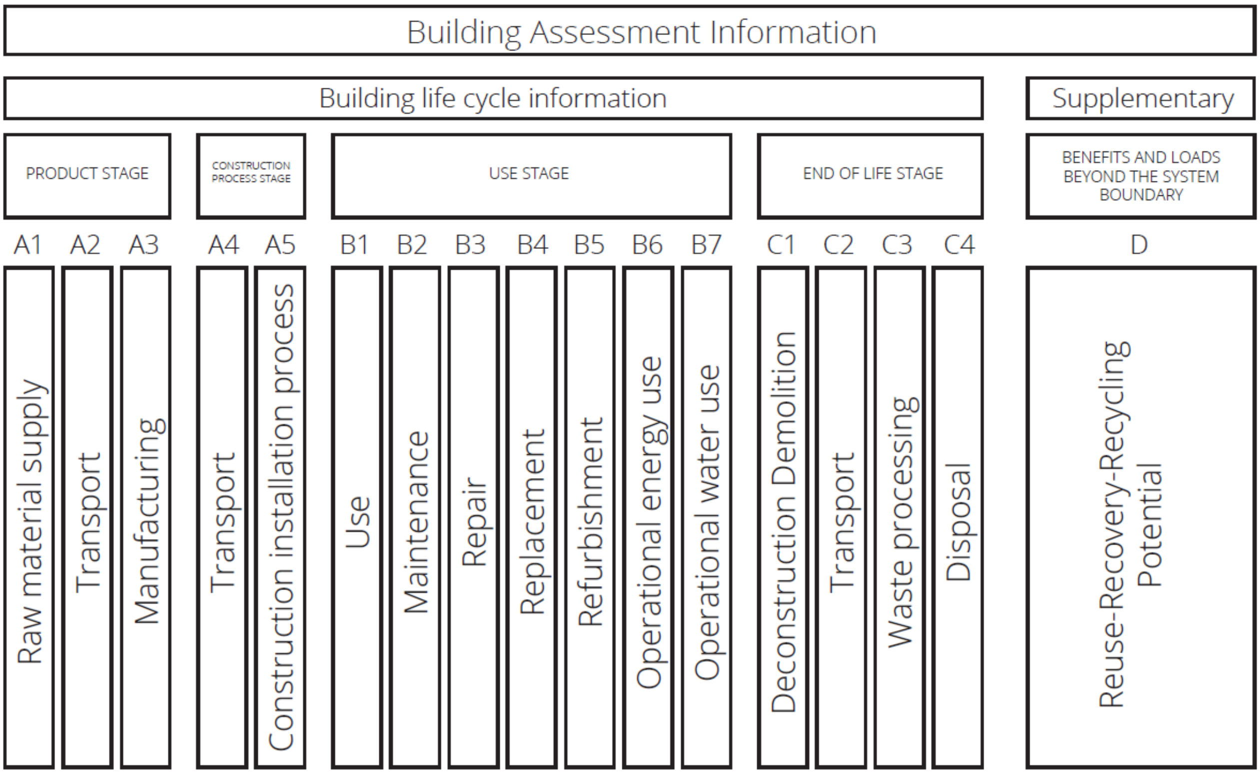


Figure 6 Stages for LCA in the building industry. Adopted from SIS (2011).

LCA studies focusing on the product stage (module A1-A3) are called cradle-to-gate studies (Moncaster et al., 2019). If the transportation module (A4) is included, it becomes a cradle-to-site study. Studies focusing on both the product stage and the construction process stage (module A1-A5) are known as cradle-to-handover while studies including the product stage, construction process stage and the use stage (module A1-B7) are called cradle-to-use studies. A cradle-to-grave study contains the product stage, construction process stage, use stage and end of life stage (module A1-C4). Lastly, studies that include all stages (A1-D) are called cradle-to-cradle studies.

Figure 7 illustrates an example of the environmental impacts from a residential building. As can be seen in the figure, phase A1-A3 together with phase B6 have the highest climate impacts (Boverket, 2021f).

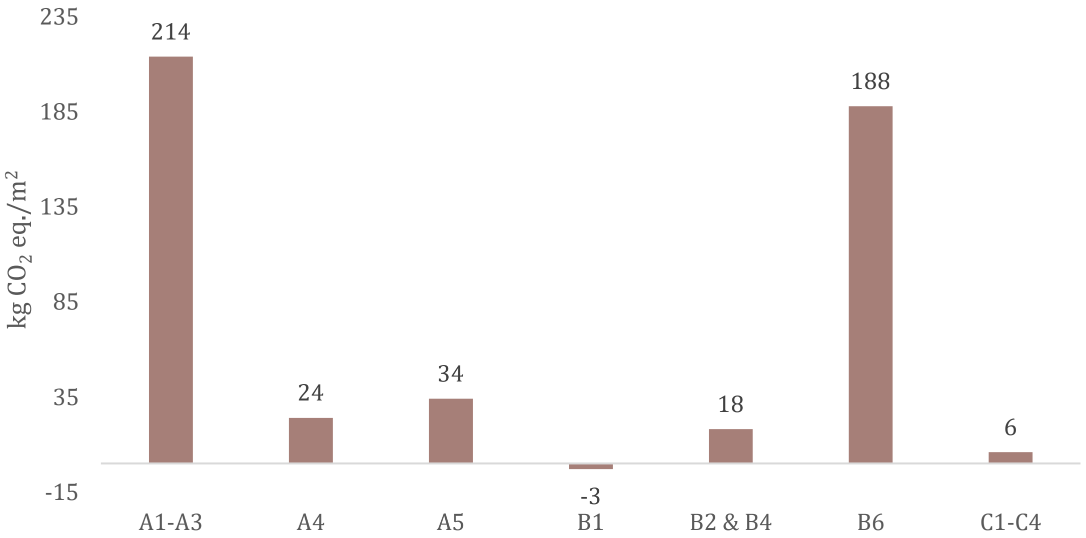


Figure 7 Example of life cycle assessment results for a residential building. Adapted from Boverket (2021f).

2.4.2 Climate declarations

From the 1st of January 2022, the Swedish government requires climate declarations on all new buildings in the country with the purpose to reduce the climate impacts from the construction phase (Boverket, 2021c). However, the legislation is not meant to introduce a maximum value or limit for the environmental impacts but rather to increase the knowledge and with that contribute to making sustainable decisions (Boverket, 2021f). This kind of political work with an environmental focus is derived from the long-term goal that Sweden by 2045 should not have any net emissions of greenhouse gases (Boverket, 2020).

The climate impact is calculated by multiplying the amount of resources with the generic or specific data (Boverket, 2021b). Generic data represents the general products on the market and is usually applied in an early stage when all products are set (Boverket, 2020). The generic data can be replaced with specific data in the later stages of the project which will result in a more representative and correct climate impact. Boverket holds a database of data to use for the calculations (Boverket, 2021a). The climate declaration is considering the product stage of the building life cycle, that is module A1 to A5 (Boverket, 2021d). The final climate impact is lastly divided with the building area and presented as kg CO_2/m^2 BTA.

2.4.3 Circularity in the built environment

Today, the building industry consists of mostly linear flows of products and waste (Göteborgs Stad, 2020). This requires large extraction of natural and scarce resources and an extensive waste disposal. Further, the extraction, transportation, and production cause large amounts of emissions and other environmental problems. In connection with the buildings becoming more energy efficient, the choice and usage of materials is considered more and more important. A possible action to reduce the environmental impacts from the sector is to proceed to a more circular approach. Reuse and recycling of building materials will reduce the use of natural and scarce resources. A circular building and demolition process consider everything from deconstruction and project planning to construction operation and maintenance as illustrated in Figure 8.

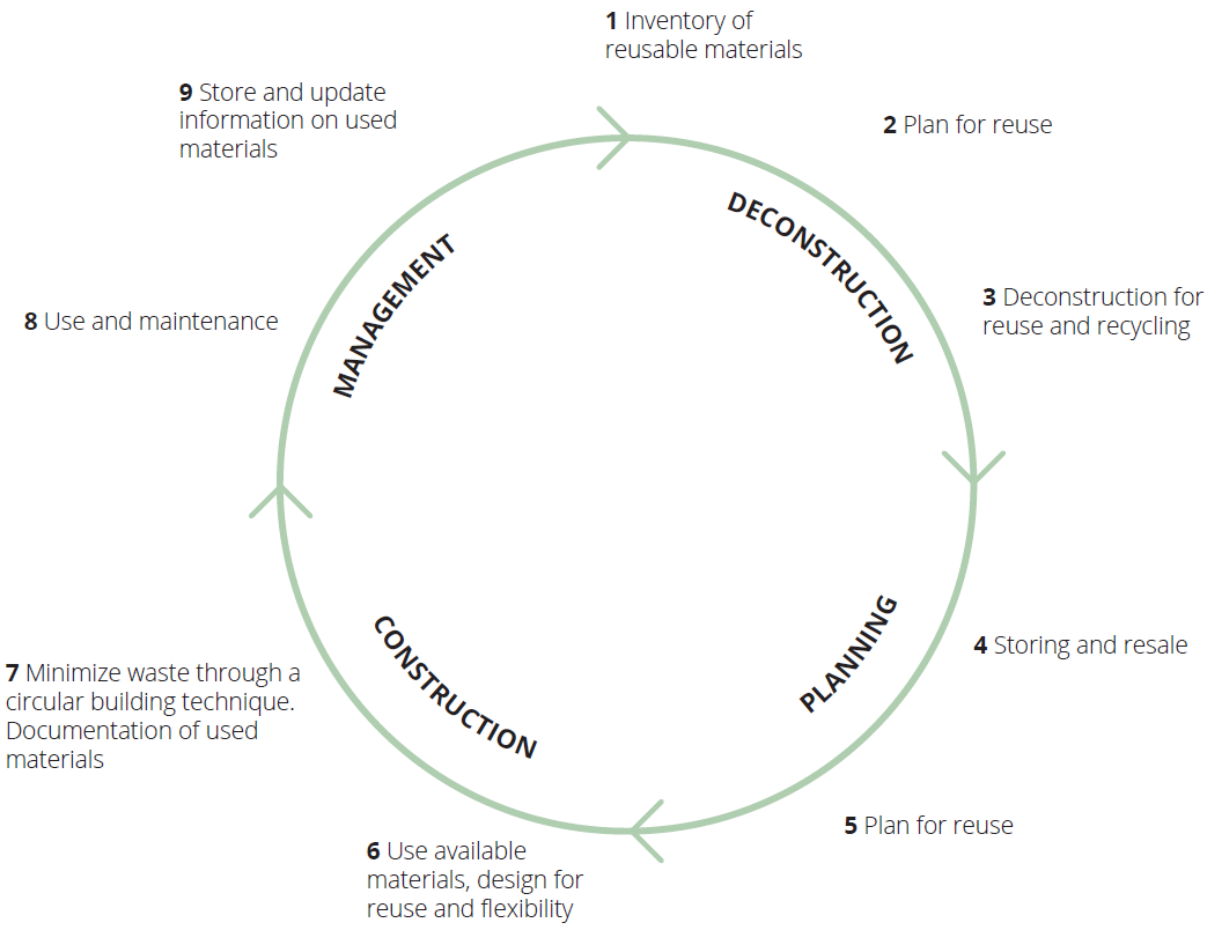


Figure 8 A circular building- and deconstruction process. Adapted from Göteborgs Stad (2020).

Circularity can be applied to the building sector in multiple ways, both through design and construction strategies (Malabi Eberhardt, Rønholt, et al., 2021). For one thing, it is possible to use materials with low climate impact and reduce the amount of materials and for another it is possible to design for deconstruction, adaptability and durability. The circular economy aims at energy and material resource efficiency, promoting low-carbon footprints and minimizing waste, goals that can be achieved through designing durable components that are easy to deconstruct and reuse several times in a closed-loop cycle (Cruz Rios & Grau, 2020).

Reuse is part of the circular economy concept *the 3R's: reduce, reuse, and recycle* (Minunno et al., 2020). Recycling is considered as the most applied procedure even though it is claimed to be the least beneficial due to losses and contamination from the recycling process. Further, recycling is an energy and resource-intensive process that puts additional pressure on the environment despite its ability to divert waste from landfills (Rakhshan et al., 2020). Recycling does contribute to the conservation of materials but with a rather high climate impact if compared to other methods (Rakhshan et al., 2020). Instead, reuse of building materials and components such as beams, columns and brick yield a lower environmental impact. Reuse in circular economy means the reuse of a material or component as it is (Cruz Rios & Grau, 2020). The material and component can however go through refurbishment or remanufacturing but not recycling.

2.5 The residential building project Selma 2 Block 10

Gothenburg is the second largest city in Sweden with almost 580 000 inhabitants in 2019 (Göteborgs Stad, 2021b). In the 2000’s the number of inhabitants has increased with around 100 000 persons and the population growth is expected to continue in the future with 250 000 more inhabitants by 2050. This growth requires an urban development with both new accommodations and public buildings. The city of Gothenburg has a comprehensive plan for the future development with the overall goal to be sustainable. The 17 sustainable development goals will serve as guidance with goal number 11, *make cities and human settlements inclusive, safe, resilient, and sustainable*, considered as the most relevant. The plan points out some parts of the city as prioritized development areas.

The district Backa is one of these areas where 3000 new accommodations are planned in the quarter Selma Stad (Selma Stad, n.d.). The area is being developed in four stages (Persson, 2018). Stage 1 is focused on the square Selma Lagerlöfs torg with a planned sports centre, nursery school, community health centre, commercial centre, town hall and 1000 accommodations. Stage 2 involves Litteraturgatan south of Selma Lagerlöfs torg where additional 2800 accommodations are planned. Similar to stage 2, stage 3 involves Litteraturgatan but north of Selma Lagerlöfs torg where another 300 new accommodations will be built. And finally, stage 4 is preparing for 1000 more accommodations. Selma 2 Block 10 is a residential building project that is part of the development of Selma Stad in the district Backa in Gothenburg. The project is managed by Framtiden Byggutveckling and is planned to be completed in the autumn 2023. Figure 9 below illustrates where Selma 2 Block 10 is located at Litteraturgatan.

Figure 9 Site plan of Litteraturgatan. Provided by Framtiden Byggutveckling (n.d.).

The building consists of three main bodies, as can be seen in Figure 10, of which one is 5 floors and two are 6 floors high. There will be a total amount of around 66 apartments in the building and the BTA is set to 5550 m^2. Table 1 describes further information on the building project.

Table 1 Description of Selma 2 Block 10 (Framtiden Byggutveckling, personal communication, April 29, 2022).

Number of floors	Number of apartments	BTA	BYA	Number of staircases
5.645 (5 and 6 floors)	66 (approx.)	5550 m^2	983.2 m^2	3

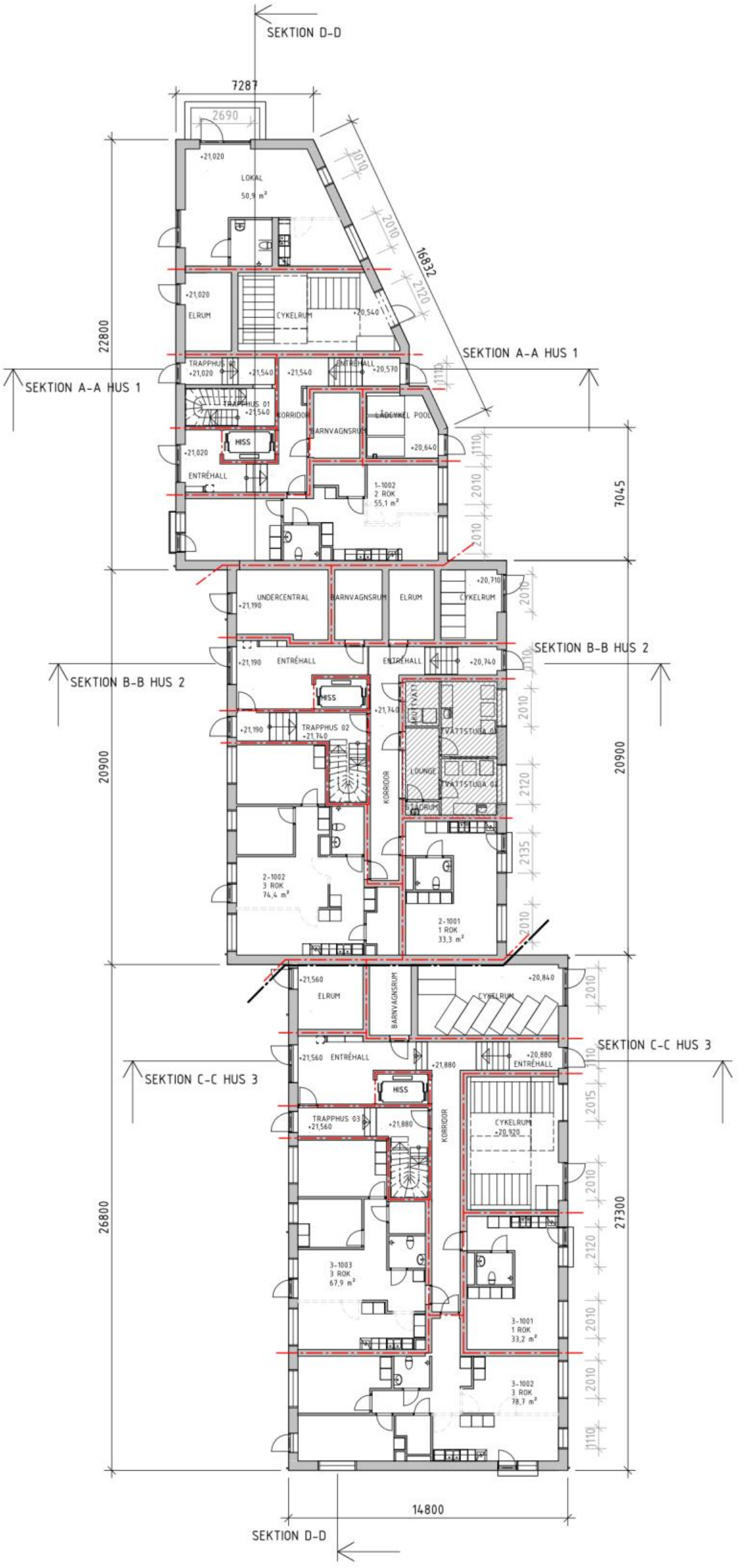


Figure 10 Preliminary plan of Selma 2 Block 10. Provided by Framtiden Byggutveckling (n.d.).

The project in its whole consists of a variety of different materials. Table 2 describes the included building parts and materials in the case study. The materials are provided by Framtiden Byggutveckling and is probable materials in the different building parts based on the existing design when conducting the case study. Deviations can occur when the design is further developed.

Table 2 Included building parts and materials based on pre-existing calculations on the building project.

Building part	**Building material**
Foundation	EPS insulation Ready-mix concrete C12/15 Plastic vapour control layer Self-levelling mortar Concrete C30/37 Reinforcement steel
Frame	Steel Aggregate Gypsum board Glass wool insulation Cross-laminated timber Gypsum board (floorboard) Fibreboard Ready-mix concrete C30/37 Reinforcement steel
Roof	Plastic vapour control layer Gypsum board Wood scantling Roof felt Cross-laminated timber Cellulose fibre (loose wool)
Facade	Gypsum board Plastic vapour control layer Wood scantling Cellulose fibre (boards) Brick
Windows and doors	Steel door Aluminium profile for windows and doors Float glass Wooden decking, cladding and planed timber
Inner walls	Cross-laminated timber Gypsum board Gypsum board (fireproof) Wood scantling Cellulose fibre (boards)

3 METHODOLOGY

This chapter provides an explanation of the methods used in the thesis report. The chosen approach to answer the research questions was through mixed methods of both qualitative and quantitative character. The research process consisted of two main parts as illustrated in Figure 11: a literature review and a case study of Selma 2 Block 10 including LCA calculations and interviews. The results from the literature review were aimed to explore RQ1, RQ2 and RQ3 while the results from the case study were used to answer RQ4.

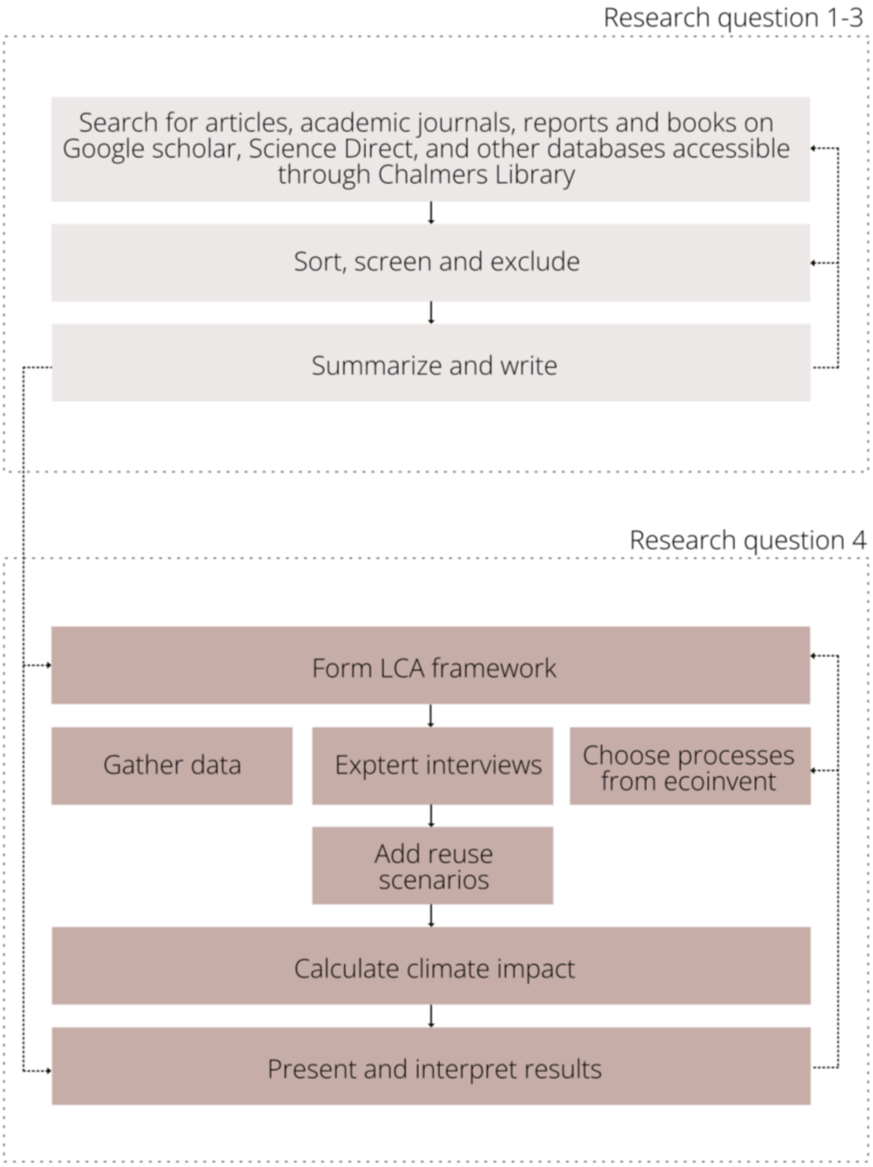


Figure 11 The methods of conducting the thesis.

3.1 Literature review

The literature review was conducted to map existing knowledge within the field regarding reuse in the built environment. This knowledge was necessary to answer the three first research questions: *RQ1 Which building materials (e.g., wood, steel and concrete) and parts (e.g., foundation, facade and roof) generally have the highest climate impact in building projects?*, *RQ2 Which building materials are possible to reuse, and to what extent can they be reused?* and *RQ3: What possible trade-offs and challenges needs to be taken into consideration when reusing building materials?*

The literature review consisted of literature from the databases Google scholar, Science Direct, and other databases accessible through Chalmers Library together with other relevant books and reports. Key words used in the search process were “reuse”, “reuse potential”, “recycle”, “building”, “building materials”, “building components”, “deconstruction”, “environmental impact” and “climate impact”.

3.2 LCA of the case study Selma 2 Block 10

A case study of quantitative character was made on the residential building project Selma 2 Block 10 to quantify the difference in carbon footprint when reusing building materials in comparison to only new materials. The final results from the assessment were necessary to answer the fourth research question: *RQ4 With how many percentages can the carbon footprint be reduced by reusing building materials in comparison to using only new materials in the residential building project Selma 2 Block 10?*

The chosen tool for the quantitative assessment of the case study is life cycle assessment (LCA). In the following sections, the different procedural steps of LCA are explained as well as the expert interview inclusion in the case study. Lastly the software openLCA used for the assessment is shortly described.

3.2.1 Life cycle assessment

The LCA procedure consists of four different parts: goal and scope definition, inventory analysis, impact assessment and interpretation (SIS, 2006). Figure 12 illustrates the different procedural steps and their connection. The international standard for LCA is called ISO. The general requirements are given by the standard ISO 14040 (Baumann & Tillman, 2004) and ISO 14044 describes the detailed requirements for conducting an LCA (SIS, 2006).

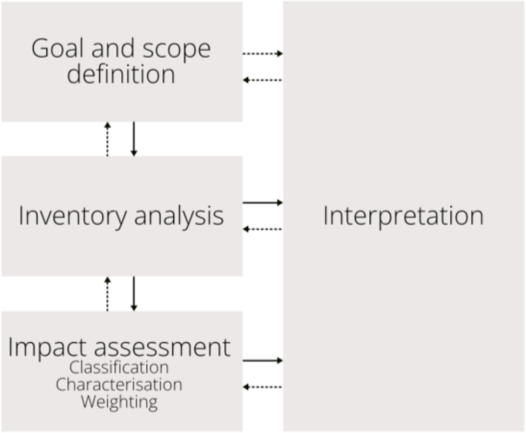


Figure 12 The LCA procedure. Adapted from SIS (2006).

3.2.1.1 Goal and scope

The first part of the LCA procedure is the goal and scope definition (Baumann & Tillman, 2004). In this step the product and the purpose of the study is decided on. The goal definition states the intended application, purpose and audience while the scope definition involves the decisions related to which options to model, initial flowchart, functional unit, impact categories, method of impact assessment, system boundaries, allocation, data quality requirements, assumptions and limitations. The first step also includes the choice between using accounting or change oriented LCA.

Functional unit
The functional unit is a quantitative term that states the function of the product system (Baumann & Tillman, 2004). It is essential for comparison and could for example be set as *m*^{2} *and year* for the product *flooring* or *person and km* for the service *transportation*.

Impact categories
The impact categories decide what environmental impacts to take into account in the assessment and which data that will be collected during inventory analysis (Baumann & Tillman, 2004). Examples of impact categories are resource use, global warming potential (GWP), acidification and eutrophication.

System boundaries
System boundaries are set in relation to natural systems, geography, time and technical systems to know what life cycle phases to include, where the processes take place, what time horizon to consider and how to handle allocation problems (Baumann & Tillman, 2004).

Data quality
Data quality requirements is an important part of the goal and scope definition since it affects both the workload and the reliability of the results (Baumann & Tillman, 2004). The ISO standards describe different aspects of data quality-based relevance, reliability and accessibility.

3.2.1.2 Inventory analysis

In the second step of the LCA procedure the systems model is built according to the goal and scope definition (Baumann & Tillman, 2004). This part includes flow model construction, data collection and calculations. The flow model is commonly a flowchart that illustrates the processes in the system and the flows between these processes. The data collection includes inputs and outputs to and from all processes. The calculations are made on pollutants and resource use in relation to the functional unit. The results are often presented as graphic presentations such as bar charts.

3.2.1.3 Impact assessment

The life cycle impact assessment (LCIA) describes the environmental consequences by translating the environmental loads identified in the inventory analysis into the chosen impact categories (Baumann & Tillman, 2004). The impact assessment consists of the two mandatory steps classification and characterisation and the optional step weighting. Classification is when the inventory parameters are sorted according to what impact categories they contribute to. Characterisation is when the relative contribution of the emissions and resource use are calculated by for example aggregating the emissions to one indicator as illustrated in Figure 13. Weighting enables further aggregation of the characterisation results across impact. The reasons for LCIA are to make the results more comprehensible, easier to communicate and to improve the readability.

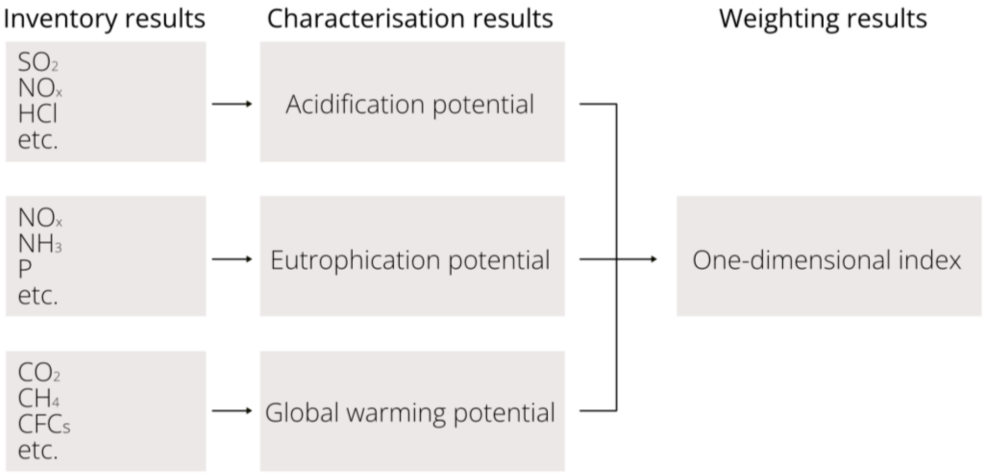


Figure 13 Example of stepwise aggregation of information in LCA. Adapted from Baumann & Tillman (2004).

To simplify the LCA process there are a number of ready-made LCIA methods developed (Baumann & Tillman, 2004). If using one of the ready-made LCIA methods, the practitioner does not need to go into detail into the classification and characterization steps. This is possible because the environmental information for pollutants and resources is aggregated to an index or a characterization indicator and the environmental loads from pollutants or resources are measured on a common scale. Examples of ready-made LCIA methods are Ecoindicator´99, CML and EPS.

3.2.1.4 Interpretation

The last part of the LCA procedure, the interpretation, is essential for making conclusions from the results (Baumann & Tillman, 2004). The raw results are often hard to comprehend and therefore a refinement is necessary. This can be done by for example identifying critical data or screening the raw results.

3.2.2 Interviews

There are different types of interviewing styles: structured interviews, semi-structured interviews and unstructured interviews (Duncan & Holtslander, 2012). Structured interviews include asking the same questions to each interviewee and have no room for discussions beyond the set of questions. Semi-structured interviews are more flexible and include both a set of guiding questions and room for discovering topics further. Unstructured interviews are more similar to conversations where the researcher has an idea of what topics to investigate but no specific set of questions. The type of interview style that will be used in the case study for this thesis is of the type structured interview, where the interviewees will answer yes or no to if the materials included in Selma 2 Block 10 are possible to reuse in the building project or not.

3.2.3 OpenLCA

OpenLCA is a software that can be used for making life cycle assessments or sustainability assessments (Ciroth et al., 2020). It is an open-source software developed by GreenDelta in 2006. The software itself does not contain any database. Therefore, a database, like ecoinvent, needs to be imported into the programme. In openLCA it is possible to model flows, inputs, outputs and processes that form the base for the assessment.

4 RESULTS: LITERATURE REVIEW

The next paragraphs present the results of the literature review on climate impacts and recyclability of different building materials and parts. A total of around 20 academic journals, reports and books were reviewed, and the most relevant and interesting parts are presented in this thesis.

4.1 Building materials and parts with the highest climate impact

The strong focus on improvements of the operational stage within the building sector have resulted in more energy efficient buildings (Malabi Eberhardt, Rønholt, et al., 2021). Subsequently, the embodied environmental impacts of building materials represent a large share of the impacts from the building´s life cycle as can be seen in Figure 7. The operational impacts were in the past the only issue evaluated when looking at environmental performance of buildings (Cabeza et al., 2021). However, the awareness of embodied energy (EE) has increased significantly. Embodied energy can today account for more than 50% of the total life cycle impacts depending on the building.

Embodied energy as a notion was first used in the end of the 1970s and has been defined in various ways. A definition by Graham Treloar et al. (2001) cited by Cabeza et al. (2013) reads as follows: “the energy required to provide a product (both directly and indirectly) through all processes upstream (i.e., traceable backwards from finished product to consideration of raw materials)”. Grace Ding (2004) cited by Cabeza et al. (2013) provides the following definition: “embodied energy comprises the energy consumed during the extraction and processing of raw materials, transportation of the original raw materials, manufacturing of building materials and components and energy use for various processes during the construction and demolition of the building”. A shorter definition cited by Cabeza et al. (2013) is “the energy consumed in production of the material” by Koskela (1992). Saghafi & Hosseini Teshnizi explaines embodied energy and carbon of a building material as “the total primary energy consumed (carbon released) over its life time” (Saghafi & Hosseini Teshnizi, 2011).

Assessing embodied energy is rather complex and time consuming (Koezjakov et al., 2018). Furthermore, the analyses are commonly focused on a specific location and therefore the numbers can differ among studies. Table 3 shows the embodied energy for 23 common building materials in the Netherlands. Looking more specifically at buildings, Hopkinson et al. (2019) states that steel and aluminium alone are responsible for around 51% of the total embodied energy in building materials. Moreover, concrete is responsible for around 17% of the EE in building materials.

Table 3 Embodied energy for 23 commonly used building materials in the Netherlands. Adopted from (Koezjakov et al., 2018).

Material	**EE (MJ/kg)**	**Material**	**EE (MJ/kg)**
Aluminium	108.7	Hardwood	10.5
Polyurethane foam (PUR)	101.6	Softwood	7.5
Expanded polystyrene (EPS)	88.7	Argon	6.9
Extruded polystyrene (XPS)	87.5	Aerated concrete	3.6
Polyvinylchloride (PVC)	67.6	Gypsum plaster	3.6
Zinc	53.2	Brick, clay	3.1
Bitumen	51.1	Reinforced concrete	2.15
Mineral wool	16.7	Precast concrete	1.34
Wood fibre	16.1	Sand cement	1.07
Plywood	15.1	Gravel	0.16
Primary glass	15.1	Sand	0.014
Ceramics	12.1		

A study by Malabi Eberhardt, Rønholt, et al. (2021) investigating the embodied greenhouse gas emissions (EG) of four Danish concrete buildings shows that a significant contribution to the embodied greenhouse gas emissions comes from floors and ceilings for all the analysed buildings. This is suggested to be due to the production of concrete and the frequent replacement of carpets or other floor coverings. Other parts of the buildings with high embodied greenhouse gas emissions were the outer walls. The facades of the analysed buildings were generally constructed of EG-intensive materials such as aluminium, glass, concrete, stone wool and brick that have high emissions from production. The roofs are also shown to have a noticeable contribution to the EG. It is primarily the production and replacement of insulation materials and replacement of roof felt that contributes to the embodied emissions. Moreover, the inner walls show an observable contribution to the EG where the production of concrete constitutes the largest share. However, the study emphasizes that building materials or parts can not necessarily be classified as good or bad only in terms of the embodied greenhouse gas emissions. The use context needs to be considered as well. Even though high-impact materials should be avoided as much as possible, sometimes a certain material is required for a certain function. Substituting for example materials with load-bearing functions can result in trade-offs such as additional material. The additional material will in turn increase the embodied greenhouse gas emissions. However, decomposing a building into parts and materials can help identify opportunities for optimisation by for one thing identify the impacts from individual materials and for another displaying their use context and relation to one another.

Moreover, it is concluded in the study by Malabi Eberhardt, Rønholt, et al. that embodied greenhouse gas emissions at times can be due to specific building materials (e.g. the EG-intensive materials aluminium and concrete) but that it in most cases is a combination of contributions from several materials and component groups. Further, they conclude that similarities between buildings and component can occur even though the materials used in the components or buildings are widely different. This results in difficulties making general conclusions (Malabi Eberhardt, Rønholt, et al., 2021).

4.2 Degree of reusability and recyclability

By recycling and reusing materials it is possible to conserve the embodied energy end embodied greenhouse gas emissions which can reduce the carbon footprint (Malabi Eberhardt, Rønholt, et al., 2021; Muthu et al., 2015). Likewise, disposing old materials to landfill is equal to wasting the embodied energy invested in them (Muthu et al., 2015).

According to Hopkinson et al. (2019) there is an existing trade in non-structural products for reuse. Windows is for example a non-structural component that can easily be reused (Minunno et al., 2020). However, the majority of volume, mass and value of most buildings is connected to the structural elements often made of concrete, steel, brick and masonry. Hopkins et al. (2019) considers that most structural materials are fully capable of meeting the requirements after being reused as new due to the fact that the majority of the materials are under working (elastic) load during their working time. Furthermore, Arora et al. (2020) emphasises that structural building components that are possible to reuse include beams, columns, and steel frames. Examples on non-structural components possible to reuse are windows, doors, frames, lightning, furniture, kitchen and toilet fixtures (Arora et al., 2020). Despite the huge legacy of materially intensive buildings there is still a problem with the constructions not being designed for reuse (Hopkinson et al., 2019). Therefore, the direct reuse rates are markedly low. In the UK, only 4% of all steel in buildings is reused while the percentage for concrete, brick and other masonry is even lower.

According to Strand Nyhlin & Åfreds (2022) there are several views on how reuse can contribute to saving resources. Some focus on the materials with the highest climate impact, such as concrete and steel, while others use a broader approach and consider all sorts of materials. Different materials are however more or less reusable. Doors, windows, inner walls, stairs, grating, floors, underroofs and other fixed interior products are generally easy to reuse and might be a good start for beginners. Other materials such as brick, wood, concrete and roof tiles are additional reusable products. In the following sections, nine common building materials will be presented together with a description of their reusability.

Concrete

Not only being one of the materials with the highest climate impact in the building industry, concrete is also suitable for reuse due to its long lifetime (Strand Nyhlin & Åfreds, 2022). Concrete is today widely reused as road base material. This practice might be considered as wasteful since crushing concrete is a downcycling process. However, using crushed concrete instead of extracting virgin materials for that purpose is in many cases beneficial. Moreover, crushed concrete can be reused as aggregate in new concrete. Research has shown that crushed concrete can replace virgin aggregate without increasing the amount of cement. 5 percent of the virgin aggregate can be replaced with crushed concrete. The highest environmental saving is however gained if reusing an entire concrete frame. This can be done by renovation, replacing the facades or adding additional floors to an already existing building. This procedure saves emissions from both the production of concrete and transportation. Another possibility is to reuse prefabricated concrete elements. One study investigating the reuse of double-T-concrete showed that it is possible to save 1.23 GJ of energy, reduce 147 kg of carbon dioxide emissions from production and reduce the water and air emissions with 50% per cubic metre of product if reusing the concrete components instead of using recycled or new components (Hopkinson et al., 2019).

Wood

Wood has, similarly to concrete, long lifetime and additionally, it is an easy procedure to make tests to verify the quality of old wood products (Strand Nyhlin & Åfreds, 2022). Wood in good condition can be used as new wood in products such as furniture and interior panelling. Floorings made of wood can be disassembled and reinstalled. Likewise, cross-laminated timber and other mechanically installed wood products are possible to deconstruct and reuse. Moreover, it is claimed that reuse of timber sections can reduce the environmental impact by 83% (Rakhshan et al., 2020). Additionally, the reuse potential of a prefabricated timber structure is argued to be more than 69% (Margherita et al., 2021).

Brick

Reusing brick has been a difficult procedure due to complications in separating the brick from the mortar (Strand Nyhlin & Åfreds, 2022). Today however, there are more developed methods which enables reusage of the material. Reusing brick equals to a 96% saving in climate impact and Hopkinson et al. (2019) states that reusing one brick saves 0.5 kg of carbon dioxide emissions if you compare reused and new bricks. The mortar can be reused as road base material or other filling (Avfall Hälsingland, n.d.).

Sheet

According to Strand Nyhlin & Åfreds (2022), sheet has a lifetime of at least 100 years and is 100% reusable. Sheet is available in copper, aluminium, zinc and steel used as for example roofing or facades in buildings. Due to the long lifetime, sheet can be reused in a good way as long as they are not destroyed by rust or other.

Steel

Steel can easily be recycled by melting scrap and almost all steel is today recycled (Strand Nyhlin & Åfreds, 2022). Reusing the material would, however, decrease the environmental impact further. Strand Nyhlin & Åfreds (2022) emphasises that steel is suitable for reuse due to the standardized dimensions of the products. Reused steel can be used for almost all purposes, even for load bearing structures, as long as the material have not been used in bridges where the loading can cause small cracks in the material. By reusing steel, the emissions can be decreased to 100 kg CO_2/ton in comparison to the ordinary emissions from steel production that is 3000 kg CO_2/ton. Using recycled steel scrap equals to a reduction of the climate impacts by 50% compared to producing steel from virgin materials. Hopkinson et al. (2019) states that reusing a steel structure without melting results in a 30% saving in energy and carbon dioxide emissions.

Gypsum
Gypsum boards are in practice possible to deconstruct and reuse in its whole if the deconstruction is done in the right way (Strand Nyhlin & Åfreds, 2022). This is however not a common practice. Instead, it is more common to recycle waste from production by crushing it and adding it to the new production, even though this practice is limited too. It is possible to add old and used gypsum in the production of new material, but one complication is that most gypsum boards are lacquered and therefore hard to recycle.

Insulation
According to Strand Nyhlin & Åfreds (2022), mineral wool is 100% reusable. Moreover, glass wool can be reused as long as it is kept dry and packaged.

Roof felt
Traditionally, roof felt has been incinerated as the end-of-life treatment (Återvinning Stockholm, n.d.). However, the company Tarpaper recycling have started a business where they recycle roof felt in asphalt production.

Glass
Glass is in buildings mainly used in windows, facades, and interior design (Strand Nyhlin & Åfreds, 2022). Windows are often replaced before it is needed which opens up for reuse. However, reusing windows can imply complications. There is a risk that old windows do not meet the requirements regarding energy and U-values.

4.3 Trade-offs and challenges

Even though the construction industry today follows a linear business model, reuse as a practice is nothing new (Margherita et al., 2021). However, the reimplementation of the procedure is hindered by various trade-offs and challenges. In the following sections, ten trade-offs and challenges connected to reuse in the building industry will be presented.

Culture, norms, and traditions
According to Strand Nyhlin & Åfreds (2022), reuse is often associated with poor quality, old-fashionedness and lack of aesthetics. This attitude is not justified but affects the reuse process within the building industry, especially since the introduction of reuse in companies often is carried out through personal incentives. Firms with experience of reuse often conclude that the process is difficult due to the still well-established linear business model. Especially if the clients do not support reuse, the designers will not run the risk of reusing components and materials (Rakhshan et al., 2020). Moreover, there is a fear among architects and constructors of using inferior products that will cause injuries (Frändberg & Nyqvist, 2021). At the sector level, there also exists an industry scepticism and an unwillingness to change (Strand Nyhlin & Åfreds, 2022). Nevertheless, an increase of reuse will not benefit from continuing with a business-as-usual approach but rather by introducing projects focusing on reuse. Studies, however, often focus on the negative approach towards reuse which creates opposition towards the implementation of the practice (Margherita et al., 2021).

Quality and performance

Another problem with reuse is that buildings are not designed to be deconstructed (Margherita et al., 2021) which results in damage of the building components during the deconstruction phase (Frändberg & Nyqvist, 2021). It is for example hard to separate floor that is glued to the concrete slab or gypsum that is glued to wood. Damage can also be caused by water, corrosion, living organisms, degradation and joints (Rakhshan et al., 2020). Furthermore, there is also a risk that materials and components used in old buildings contain hazardous substances (Frändberg & Nyqvist, 2021). Therefore, some materials are not desired to keep in a circular flow. Moreover, there is a lack of standardised quality controls of old materials which increases the uncertainty about the performance (Strand Nyhlin & Åfreds, 2022). Frändberg & Nyqvist (2021) also states that there is a risk with health and safety during deconstruction. Machnanical demolition techniques might be more safe than manual deconstruction.

Offering of goods

A market for reusable products is yet rather unestablished and there is currently an imbalance between supply and demand (Strand Nyhlin & Åfreds, 2022). In Sweden, there are only a few companies focusing on purchasing, storing and selling old building materials. Further, buyers often inquire large amounts of the same type of product and without a comprehensive market for reusable materials the research for the right products is often too time consuming. Frändberg & Nyqvist (2021) states that the market for reclaimed products is unpredictable due to uncertainties regarding available quantities, qualities, size and price. Therefore, it might be needed to buy from several small-scale suppliers.

Knowledge

The lack of knowledge can hinder reuse of building products in various ways (Frändberg & Nyqvist, 2021). Rakhshan et al. (2020) argues that the lack of experience among companies affects the reuse of building components in a negative way. Frändberg & Nyqvist (2021) states that there is a lack of studies on the environmental, economic and social benefits of reuse. Moreover, there is a lack of successful examples and methods for deconstruction of old buildings. Frändberg & Nyqvist (2021) further declares that there is a lack of knowledge on the availability of reused products, the opportunities for reuse and the value for reused materials. Additionally, stakeholders are considered to have a lack of knowledge regarding how the building materials relate to embodied energy and how that affects the costs for construction.

Storing and logistics

When reusing materials, it is often hard to find the right material in the right time (Frändberg & Nyqvist, 2021; Strand Nyhlin & Åfreds, 2022). Therefore, it is often needed to first find materials to reuse and then design the building based on those products (Strand Nyhlin & Åfreds, 2022). This requires storing which can be costly. Moreover, it is important that the storing facility is located close to the building site. Otherwise, transportation can cause additional emissions.

Time

Frändberg & Nyqvist (2021) describes that it requires 3 times more time to decontruct a building in comparion to demolition while Rakhshan et al. (2020) means that it can require up to 5 times more time. Moreover, time is also required to carefully sort the different building materials. The design process is also more time consuming if reusing materials due to additional effort put into adapting the design to the available materials and components (Frändberg & Nyqvist, 2021). Furthermore, quality controls also requires additional time.

Economy

Economy is a central part of building projects and therefore it is important that reuse of building materials is a financially secure business (Strand Nyhlin & Åfreds, 2022). All the challenges connected to time explained above also require additional costs. A longer deconstruction time is more costly (Frändberg & Nyqvist, 2021). Likewise, sorting requires additional money. Furthermore, using old materials is often associated with higher costs due to the more labour-intensive deconstruction process (Rakhshan et al., 2020). Moreover, a longer design process requires more money equally as quality controls (Frändberg & Nyqvist, 2021). The uncertainties associated with reuse can also result in complications when loaning money from banks (Strand Nyhlin & Åfreds, 2022). An early purchase of materials also requires additional storage which is costly (Rakhshan et al., 2020). Frändberg & Nyqvist (2021) also describes that new products are usually not significantly more expensive than reclaimed ones which makes new materials favorable.

Flexibility
Reuse of old building materials requires a flexible design process which requires additional effort (Rakhshan et al., 2020). Changes must be possible if the planned material for some reason appears to be unserviceable. Furthermore, there is no possibility to fabricate required shapes. Instead, the available materials influence the design, rather than the other way around.

Requirements, laws and regulations
Even though reusing building materials is often discussed and encouraged within the building sector there are still no requirements that push the development further (Rakhshan et al., 2020; Strand Nyhlin & Åfreds, 2022). The lack of requirements and regulations contributes to the continuation of the linear business model which in turn hampers the achievement of the global sustainability goals (Strand Nyhlin & Åfreds, 2022). Frändberg & Nyqvist (2021) further states that it can be hard to get approval from authorities to reuse products.

Certifications
Environmental certifications such as LEED and BRREAM are ways to guide the building sector towards more sustainable buildings (Strand Nyhlin & Åfreds, 2022). Some certifications reward reuse but the connection is vague, and no deductions are done if reuse is not considered at all. It can also be argued that the certification system results in a moderate sustainability effort when the companies only focus on achieving the minimum requirements.

4.4 Reference values for buildings in Sweden

According to a commissioned research report investigating reference values for new buildings in Sweden, the product and construction process stage (module A1-A5 in the building life cycle) is responsible for around 80% of the climate impact (Malmqvist et al., 2021). The report analysed 68 buildings of which 19 were residential buildings, 14 preschools, 11 offices, 11 small houses, 10 schools, 2 commercial buildings and 1 sports centre.

Looking at all building types included in the analysis, concrete, steel, reinforcement and metals are responsible for around 60% of the overall climate impacts (Malmqvist et al., 2021). Concrete itself constitutes 40% of the total climate impact and for offices and apartment buildings concrete and metals are responsible for over 70% of the climate impact. An important aspect is that the dominating material in the framework of apartment buildings often is concrete. Another high impact material is insulation which in average is responsible for 15% of the climate impacts. This percentage is higher for smaller buildings. Figure 14 below illustrates the materials with the highest climate impact for the residential buildings, offices and small houses analysed in the research report by Malmqvist et al. (2021).

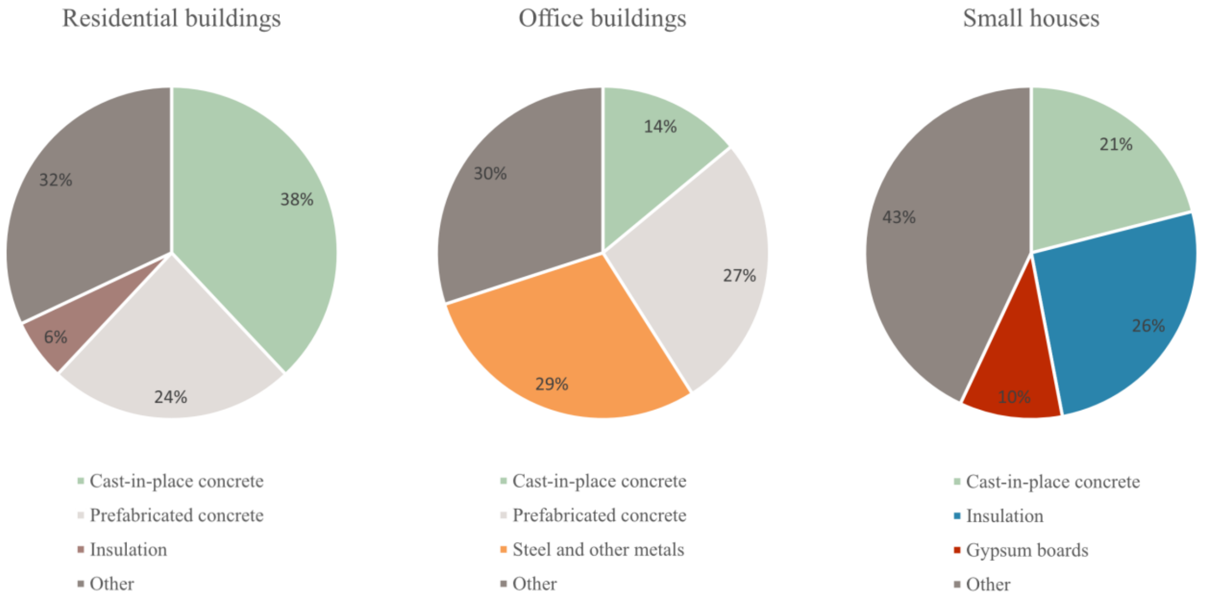


Figure 14 Building materials with the highest climate impact for three different types of buildings analysed by Malmqvist et al. (2021).

The framework of buildings is identified as one main factor affecting the size of the climate impact (Malmqvist et al., 2021). The framework generally has the highest climate impact, especially for buildings with multiple floors (i.e., apartment buildings and offices) while the foundation generally has the highest climate impact for buildings with only a few floors. According to the analysis apartment buildings with a wooden framework generally has a lower climate impact compared to apartment buildings with other materials used in the frame. Nevertheless, the frame seldom consists of merely one material but rather a combination of materials. When categorizing the framework, it is therefore often a simplification depending on the dominating material. Figure 15 below illustrates the building parts with the highest climate impact for the residential buildings, offices and small houses analysed in the research report by Malmqvist et al. (2021).

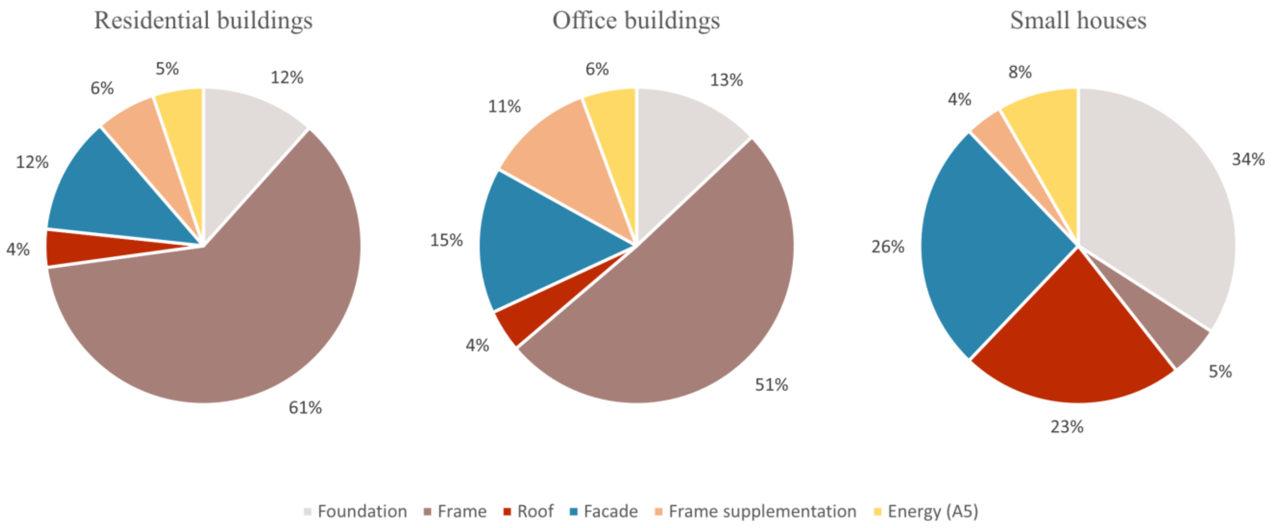


Figure 15 Building parts with the highest climate impact for the residential buildings, offices and small houses analysed in the research report by Malmqvist et al. (2021).

Looking at the total climate impacts for the residential buildings, offices and small houses analysed in the research report by Malmqvist et al. (2021), the residential buildings have an average total climate impact of 309 kg CO_2 eq./m^2 BTA for the building life cycle stages A1-A5. The average result for the offices is slightly lower at 302 kg CO_2 eq./m^2 BTA while the average total climate impact for the small houses is significantly lower at 132 kg CO_2 eq./m^2 BTA as illustrated in Figure 16 below.

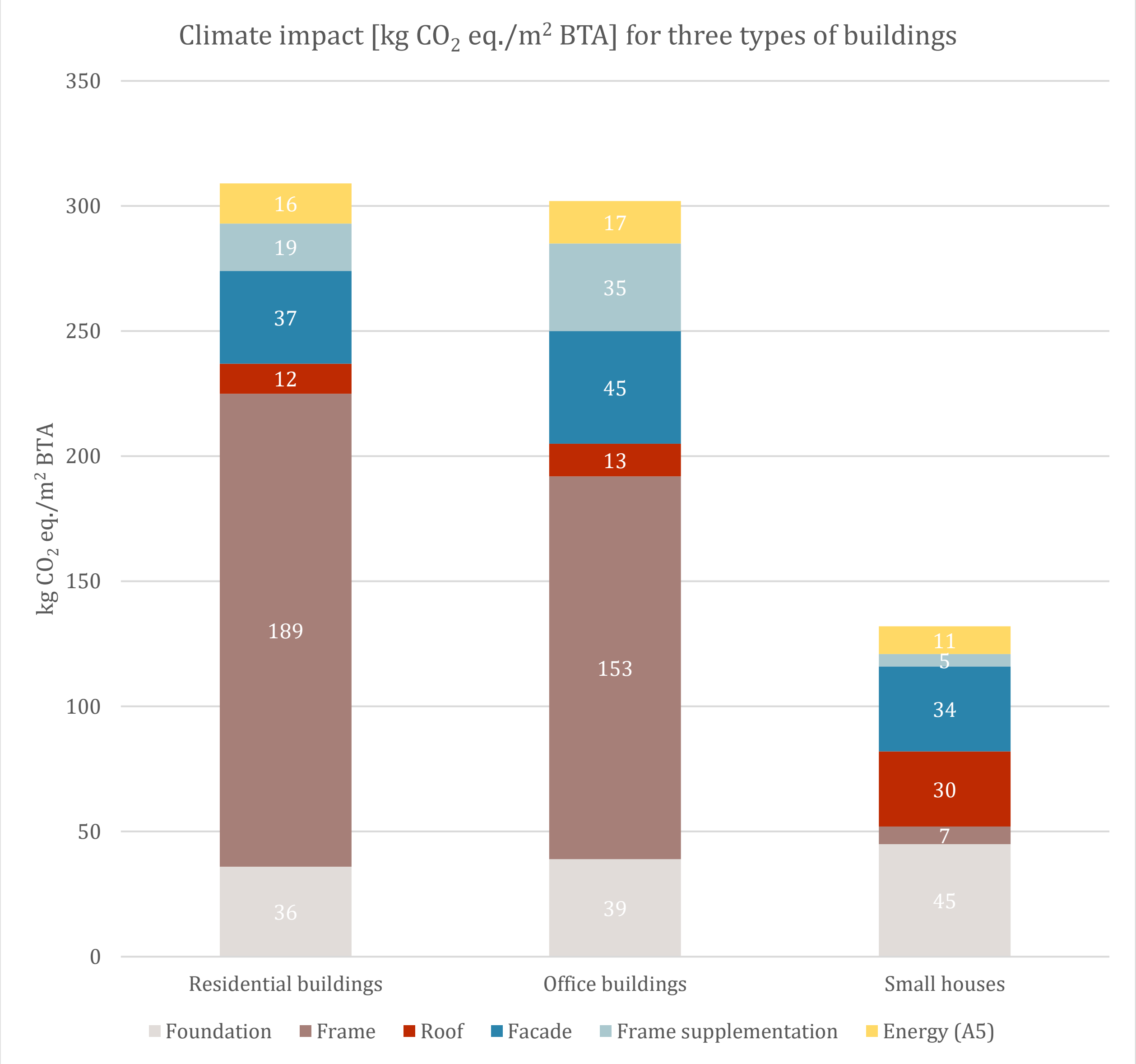


Figure 16 Climate impact in kg CO_2 eq./m^2 BTA for three different types of buildings analysed by Malmqvist et al. (2021). The climate impact considers phases A1-A5.

5 RESULTS: LCA OF THE CASE STUDY SELMA 2 BLOCK 10

In the following sections, the importance of material choices in buildings are quantitatively assessed through an LCA, applied on the residential building project Selma 2 Block 10. The results from the LCA are used to compare 4 different scenarios to conclude if the carbon footprint from the building project can be reduced when reusing building materials. The scenarios are further explained in section 5.2.1 below.

5.1 Goal of the case study

The goal of the case study is to investigate the climate benefits of reusing building materials. More specifically, the intended application of the case study is to compare the carbon footprint of the residential building project Selma 2 Block 10 when using virgin materials and reused materials. The results aim to guide the entrepreneurs and architects in the continuing planning of the project regarding material choices. Furthermore, the results are meant to contribute to a dialogue on the climate benefits of reusing building materials in the building industry.

The specific issue to be investigated is the fourth research question:

- *With how many percentages can the carbon footprint be reduced by reusing building materials in comparison to using only new materials in the residential building project Selma 2 Block 10?*

5.2 Scope of the case study

The conducted LCA is of the type change oriented comparative LCA that looks forward in time to compare alternative choices of action. The study is performed with the life cycle assessment software openLCA version 1.11.0 and the database ecoinvent version 3.8 as well as additional data from Boverkets klimatdatabas.

5.2.1 Scenarios

For the purpose of accounting for the reduction in CO_2 eq. emissions when reusing building materials in Selma 2 Block 10, four different scenarios have been modelled. The difference between the scenarios is what materials that are new materials and what materials are reused materials in the different building parts. Flowcharts for the scenarios are presented in Figure 17 and Figure 18 and further explanation on what materials that will be reused is presented in section 5.4.

Scenario 1 (S1) is used as a reference case where only new materials are used in Selma 2 Block 10. Both the raw material extraction and the manufacture of materials as well as the transportations are considered in the calculations for scenario 1.

Scenario 2 (S2) is the first material reuse case where materials deconstructed from other buildings are reused in Selma 2 Block 10. Which materials that are reused in the project will be based on expert interviews. All environmental loads from the deconstructed materials are allocated to the deconstructed buildings. In that sense only the transportation of the materials to the building site is considered. The transportation distances are based on Boverkets klimatdatabas for reused building products. The materials that are not possible to deconstruct from other buildings and reuse in Selma 2 Block 10 will be modelled equally as in scenario 1.

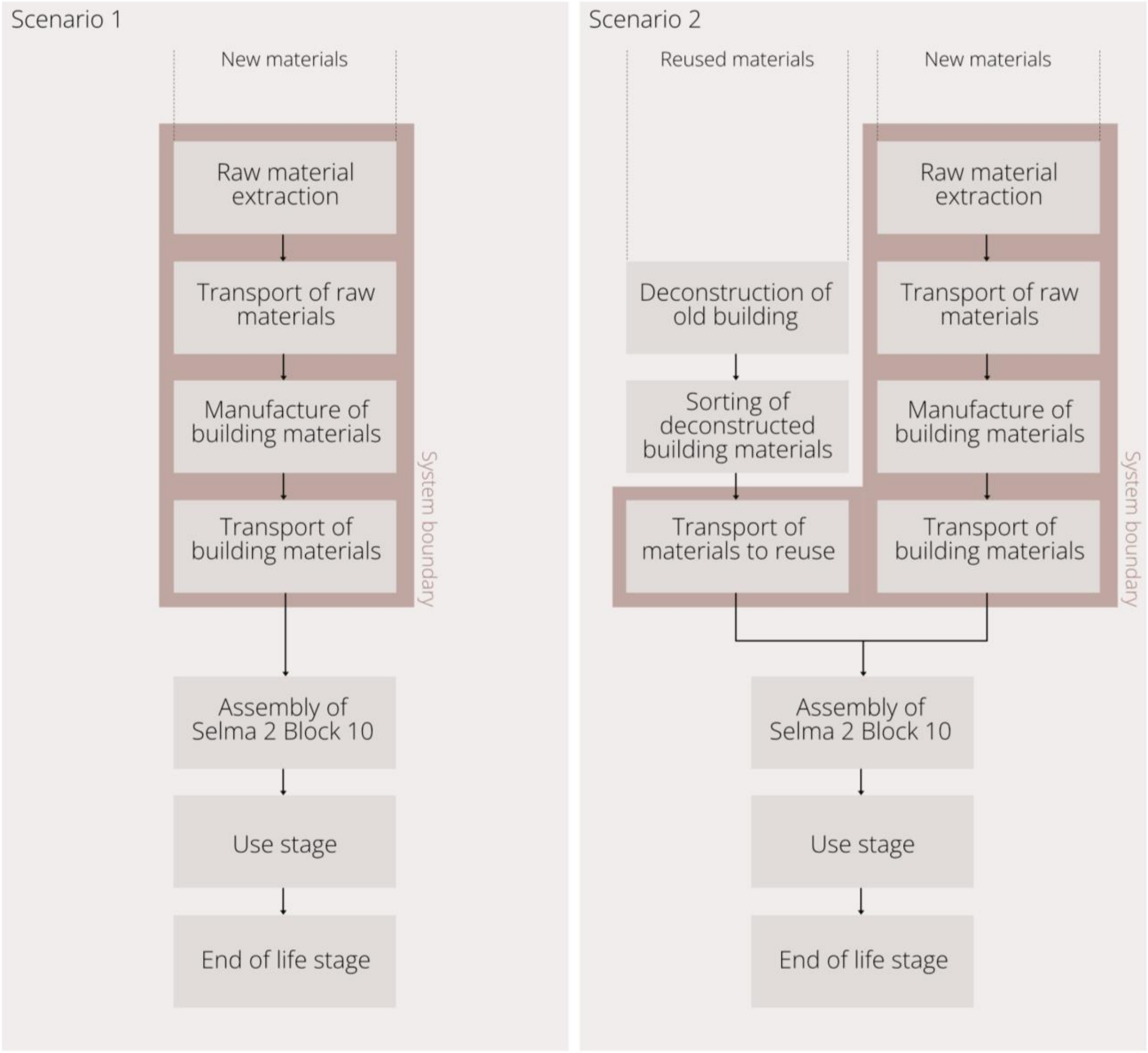


Figure 17 Flowchart of scenario 1 and 2 illustrating the systems to be studied.

Scenario 3 (S3) is the second material reuse case where only the materials in the building parts with the highest climate impact will be considered. The building parts with the highest climate impact will be based on the results from the literature review that stated the frame, facade, foundation and roof as the parts with highest climate impact. All environmental loads from the deconstructed materials are allocated to the deconstructed buildings. In that sense only the transportation of the materials to the building site is considered for the reused materials. The transportation distances are based on Boverkets klimatdatabas for reused building products. The materials that are not possible to deconstruct from other buildings and reuse in Selma 2 Block 10 and the materials that are included in the building parts other than those with the highest environmental impact will be modelled equally as in scenario 1.

Scenario 4 (S4) is the third material reuse case where all materials are modelled as reused materials from other deconstructed building. All building materials are assumed to be possible to deconstruct from other buildings and reuse in Selma 2 Block 10. All environmental loads from the deconstructed materials are allocated to the deconstructed buildings. In that sense only the transportation of the materials to the building site is considered. This scenario represents a best-case scenario but does not represent the actual reality regarding reuse possibilities.

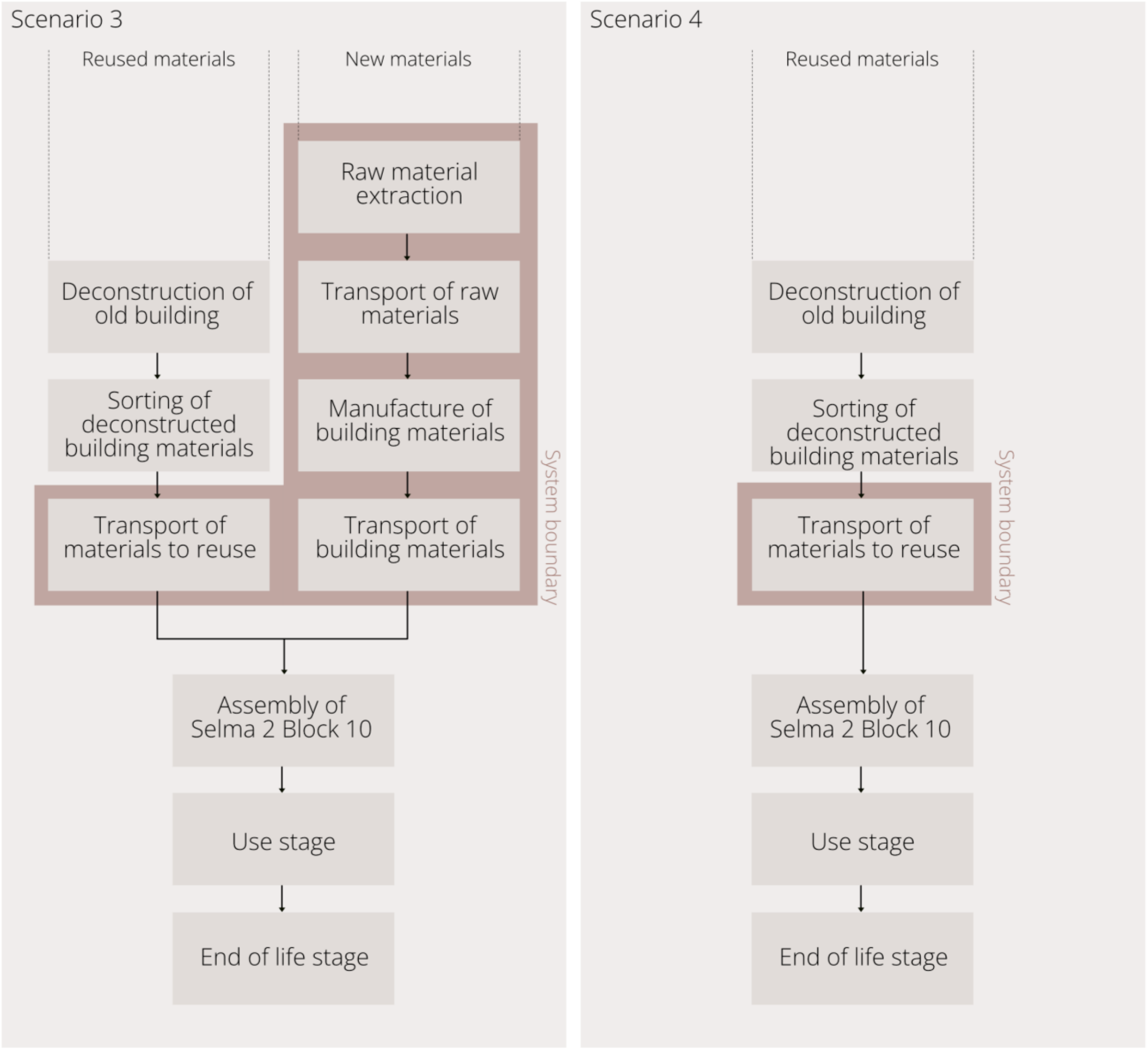


Figure 18 Flowchart of scenario 3 and 4 illustrating the systems to be studied.

5.2.2 Functional unit

Given that the function of the case study is to investigate the CO_2 eq. emission reductions from reusing building materials, the functional unit is set to *1 m^2 BTA*. In this way, the results from the different scenarios can be compared to each other based on the area of the building.

5.2.3 Impact category and method of impact assessment

Since the focus of the thesis is CO_2 eq. emissions from building materials, the chosen impact category is climate change with the categorization factor global warming potential in the time perspective of 100 years (GWP_{100}) given in kg CO_2 eq. The impact assessment method used in openLCA is the ready-made LCIA method CLM version 4.8 (2016).

5.2.4 System boundaries

The conducted study is of the type cradle-to-site which includes the life cycle stages A1, A2, A3 and A4 as illustrated in Figure 19. The construction installation process (A5) is excluded which is justified due to similar construction processes between the different scenarios. The building parts considered in the study are facade, foundation, frame, inner walls, roof and windows and doors. Table 2 shows a more exhaustive list on the building parts and the materials included.

The study period is set to 50 years which is the estimated lifetime of the building project according to Framtiden Byggutveckling. The geographical boundaries are set to Sweden. However, the database used for the LCA calculations, ecoinvent, is a Swiss database. Therefore, there are no Swedish data available from the database. Instead, Swiss or European data is used. If no Swiss or European data is available, global data is used. The data taken from Boverkets klimatdatabas is based on Sweden and is used for the transportation distances in the LCA calculations.

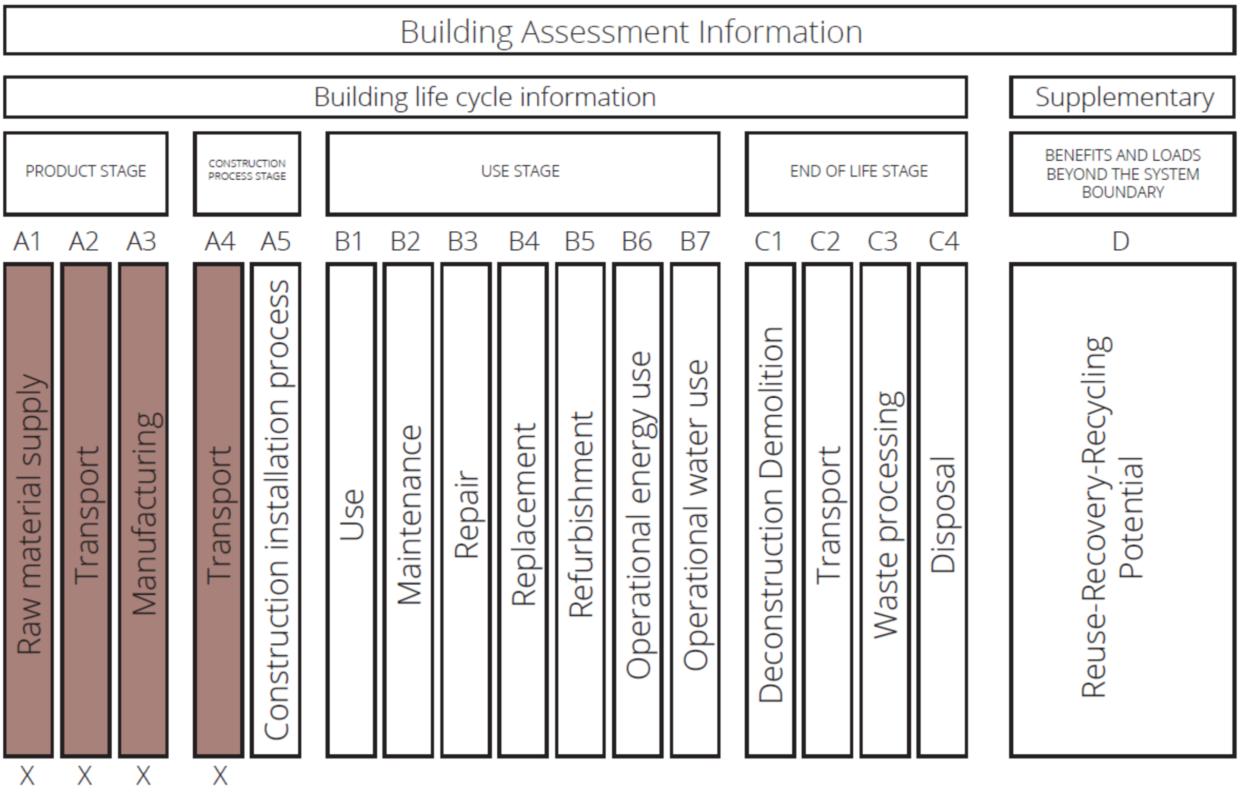


Figure 19 LCA stages included in the case study.

5.2.5 Data collection

The data on the type of building materials included in the different building parts of Selma 2 Block 10 is provided by Framtiden Byggutveckling. Likewise, the data on the mass of the different materials are also provided by Framtiden Byggutveckling. The calculations on the CO_2 eq. emissions are conducted in openLCA, and the data used for the building phases A1-A3 are based on generic data from the database ecoinvent version 3.8 that represent Swiss, European or global data. As Swedish data is not accessible, the used data is chosen to resemble Swedish data as far as possible by selecting providers from countries with similar production systems as Sweden. The calculations of the building phase A4 are based on generic data from Boverkets klimatdatabas that represent Swedish conditions. See Appendix II for a summary of the transportation data.

5.2.6 Assumptions and limitations

Some assumptions and limitations are made due to lack of time and data.

- The thesis will only consider the product stage and the transportation in the construction process stages of the building life cycle (i.e., stage A1-A4) and not the use stage and end of life stages (i.e., stage B and C).
- It is assumed that there are available materials from already deconstructed buildings to be reused in Selma 2 Block 10.
- It is assumed that that all environmental loads from the deconstructed materials reused in Selma 2 Block 10 are allocated to the already deconstructed buildings.
- Not all building parts are included in the LCA. Installations are for example not included.
- The case study does not investigate what impacts the materials have if reused after Selma 2 Block 10 is deconstructed.

5.3 Expert interviews regarding reusability of the building materials in Selma 2 Block 10

Two interviews with experts within reuse of building materials were conducted to determine what building materials that were possible to reuse in Selma 2 Block 10. The results from the interviews are presented in Table 4.

The first interviewee was an expert in circular and sustainable buildings working at the company IVL with one and a half year of experience in that specific post. The second interviewee was a person with 10 years of experience within the real estate sector and founder of a company which offers everything from in-service training and implementation of new methods of working to inventory of reusable materials and guidance for reuse in building projects. It was assumed that all materials required in Selma 2 Block 10 were available as reusable materials from other already deconstructed buildings.

The interviewees were in agreement regarding most materials. It was considered possible to reuse all sorts of wood, both cross-laminated timber, wood scantlings and fibreboards. Brick was a definite product to reuse while gypsum was considered possible but not probable to reuse due to difficulties in deconstructing them without breaking. All insulation was noted as reusable except EPS insulation from another ground. The second interviewee, however, argued that EPS insulation could be reused in Selma 2 Block 10 if taken from another building part than the ground, for example a facade, of a deconstructed building. Windows and doors were noted as reusable but if using windows and doors from a deconstructed building in Selma 2 Block 10 the airproofing and U-value were said to be inspected. The roof felt was not possible to reuse in the project. Other materials stated as hard or impossible to reuse were the plastic vapour control layer and the self-levelling mortar. Concrete was considered reusable if it came from the frame but not from the foundation. Regarding steel, it was possible to reuse from a deconstructed frame (e.g., steel pillars) but the reinforced steel was not stated as reusable.

Table 4 Answers from the interviewees on what building materials in Selma 2 Block 10 that can be reused from other deconstructed buildings (personal communication, May 2, 2022).

Building part	**Building material**	**Interviewee 1**	**Interviewee 2**
Foundation	EPS insulation	No	Yes
	Ready-mix concrete C12/15	No	No
	Plastic vapour control layer	No	No
	Self-levelling mortar	No	No
	Concrete C30/37	No	No
	Reinforcement steel	No	No
Frame	Steel	Yes	Yes
	Aggregate	Yes	Yes
	Gypsum board	Maybe	No
	Glass wool insulation	Yes	Yes
	Cross-laminated timber	Yes	Yes
	Gypsum board (floorboard)	No	No
	Fibreboard	Yes	Yes (if screwed)
	Ready-mix concrete C30/37	Yes	Yes
	Reinforcement steel	No	No
Roof	Plastic vapour control layer	No	No
	Gypsum board	Maybe	No
	Wood scantling	Yes	Yes
	Roof felt	No	No
	Cross-laminated timber	Yes	Yes
	Cellulose fibre (loose wool)	Yes (if gathered)	Yes
Facade	Gypsum board	Maybe	No
	Plastic vapour control layer	No	No
	Wood scantling	Yes	Yes
	Cellulose fibre (boards)	Yes	Yes
	Brick	Yes	Yes
Inner walls	Cross-laminated timber	Yes	Yes
	Gypsum board	Maybe	No
	Gypsum board (fireproof)	Maybe	No
	Wood scantling	Yes	Yes
	Cellulose fibre (boards)	Yes	Yes
Windows and doors	Steel door	Yes	Yes
	Aluminium profile for windows and doors	Yes	Yes
	Float glass	Yes	Yes
	Wooden decking, cladding and planed timber	Yes	Yes

5.4 Inventory analysis of the case study

In this section, the inventory analysis is provided for the building parts included in the case study. The tables describe what materials and providers are chosen from the database ecoinvent and what materials are modelled as reused for the different scenarios. All transports are made by lorries with the euro emissions standard Euro 5 according to Framtiden Byggutveckling and their environmental requirements on transportation (Framtiden Byggutveckling, personal communication, May 10, 2022). For more detailed inventory data see Appendix I for pre-existing inventory list of Selma 2 Block 10, Appendix II for transportation data and Appendix III for ecoinvent input data.

5.4.1 Foundation

The foundation consists of mostly concrete, but also reinforcement steel used in the concrete, EPS insulation, plastic vapour layer and self-levelling mortar as seen in Table 5.

In ecoinvent, the chosen material for EPS insulation is *polystyrene foam slab for perimeter insulation* with a density of 33 kg/m^3 and a thermal conductivity of 0.033 W/mK. The raw material extraction and transportation of the raw materials are included as well as the expanding of the polystyrene granulate and the forming of slabs. The energy required for the packaging of the product is not included. Further, the dataset is based on Switzerland. Comparing with the pre-existing inventory list of Selma 2 Block 10 (see Appendix I) the thermal conductivity is similar.

Two sorts of concrete are utilized in the foundation, partly C30/37 and partly C12/15. In ecoinvent, the chosen process for the C30/37 concrete is *concrete production, 30 MPa* which represents the ready-mix concrete with 30 MPa compressive strength at 28 days. The dataset is based on Austrian data and includes the whole manufacturing processes. For C12/15 the *concrete, normal* is chosen due to the lack of concrete with the compressive strength 12 MPa. The dataset represents Switzerland and includes the entire manufacturing process.

A plastic vapour control layer was not accessible in ecoinvent version 3.8 and therefore the chosen process is *packaging film production, low density polyethylene*. However, this packaging film is made of polyethylene and should therefore have somewhat similar production processes. The dataset is based on European data and includes the plastic amount and the transport of the plastic from the production site to the converting site as well as the plastic film extrusion.

The process from ecoinvent representing the self-levelling mortar is *cement mortar production*. The dataset is based on Swiss data and includes raw material provision, raw material mixing, packing, and storage as well as the transportation to the production plant.

Lastly, the process chosen to represent the reinforcement steel is *reinforcing steel production* which is based on data from Europe except Austria.

Table 5 Building materials included in the foundation and the chosen process from the database ecoinvent as well as the location.

Building material	ecoinvent	Location
EPS insulation	polystyrene foam slab for perimeter insulation	Switzerland
Ready-mix concrete C12/15	concrete, medium strength	Switzerland
Plastic vapour control layer	packaging film, low density polyethylene	Europe
Self-levelling mortar	cement mortar	Switzerland
Concrete C30/37	concrete, 30MPa	Austria
Reinforcement steel	reinforcing steel	Europe without Austria

From the interviews it can be concluded that most of the materials in the foundation were not considered reusable. Only the EPS insulation could be reused but only if the material was taken from other building part than a foundation. Table 6 below describes what materials are modelled as reused for the four scenarios.

Table 6 Explanation of building materials in the foundation that are modelled as reused in openLCA for scenario 1, 2, 3 and 4.

Building material	**Reused in:**	**S1**	**S2**	**S3**	**S4**
EPS insulation		No	Yes	Yes	Yes
Ready-mix concrete C12/15		No	No	No	Yes
Plastic vapour control layer		No	No	No	Yes
Self-levelling mortar		No	No	No	Yes
Concrete C30/37		No	No	No	Yes
Reinforcement steel		No	No	No	Yes

All transportation distances for the materials included in the foundation are based on Boverkets klimatdatabas. Further details can be found in Appendix II.

5.4.2 Frame

The frame for Selma 2 Block 10 is made of a cross-laminated timber structure with steel pillars and a staircase made of concrete. However, the frame consists of a variety of other materials as well. As can be seen in Table 7, it also includes aggregate, gypsum boards, glass wool insulation and reinforcement steel.

In ecoinvent, the chosen process for steel is *steel, unalloyed* which represent the production of primary steel. The dataset is based on European data and includes everything from the pre-treatment of hot metal to casting.

For the aggregate, the process *gravel production, crushed* is used due to lack of aggregate materials in ecoinvent version 3.8. The dataset is based on Swiss data and includes the whole manufacturing process, transport, and infrastructure.

The gypsum board as well as the gypsum floorboard is modelled with the process *gypsum, plasterboard production* from ecoinvent version 3.8. The dataset is based on Switzerland and represents the production from natural gypsum.

For the cross-laminated timber used in the frame, the process *cross-laminated timber production* is chosen. The dataset is based on German cross-laminated timber and includes the inputs to and outputs from the production processes as well as the available process emissions.

The fibreboard is chosen to be modelled with the process *medium density fibreboard production*. The dataset is based on European data and includes all the materials and fuels needed for production and ends at the factory gate.

In ecoinvent, the chosen process for the C30/37 concrete is *concrete production, 30 MPa* which represents the ready-mix concrete with 30 MPa compressive strength at 28 days. The dataset is based on Austrian data and includes the whole manufacturing processes.

Lastly, the process chosen to represent the reinforcement steel is *reinforcing steel production* which is based on data from Europe except Austria.

Table 7 Building materials included in the frame and the chosen process from the database ecoinvent as well as the location.

Building material	**ecoinvent**	**Location**
Steel	steel, unalloyed	Europe
Aggregate	gravel, crushed	Switzerland
Gypsum board	gypsum, plasterboard	Switzerland
Glass wool insulation	glass wool mat	Switzerland
Cross-laminated timber	cross-laminated timber	Europe
Gypsum board (floorboard)	gypsum, plasterboard	Switzerland
Fibreboard	medium density fibreboard	Europe
Ready-mix concrete C30/37	concrete 30MPa	Austria
Reinforcement steel	reinforcing steel	Europe without Austria

The interviews revealed that it is possible to choose reused products for around half of the materials in the frame. However, not the gypsum boards and reinforcement steel due to difficulties in deconstructing them without damage. Table 8 below describes what materials are modelled as reused for the four different scenarios.

Table 8 Explanation of building materials in the frame that are modelled as reused in openLCA for scenario 1, 2, 3 and 4.

Building material	**Reused in:**	**S1**	**S2**	**S3**	**S4**
Steel		No	Yes	Yes	Yes
Aggregate		No	Yes	Yes	Yes
Gypsum board		No	No	No	Yes
Glass wool insulation		No	Yes	Yes	Yes
Cross-laminated timber		No	Yes	Yes	Yes
Gypsum board (floorboard)		No	No	No	Yes
Fibreboard		No	Yes	Yes	Yes
Ready-mix concrete C30/37		No	Yes	Yes	Yes
Reinforcement steel		No	No	No	Yes

All transportation distances for the materials included in the frame except for the aggregate are based on Boverkets klimatdatabas. Aggregate is not included in Boverkets klimatdatabas and therefore the transportation distances for this material is based on the EPD library from the International EPD system (The international EPD system, n.d.). Further details can be found in Appendix II.

5.4.3 Roof

Selma 2 Block 10 is designed to have a roofing felt roof consisting of everything from cross-laminated timber and wood scantlings to insulation, plastic vapour control layer and gypsum boards, as can be seen in Table 9.

As explained in section 5.4.1, a plastic vapour control layer was not accessible in ecoinvent version 3.8 and therefore the chosen process is *packaging film production, low density polyethylene*. However, this packaging film is made of polyethylene and should therefore have somewhat similar production processes. The dataset is based on European data and includes the plastic amount and the transport of the plastic from the production site to the converting site as well as the plastic film extrusion.

The gypsum board is modelled with the process *gypsum, plasterboard production*. The dataset is based on Switzerland and represents the production from natural gypsum.

For the wood scantlings, the process *structural timber production* is chosen. The dataset is based on German samples and includes inputs and outputs of materials, fuels and emissions for and from the production until the factory gate.

The production of roof felt is not available in ecoinvent version 3.8 and therefore an own process, named *roof felt production*, was created. The modelling of the process is based on the paper *Comparing life cycle assessment modelling of linear vs. circular building components* (Eberhardt et al., 2019) which states that 1 m^2 of roof felt consists of 4 kg bitumen, 1.1 kg slate and 0.2 kg polyester. However, the energy for producing the actual roof felt out of these materials are not included.

For the cross-laminated timber used in the roof, the process *cross-laminated timber production* is chosen. The dataset is based on German cross-laminated timber and includes the inputs to and outputs from the production processes as well as the available process emissions.

Lastly, for the cellulose fibre the process *cellulose fibre production* is chosen. It describes the production of 1 kg of cellulose fibre from wastepaper with a thermal conductivity of 0.038 W/mK and a density of 30-60 kg/m^3. The dataset is based on Switzerland and includes the production of the cellulose fibre until factory gate.

Table 9 Building materials included in the roof and the chosen process from the database ecoinvent as well as the location.

Building material	**ecoinvent**	**Location**
Plastic vapour control layer	packaging film, low density polyethylene	Europe
Gypsum board	gypsum, plasterboard	Switzerland
Wood scantling	structural timber	Europe
Roof felt	roof felt, production (own process)	Denmark
Cross-laminated timber	cross-laminated timber	Europe
Cellulose fibre (loose wool)	cellulose fibre	Switzerland

From the interviews it can be concluded that half of the materials in the roof can be reused in Selma 2 Block 10. However, not the plastic vapour control layer, the gypsum boards or the roof felt. Table 10 below describes what materials are modelled as reused for the four scenarios.

Table 10 Explanation of building materials in the roof that are modelled as reused in openLCA for scenario 1, 2, 3 and 4.

Building material	Reused in:	S1	S2	S3	S4
Plastic vapour control layer		No	No	No	Yes
Gypsum board		No	No	No	Yes
Wood scantling		No	Yes	Yes	Yes
Roof felt		No	No	No	Yes
Cross-laminated timber		No	Yes	Yes	Yes
Cellulose fibre (loose wool)		No	Yes	Yes	Yes

All transportation distances for the materials included in the roof are based on Boverkets klimatdatabas and further details can be found in Appendix II.

5.4.4 Facade

The facade of Selma 2 Block 10 is a brick facade but includes additional materials such as wood scantlings, plastic vapour control layer, insulation and gypsum boards, as can be seen in Table 11.

The gypsum boards in the facade are modelled with the process *gypsum, plasterboard production*. The dataset is based on Switzerland and represents the production from natural gypsum.

As explained twice before, a plastic vapour control layer was not accessible in ecoinvent version 3.8 and therefore the chosen process is *packaging film production, low density polyethylene*. However, this packaging film is made of polyethylene and should therefore have somewhat similar production processes. The dataset is based on European data and includes the plastic amount and the transport of the plastic from the production site to the converting site as well as the plastic film extrusion.

For the wood scantlings in the facade, the process *structural timber production* is chosen. The dataset is based on German samples and includes inputs and outputs of materials, fuels and emissions for and from the production until the factory gate.

For the cellulose fibre the process *cellulose fibre production* is chosen. It describes the production of 1 kg of cellulose fibre from wastepaper with a thermal conductivity of 0.038 W/mK and a density of 30-60 kg/m^3. The dataset is based on Switzerland and includes the production of the cellulose fibre until factory gate.

Lastly, the chosen process to represent the brick is *clay brick production*. The dataset is based on datasets from Germany, Switzerland and Austria and includes everything from the first grinding process, wet process (second grinding, mixing and plastifying), storage, forming (an extruding molding method) and cutting to drying, firing, loading, packing and storage.

Table 11 Building materials included in the facade and the chosen process from the database ecoinvent as well as the location.

Building material	ecoinvent	Location
Gypsum board	gypsum, plasterboard	Switzerland
Plastic vapour control layer	packaging film, low density polyethylene	Europe
Wood scantling	structural timber	Europe
Cellulose fibre (boards)	cellulose fibre	Switzerland
Brick	clay brick	Europe

According to the interviewees, 3 out of 5 materials are possible to reuse in the facade of Selma 2 Block 10. However, as the case for the gypsum boards and plastic vapour layer in all building parts, these materials are not reusable. Table 12 below describes what materials are modelled as reused for the four scenarios.

Table 12 Explanation of building materials in the facade that are modelled as reused in openLCA for scenario 1, 2, 3 and 4.

Building material	**Reused in:**	**S1**	**S2**	**S3**	**S4**
Gypsum board		No	No	No	Yes
Plastic vapour control layer		No	No	No	Yes
Wood scantling		No	Yes	Yes	Yes
Cellulose fibre (boards)		No	Yes	Yes	Yes
Brick		No	Yes	Yes	Yes

All transportation distances for the materials included in the facade are based on Boverkets klimatdatabas and further details can be found in Appendix II.

5.4.5 Windows and doors

The chosen material for the window profiles in Selma 2 Block 10 is aluminium and the windows naturally also include glass. The doors are chosen to be made of steel and additional wood is required for joinery applications. Table 13 shows what materials are included in the windows and doors.

Due to the lack of a process representing the production of a door entirely made of steel in ecoinvent version 3.8, the process chosen for the outer door is *door production, outer, wood-aluminium*. The dataset represents the production of an average entrance door with a door frame made of steel and a door leaf made of wood and aluminium. The data is based on Europe and more specifically on data from producers in Switzerland.

For the aluminium profiles for windows and doors, the process *window frame production, aluminium* is chosen which represents the inputs of material and processes needed to produce an aluminium window frame with 1 m^2 visible area. The dataset is based on European data and includes everything from section bar rolling for steel parts and fittings, section bar extrusion for aluminium parts, extrusion of HDPE plastic and surface treatment to all the road transport at different production phases, the heat waste and the disposal of the plastic cuttings.

The chosen process for the float glass is *flat glass production, uncoated* which represents the production of 1 kg of uncoated flat glass. The dataset is based on Europe and includes raw material provision, cullet addition, melting process, forming process, cooling process, cutting process and storage, transport and infrastructure.

Lastly, for the wooden decking, cladding and planed timber for joinery applications, the chosen process is *structural timber production*. The dataset is based on German samples and includes inputs and outputs of materials, fuels and emissions for and from the production of structural timber until the factory gate.

Table 13 Building materials included in the windows and doors and the chosen process from the database ecoinvent as well as the location.

Building material	**ecoinvent**	**Location**
Steel door	door, outer, wood-aluminium	Europe
Aluminium profile for windows and doors	window frame, aluminium, U=1.6 W/m^{2}K	Europe
Float glass	flat glass, coated	Europe
Wooden decking, cladding and planed timber	structural timber	Europe

From the interviews it can be concluded that all materials used in the windows and doors can be reused in Selma 2 Block 10. Table 14 below describes what materials are modelled as reused for the four scenarios.

Table 14 Explanation of building materials in the windows and doors that are modelled as reused in openLCA for scenario 1, 2, 3 and 4

Building material	**Reused in:**	**S1**	**S2**	**S3**	**S4**
Steel door		No	Yes	No	Yes
Aluminium profile for windows and doors		No	Yes	No	Yes
Float glass		No	Yes	No	Yes
Wooden decking, cladding and planed timber		No	Yes	No	Yes

All transportation distances for the materials included in the windows and doors are based on Boverkets klimatdatabas and further details can be found in Appendix II.

5.4.6 Inner walls

The inner walls consist of mostly wood in terms of cross-laminated timber and scantlings but also gypsum and insulation, illustrated in Table 15.

The process from ecoinvent representing the cross-laminated timber is *cross-laminated timber production*. The dataset is based on German cross-laminated timber and includes the inputs to and outputs from the production processes as well as the available process emissions. The fibreboard is chosen to be modelled with the process *medium density fibreboard production*. The dataset is based on European data and includes all the materials and fuels needed for production and ends at the factory gate.

The gypsum board as well as the fireproof gypsum board is modelled with the process *gypsum, plasterboard production* from ecoinvent version 3.8. The dataset is based on Switzerland and represents the production from natural gypsum.

For the wood scantlings in the inner walls, the process *structural timber production* is chosen. The dataset is based on German samples and includes inputs and outputs of materials, fuels and emissions for and from the production until the factory gate.

Lastly, for the cellulose fibre the process *cellulose fibre production* is chosen. It describes the production of 1 kg of cellulose fibre from wastepaper with a thermal conductivity of 0.038 W/mK and a density of 30-60 kg/m^3. The dataset is based on Switzerland and includes the production of the cellulose fibre until factory gate.

Table 15 Building materials included in the inner walls and the chosen process from the database ecoinvent as well as the location.

Building material	**ecoinvent**	**Location**
Cross-laminated timber	cross-laminated timber	Europe
Gypsum board	gypsum, plasterboard	Switzerland
Gypsum board (fireproof)	gypsum, plasterboard	Switzerland
Wood scantling	structural timber	Europe
Cellulose fibre (boards)	cellulose fibre	Switzerland

According to the interviewees, all materials in the inner walls except the gypsum boards are possible to reuse in Selma 2 Block 10. Table 16 below describes what materials are modelled as reused for the four scenarios.

Table 16 Explanation of building materials in the inner walls that are modelled as reused in openLCA for scenario 1, 2, 3 and 4.

Building material	**Reused in:**	**S1**	**S2**	**S3**	**S4**
Cross-laminated timber		No	Yes	No	Yes
Gypsum board		No	No	No	Yes
Gypsum board (fireproof)		No	No	No	Yes
Wood scantling		No	Yes	No	Yes
Cellulose fibre (boards)		No	Yes	No	Yes

All transportation distances for the materials included in the inner walls are based on Boverkets klimatdatabas. Further details can be found in Appendix II.

5.5 Climate impact assessment of the case study

This section presents the impacts from the four different scenarios when assessed for the impact category climate change. Firstly, the total impacts from all included building parts are compared. Then follows a comparison of the impacts from the individual building parts. The functional unit for the assessment is *1 m^2 BTA.*

5.5.1 Total climate impact for scenario 1, 2, 3 and 4

The total impact for Selma 2 Block 10 in kg CO_2 eq./m^2 BTA is shown in Figure 20. It is made according to the scenarios explained in section 5.2.1 where scenario 1 (S1) represents a reference case with only new materials used in the building project. Scenario 2 (S2) signifies the first material reuse case where all materials that are possible to reuse are modelled as reused. What materials that are possible to reuse are based on the expert interviews. Scenario 3 (S3) investigates the outcomes of reusing materials in the foundation, frame, roof and facade and are also based on the interviews regarding what materials are reusable. Scenario 4 (S4) is the best-case scenario where all materials are from deconstructed buildings and reused in Selma 2 Block 10.

The total emissions for scenario 1 are 254.9 kg CO_2 eq./m^2 BTA whereas for scenario 2 the total emissions are significantly lower at 60.8 kg CO_2 eq./m^2 BTA. For scenario 3 the total emissions end at 106.8 kg CO_2 eq./m^2 BTA and for scenario 4 at 2.3 kg CO_2 eq./m^2 BTA. The charts also illustrate the contribution from the different building parts where the frame, foundation and windows and doors are responsible for the majority of the impact in scenario 1 and 3 while the foundation is dominating the impacts in scenario 2. Scenario 4 have low contributions from all building parts.

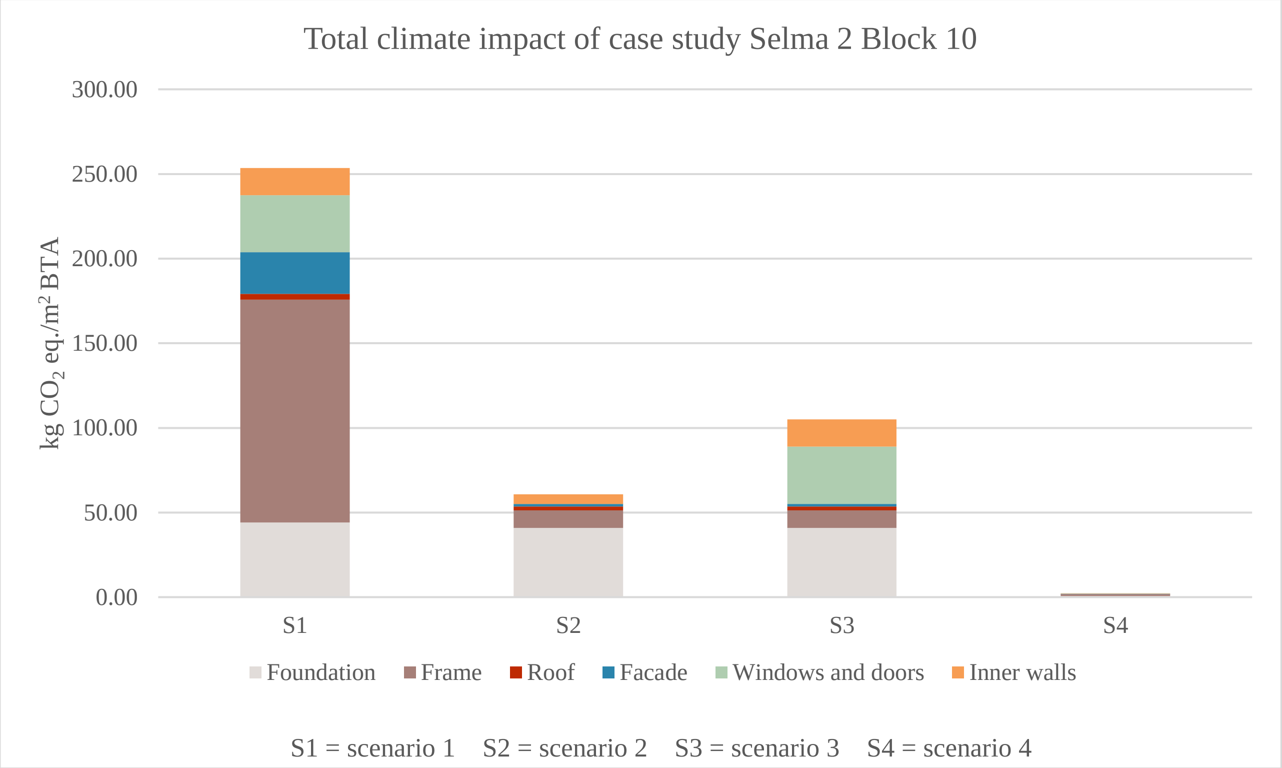


Figure 20 Total impact from Selma 2 Block 10 for the four different scenarios presented in kg CO_2 eq./m^2 BTA.

Figure 21 below illustrates the comparison of the relative results, where the scenario with maximum emissions is normalised to 100% and the other scenarios are displayed in relation to the maximum. The charts reveal that reusing materials in Selma 2 Block 10 results in a 76% reduction of CO_2 eq. emissions for the chosen system boundaries and assumptions in scenario 2. If only materials in the foundation, frame, roof and facade are reused (scenario 3) a 58% reduction will be obtained. If reusing all materials in Selma 2 Block 10 (scenario 4) the CO_2 eq. emissions will be reduced by 99%.

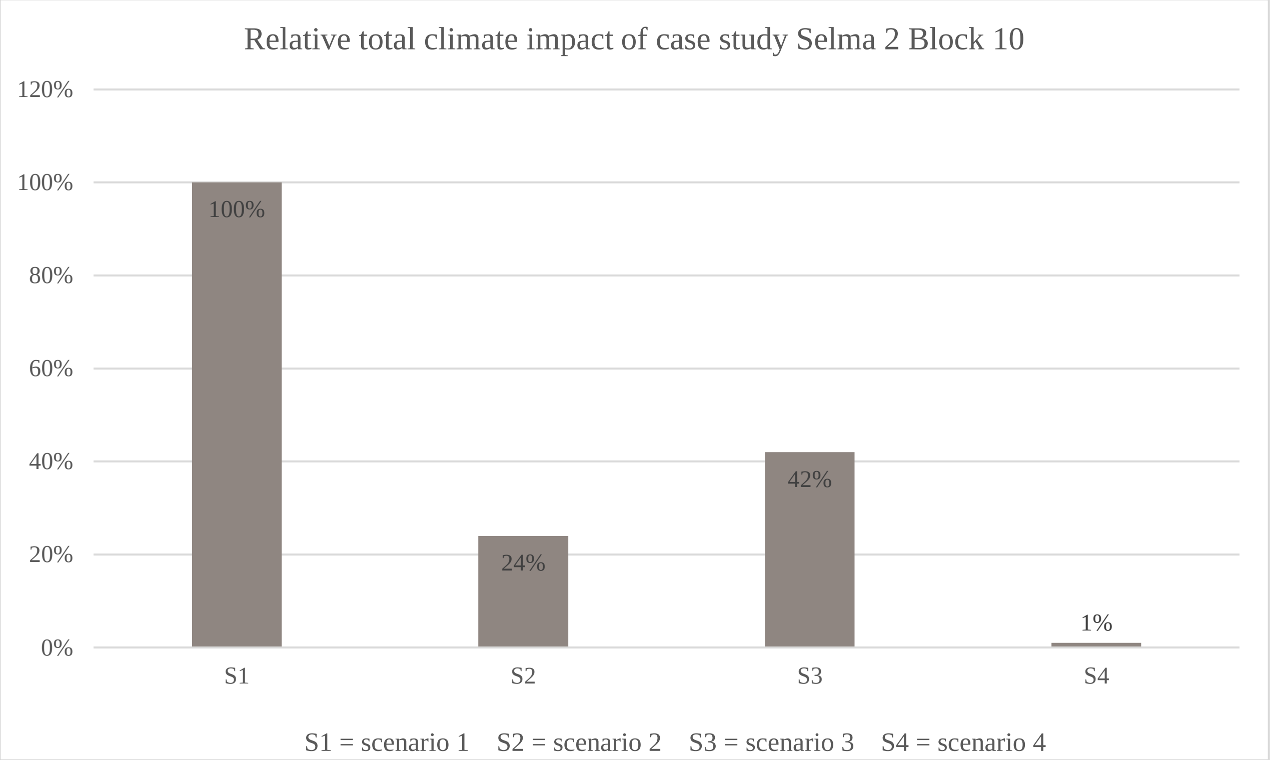


Figure 21 The relative results of the total impact from Selma 2 Block 10 for scenario 1, 2, 3 and 4.

5.5.2 Impacts from the foundation

The impact from the foundation in kg CO_2 eq./m^2 BTA is shown to the left in Figure 22. Scenario 1, 2 and 3 have results in the same order of magnitude while scenario 4 have a significantly lower number. However, scenario 1 have the highest impact with a total emission of 44.1 kg CO_2 eq./m^2 BTA. The foundation in scenario 2 and scenario 3 is responsible for 40.9 kg CO_2 eq./m^2 BTA while scenario 4 emits only 0.5 kg CO_2 eq./m^2 BTA.

Similar to the impacts in CO_2 eq./m^2 BTA, the relative impact is very similar for scenario 1, 2 and 3 while scenario 4 is considerably lower. The charts to the right in Figure 22 below reveal that reusing materials in the foundation according to scenario 2 and 3 results in a 7% reduction of CO_2 eq. emissions. If reusing all materials in the foundation (scenario 4) the CO_2 eq. emissions will be reduced by 99%.

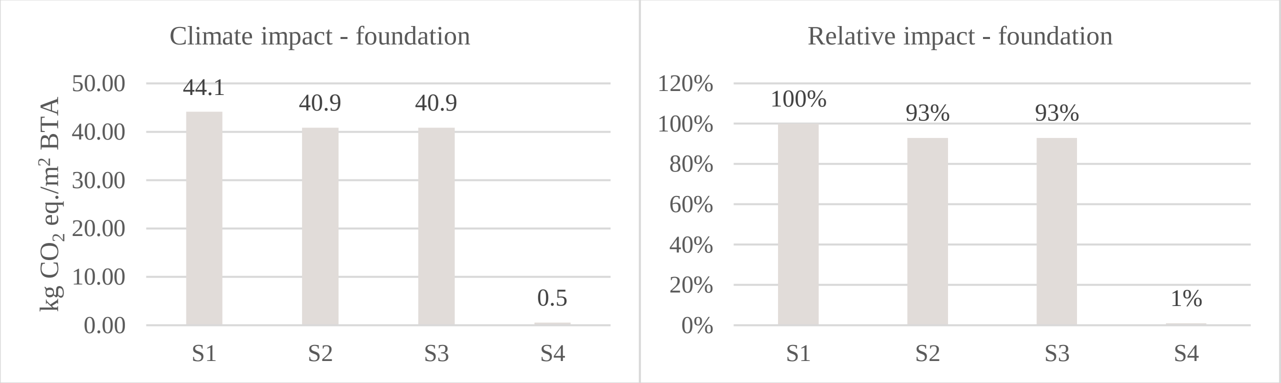


Figure 22 Total impact from the foundation for the four different scenarios presented in kg CO_2 eq./m^2 BTA to the left and the relative results from the foundation for scenario 1, 2, 3 and 4 to the right.

5.5.3 Impacts from the frame

Figure 23 illustrates the impact from the frame in kg CO_2 eq./m^2 BTA. Scenario 1 clearly has the highest impact while scenario 2, 3 and 4 have a drastically lower impact. The total emissions from the frame for scenario 1 is 131.6 kg CO_2 eq./m^2 BTA. For scenario 2 and 3 it is 10.4 kg CO_2 eq./m^2 BTA. The frame in scenario 4 is responsible for 1.1 kg CO_2 eq./m^2 BTA.

Regarding the relative impact, the charts to the right in Figure 23 below reveal that reusing materials in the frame according to scenario 2 and 3 results in a 92% reduction of CO_2 eq. emissions. If reusing all materials in the frame as in scenario 4 the CO_2 eq. emissions will be reduced by 99%.

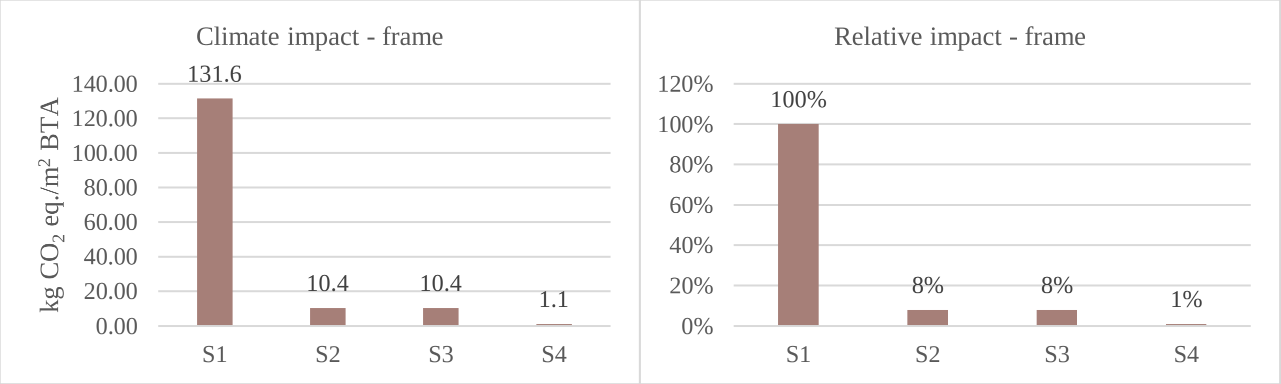


Figure 23 Total impact from the frame for the four different scenarios presented in kg CO_2 eq./m^2 BTA to the left and the relative results from the frame for scenario 1, 2, 3 and 4 to the right.

5.5.4 Impacts from the roof

The impact from the roof in kg CO_2 eq./m^2 BTA is shown to the left in Figure 24. Scenario 1 has the highest emissions at 3.4 kg CO_2 eq./m^2 BTA while scenario 2 and 3 is slightly lower at 2.3 kg CO_2 eq./m^2 BTA. Scenario 4 is significantly lower at 0.1 kg CO_2 eq./m^2 BTA.

Figure 24 below also illustrates the comparison of the relative results. By reusing materials in the roof according to scenario 2 and 3 the CO_2 eq. emissions can be reduced by 34%. If all materials are reused, as in scenario 4, a total reduction of 98% can be obtained.

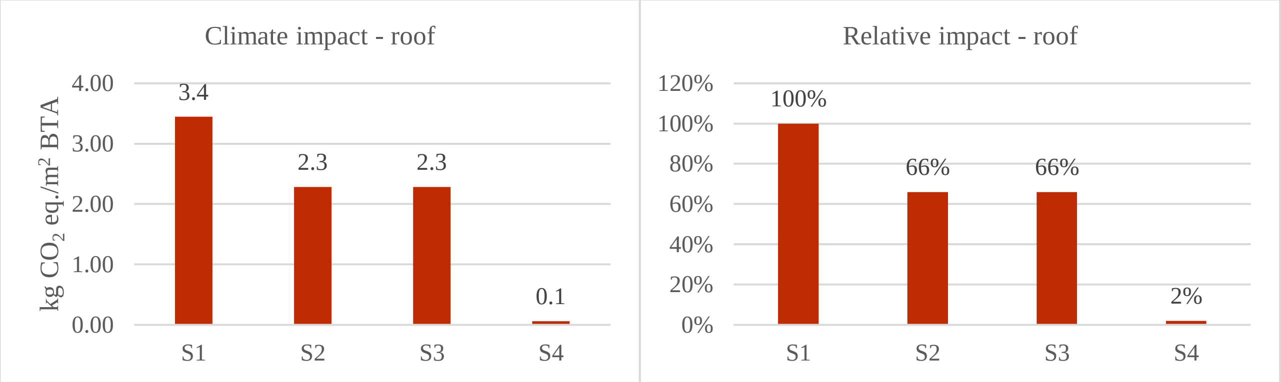


Figure 24 Total impact from the roof for the four different scenarios presented in kg CO_2 eq./m^2 BTA to the left and the relative results from the roof for scenario 1, 2, 3 and 4 to the right.

5.5.5 Impacts from the facade

Figure 25 illustrates the impact from the facade in kg CO_2 eq./m^2 BTA. Scenario 1 clearly has the highest impact while scenario 2, 3 and 4 have a drastically lower impact. The total emissions from the facade for scenario 1 is 24.5 kg CO_2 eq./m^2 BTA. For scenario 2 and 3 it is 1.6 kg CO_2 eq./m^2 BTA. The frame in scenario 4 is responsible for 0.3 kg CO_2 eq./m^2 BTA.

Furthermore, Figure 25 illustrates the relative impact from the facade for the four different scenarios. The charts reveal that by reusing materials in the facade according to scenario 2 and 3, the CO_2 eq. emissions can be reduced by 93%. If all materials are reused in the facade as in scenario 4, the reduction will be 99%.

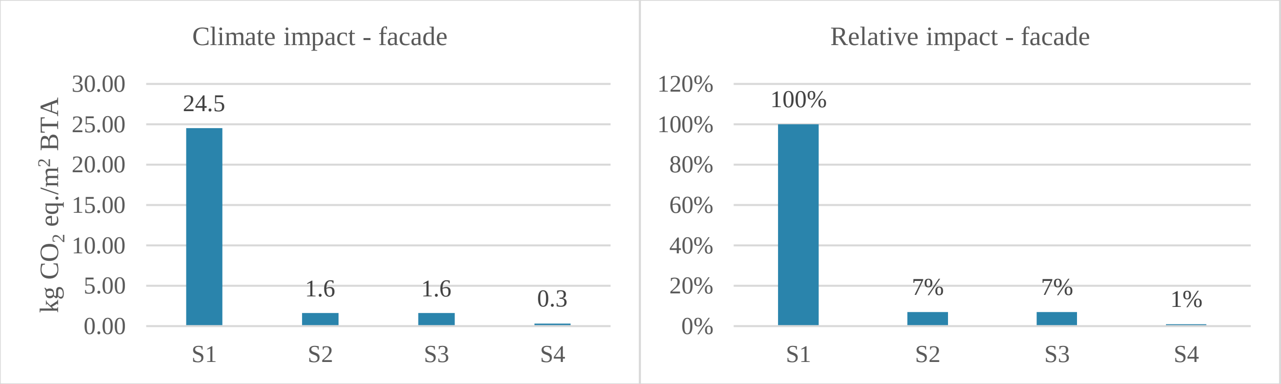


Figure 25 Total impact from the facade for the four different scenarios presented in kg CO_2 eq./m^2 BTA to the left and the relative results from the facade for scenario 1, 2, 3 and 4 to the right.

5.5.6 Impacts from the windows and doors

The impact from the windows and doors in kg CO_2 eq./m^2 BTA is shown to the left in Figure 26. Scenario 1 and 3 have the highest impacts at 35.2 kg CO_2 eq./m^2 BTA while the impact from scenario 2 and 4 is only 0.02 kg CO_2 eq./m^2 BTA.

Regarding the relative impact, the charts to the right in Figure 26 below reveal that reusing materials in the windows and doors according to scenario 2 and 4 results in a 100% reduction of CO_2 eq. emissions. For scenario 3 there is no reduction since that scenario does not involve reuse of any materials.

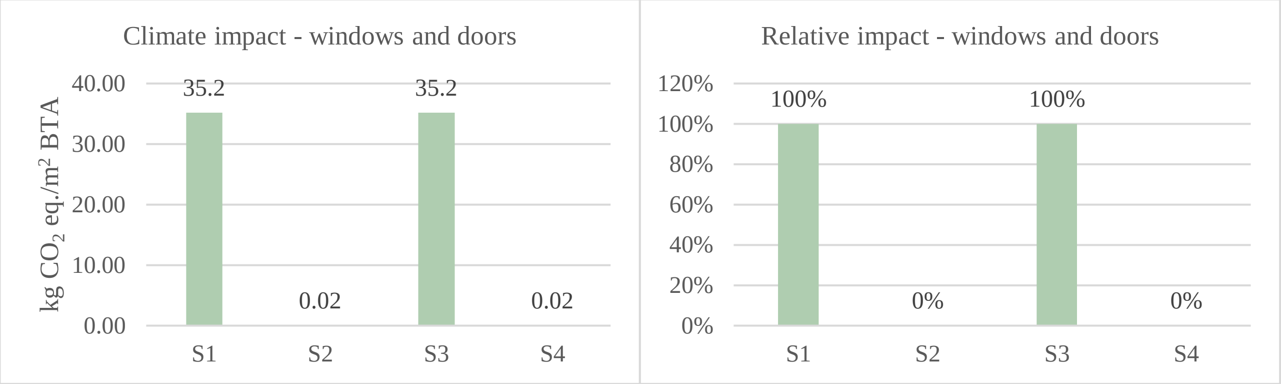


Figure 26 Total impact from the windows and doors for the four different scenarios presented in kg CO_2 eq./m^2 BTA to the left and the relative results from the windows and doors for scenario 1, 2, 3 and 4 to the right.

5.5.7 Impacts from the inner walls

The impact from the inner walls in kg CO_2 eq./m^2 BTA is shown to the left in Figure 27. Scenario 1 and 3 has the highest emissions at 16.0 kg CO_2 eq./m^2 BTA while scenario 2 and 4 is lower at 5.6 respectively 0.2 kg CO_2 eq./m^2 BTA.

Figure 27 below also illustrates the comparison of the relative results. By reusing materials in the inner walls according to scenario 2 the CO_2 eq. emissions can be reduced by 65%. If all materials are reused, as in scenario 4, a total reduction of 98% can be obtained. Scenario 3 does not imply any reduction of the CO_2 eq. emissions since there is no reuse of materials in that scenario.

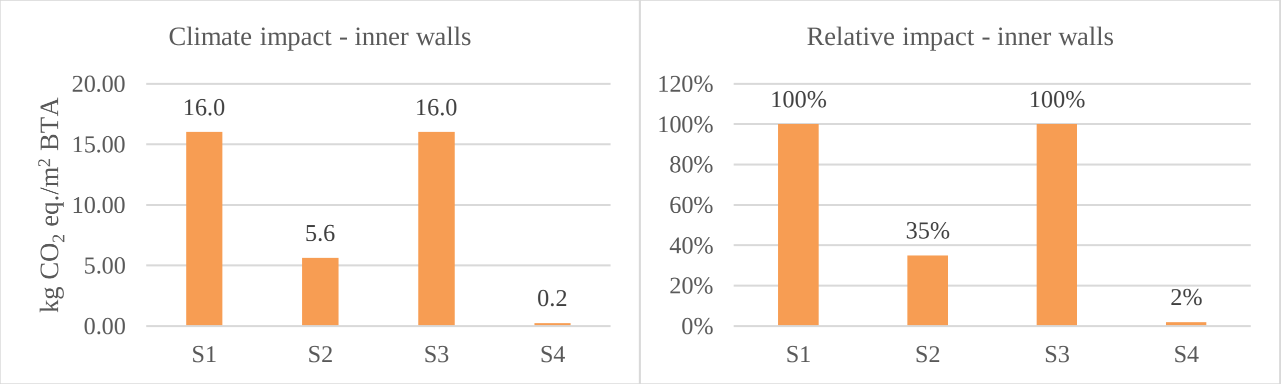


Figure 27 Total impact from the inner walls for the four different scenarios presented in kg CO_2 eq./m^2 BTA to the left and the relative results from the windows and doors for scenario 1, 2, 3 and 4 to the right.

5.6 Interpretation of the case study

In this section the results from the LCA are interpreted and verified. Firstly, an identification of significant issues based on the climate impact assessment are made. Secondly, a sensitivity analysis with respect to transportation distances for the reused materials is performed. Lastly, a comparison between the results from the climate impact assessment and reference values for buildings in Sweden is made.

5.6.1 Identification of significant issues from the case study

As stated in the goal and scope, the specific issue to be investigated in the case study was the fourth research question *RQ4: With how many percentages can the carbon footprint be reduced by reusing building materials in comparison to using only new materials in the residential building project Selma 2 Block 10?* Therefore, the most significant issues from the climate impact assessment in section 5.5 are the reductions in CO_2 eq. emissions summarized in Table 17 below.

If reusing materials in Selma 2 Block 10, it is possible to reduce the total CO_2 eq. emissions by 76% for the building life cycle stages A1-A4. If only reusing materials in the foundation, frame, roof and facade, it is possible to reduce the total climate footprint by 58%. Lastly, if reusing all materials in Selma 2 Block 10 it is possible to achieve a reduction of 99%. These results presumes that all environmental loads from the deconstructed materials reused in Selma 2 Block 10 are allocated to the already deconstructed buildings. Furthermore, the windows and doors, facade and frame have the greatest possibility to achieve large reductions in CO_2 eq. emissions with a 100%, 93% and 92% reduction respectively for scenario 2. The foundation has the lowest possibility to contribute to a smaller carbon footprint with only a 7% reduction for scenario 2.

Table 17 Summary of the percentage reduction of CO_2 eq. emissions for both the total impact from Selma 2 Block 10 and the different building parts included in the case study.

	kg CO_2 eq./m^2 BTA scenario 1	Reduction potential scenario 2	Reduction potential scenario 3	Reduction potential scenario 4
Total impact	**254.9**	**-76%**	**-58%**	**-99%**
Foundation	44.1	-7%	-7%	-99%
Frame	131.6	-92%	-92%	-99%
Roof	3.4	-34%	-34%	-98%
Facade	24.5	-93%	-93%	-99%
Windows and doors	35.2	-100%	0%	-100%
Inner walls	16.0	-65%	0%	-98%

5.6.2 Sensitivity analysis with respect to transportation distances for the reused materials

Due to the lack of knowledge regarding origin of the materials reused in Selma 2 Block 10, the transportation distances are set to 40 km according to Boverkets klimatdatabas. All transportation distances of reused building products are set to 40 km in Boverkets klimatdatabas independent of material. To analyse the influence of this, a sensitivity analysis with respect to transportation distances for the reused materials is made. The sensitivity analysis is done by changing the distances for the reused materials in scenario 2, 3 and 4 to the distances used in scenario 1 i.e., the mean values for the transportation of new materials. The transportation distances for the different building parts in scenario 2 and 3 are changed according to Table 18 below. For scenario 4, all transportation distances are changed to the average value for every building material according to Appendix I.

Table 18 Changed inputs of transportation distances for the sensitivity analysis.

Building material	**Original distance (km)**	**Distance in sensitivity analysis (km)**
Aggregate (reused)	40	449
Brick (reused)	40	640
Concrete (reused)	40	35
Insulation (reused)	40	440
Steel (reused)	40	1040
Windows and doors (reused)	40	540
Wood (reused)	40	380

With the changed inputs, the total impact for scenario 2, 3 and 4 change slightly as illustrated in Figure 28. The emissions for scenario 2 increase from 60.8 to 69.9 kg CO_2 eq./m^2 BTA. For scenario 3 the emissions increase from 106.8 to 119.3 kg CO_2 eq./m^2 BTA. Lastly, for scenario 4 the results change from 2.3 to 19.1 kg CO_2 eq./m^2 BTA. Figure 29 reveals that this equals to a 3% increase in relative impact for scenario 2, a 5% increase in relative impact for scenario 3 and a 7% increase in relative impact for scenario 4 in comparison to the original results. This implies that the transportation distances for the reused materials have an influence on the results, but the influence is not considerably large. Despite of longer transportation distances, it still seems possible to reduce the carbon footprint by reusing building materials.

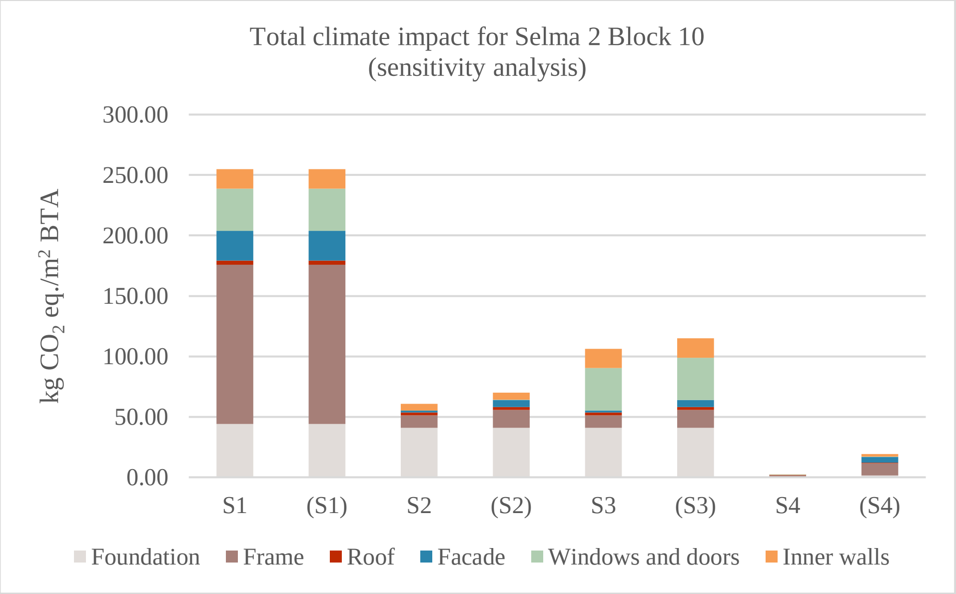


Figure 28 Total impact from Selma 2 Block 10 for the four different scenarios presented in kg CO_2 eq./m^2 BTA. S1, S2, S3 and S4 represent the original results while (S1), (S2), (S3) and (S4) represent the results from the sensitivity analysis.

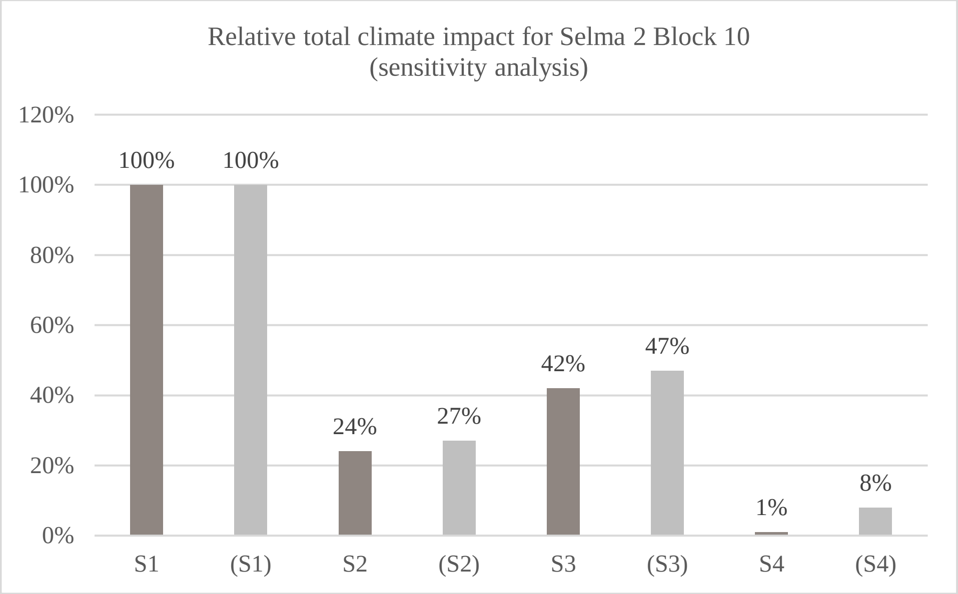
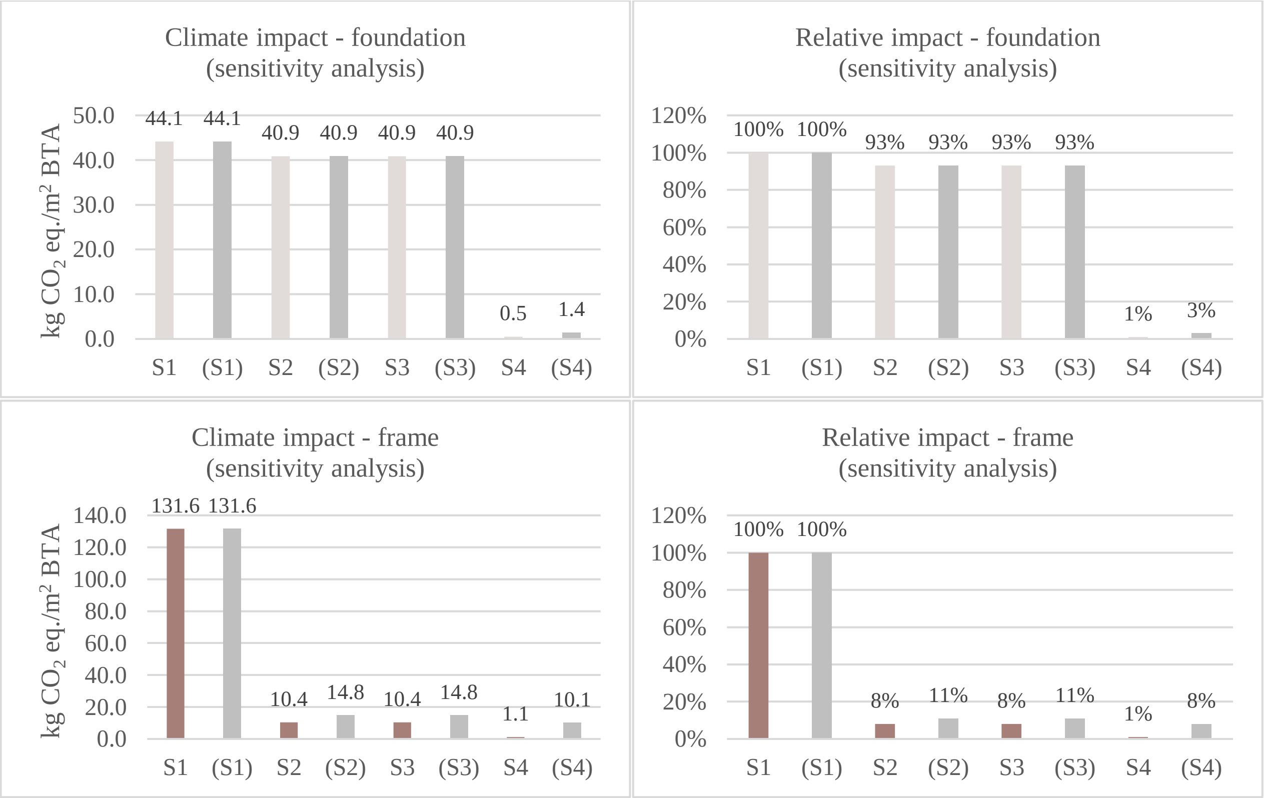


Figure 29 The relative results of the total impact from Selma 2 Block 10 for scenario 1, 2, 3 and 4. S1, S2, S3 and S4 represent the original results while (S1), (S2), (S3) and (S4) represent the results from the sensitivity analysis.

Looking at the graphs for the specific building parts, illustrated in Figure 30 below, the changed results from the sensitivity analysis follow the same pattern. The impact increases for all parts if the transportation distances are changed, expect from the foundation where the impact remains the same for scenario 2 and 3.



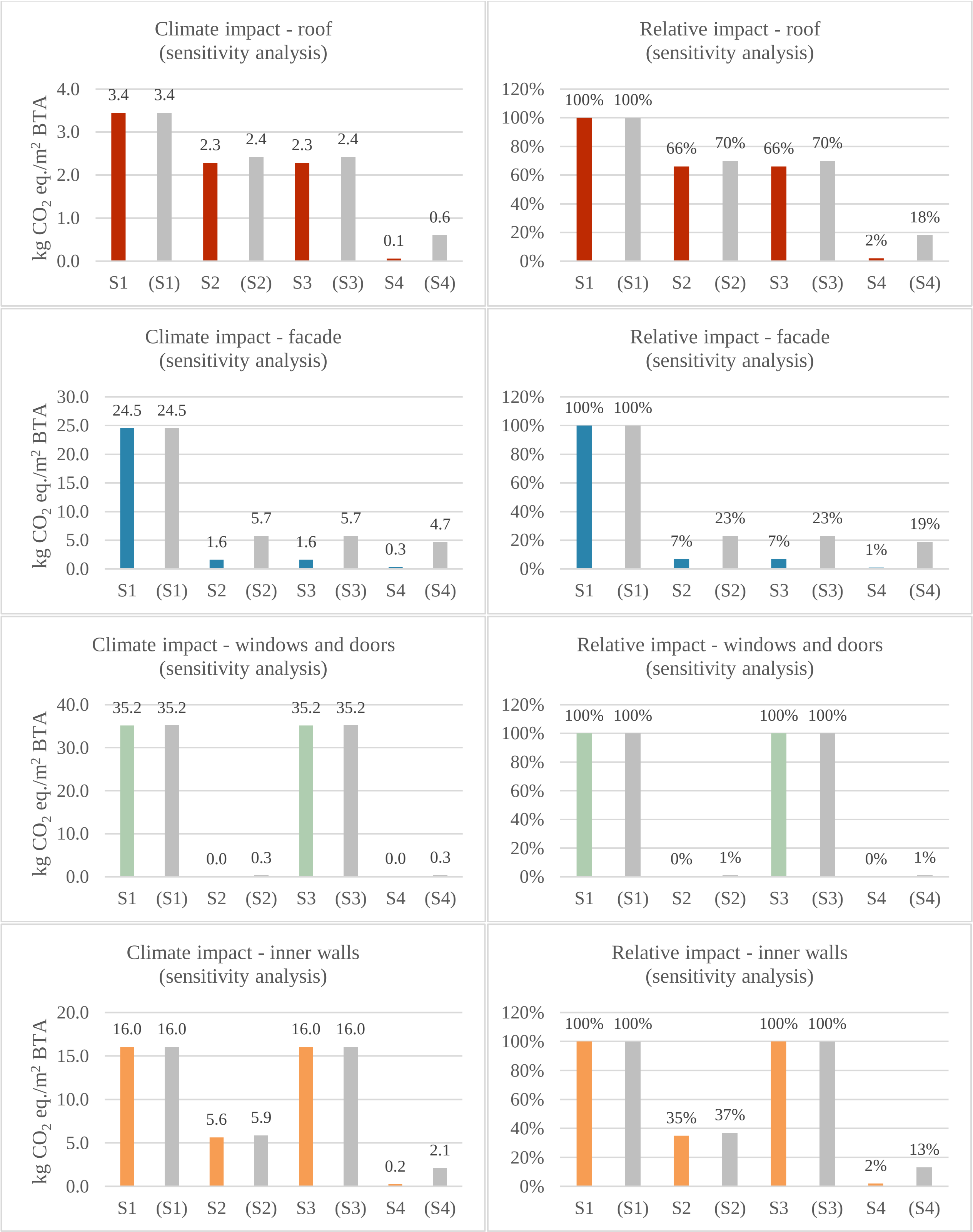


Figure 30 The total impact and relative results of the total impact from Selma 2 Block 10 for the different building parts. S1, S2, S3 and S4 represent the original results while (S1), (S2), (S3) and (S4) represent the results from the sensitivity analysis.

5.6.3 Comparison to reference values for buildings in Sweden

To verify the results, a comparison with reference values for buildings in Sweden is made. The reference values are based on the results from the research report by Malmqvist et al. (2021) introduced and described in section 4.4.

Figure 31 below is a complemented version of Figure 16 and illustrates the climate impact in kg CO_2 eq./m^2 BTA for the three different types of buildings analysed in the research report by Malmqvist et al. (2021) and Selma 2 Block 10 scenario 1. Note that the results from the research report by Malmqvist et al. (2021) includes the building life cycle phases A1-A5 while the results from Selma 2 Block 10 only considers A1-A4. Furthermore, the research report by Malmqvist et al. (2021) differs from the analysis made in this thesis regarding building parts included in the analysis. The research report by Malmqvist et al. included the foundation, frame, roof, facade, frame supplementation and energy (A5) while the included parts in this thesis are the foundation, frame, roof, facade, windows and doors and inner walls. Despite this, there are similarities between the charts and specifically between the residential buildings, office buildings and Selma 2 Block 10 scenario 1. The total climate impact for Selma 2 Block 10 is slightly lower than the total climate impact for the residential buildings and office buildings analysed by Malmqvist et al. (2021). Another similarity is that the frame clearly has the highest climate impact. The foundation and facade also have high impacts.

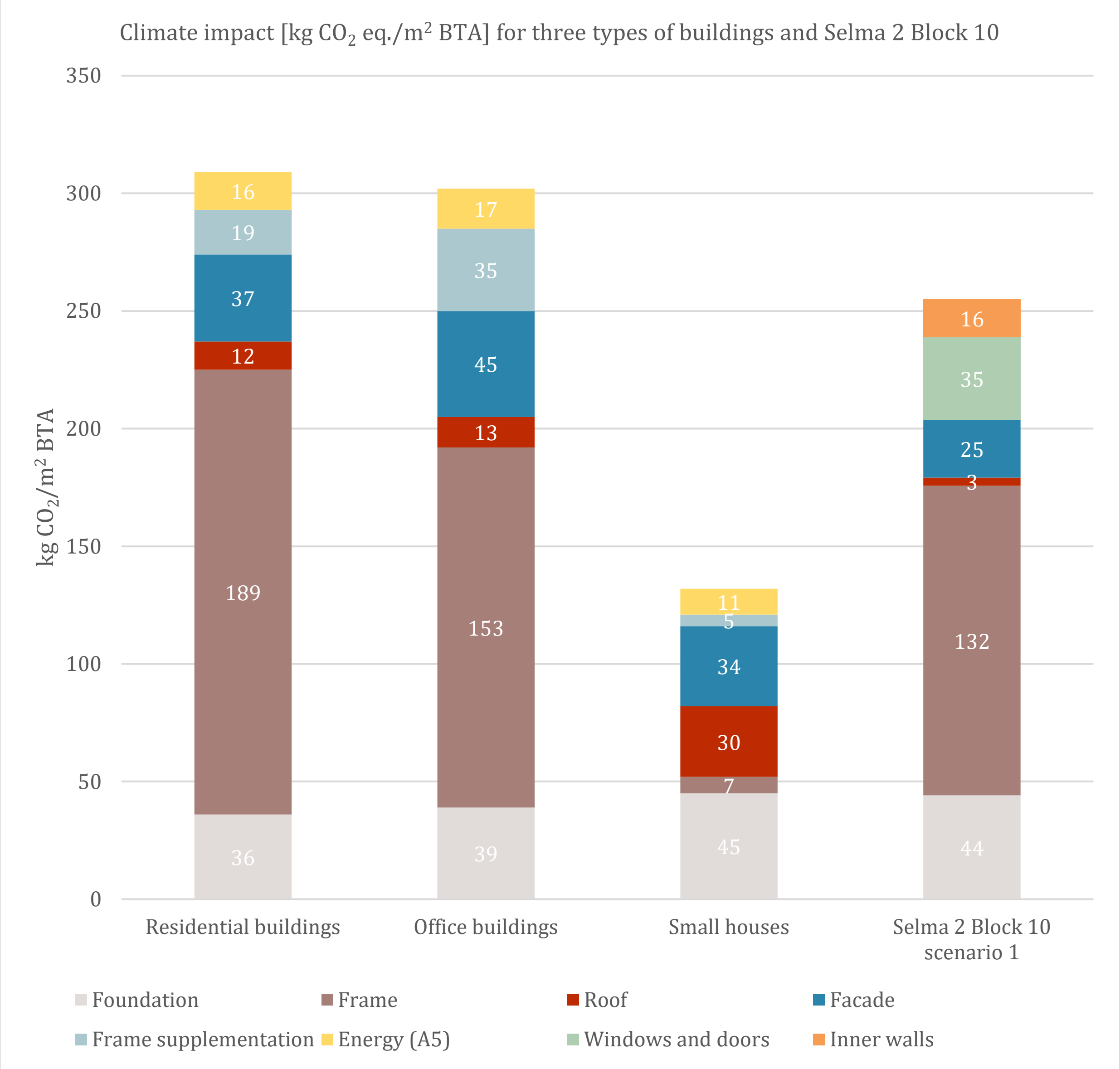


Figure 31 Comparison of climate impact in kg CO_2 eq./m^2 BTA for three different types of buildings analysed by Malmqvist et al. (2021) and Selma 2 Block 10. The climate impact considers phases A1-A5 for the residential buildings, office buildings and small houses

Given that Selma 2 Block 10 is a residential building, the most relevant comparison is between the results from the residential buildings analysed in the research report by Malmqvist et al. (2021) and the results from Selma 2 Block 10 scenario 1. The circular graphs in Figure 32 show that the frame has the highest climate impact for both studies. The frame in the residential buildings analysed by Malmqvist et al. (2021) is responsible for 61% of the climate impact, while the frame in Selma 2 Block 10 is responsible for 52%. Moreover, the foundation is responsible for the second highest climate impact for both studies. The foundation in the residential buildings analysed by Malmqvist et al. (2021) is responsible for 12% while the percentage result from the foundation in Selma 2 Block 10 is slightly higher at 17%. The facades also have similar percentage rates where the facade in the residential buildings analysed by Malmqvist et al. (2021) is responsible for 12% while the facade in Selma 2 Block 10 is responsible for 10%. The last part possible to compare between the two studies is the roof. The roofs have a rather low contribution to the total climate impact and in the residential buildings analysed by Malmqvist et al. (2021) the roof equals to 4% of the climate impact, while for Selma 2 Block 10 the roof is responsible for only 1%. In other words, the order of magnitude regarding climate impact in percentage is similar for the foundation, frame, roof and facade if comparing the results from the residential buildings analysed by Malmqvist et al. (2021) to the results from Selma 2 Block 10.

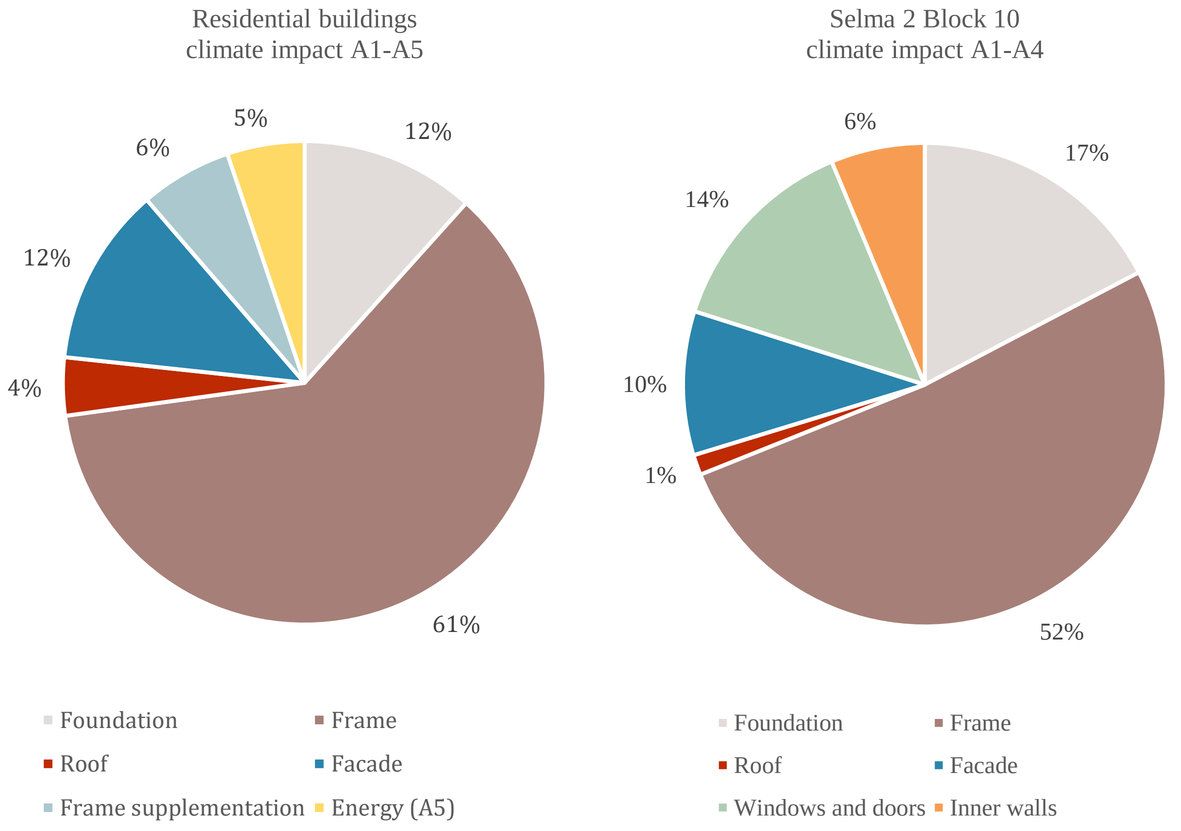


Figure 32 Climate impact in percentage from the different building parts for the residential buildings analysed in the research report by Malmqvist et al. (2021) and for Selma 2 Block 10 scenario 1.

6 ANALYSIS AND DISCUSSION

This chapter covers an analysis and discussion of the results and methods. It follows the structure of the research questions and thus firstly focuses on the results from the literature review followed by a discussion on the results from the case study. Then follows a discussion on the methods used in the thesis. Lastly, recommendations for future research are presented in the end.

6.1 Discussion of the results from the literature review

One of the main findings from the literature review was that materials can not necessarily be classified as either good or bad in terms of climate impact. Instead, the context needs to be taken into account when defining a material as sustainable or not. I believe this is relevant in most respects. It is reasonable that the climate benefits from using a material with smaller climate impact can be lost if a larger amount is required to fulfil the same purpose. However, I also consider that there is a risk with this viewpoint since it might prevent new solutions and approaches to material use in constructions. By accepting that a certain material is given in a specific building part there is a chance to overlook other alternatives that might be more environmentally friendly. I believe that it can be valuable to question the material choices within building projects and further to make assessments on climate impact to find out what alternative is most environmentally beneficial. However, to make a specific analysis on every material in all building projects is not feasible. Therefore, some guidance on preferable materials might be required.

The literature review further points out that some building materials are more energy intensive than others which in turn affects the climate impact. Aluminium, steel, concrete, insulation, and gypsum are shown to have specifically high embodied energy and with that a higher climate impact. As mentioned above, sometimes a certain material might be required for a specific purpose but I still suggest that this knowledge can guide the design of buildings in a direction that minimizes the use of energy intensive materials. Further, it is important to optimize the use of the materials and make sure that only the required amount is used. This requires developed knowledge within the field of building construction.

Regarding the design stage, the literature review revealed that it plays an important role for creating buildings with low carbon footprints. However, I believe that the CO_2 eq. emission reductions are not accomplished by identifying what materials can be reused in a certain project, but rather by designing a building based on available materials to reuse and finally constructing the building with those reused materials. The literature stated that there is currently an imbalance between the supply and demand of products to reuse. This, however, might change in the future if material banks with reusable products are further developed. If so, old building materials might be equally accessible as new materials and therefore easier to use. I understand that the effort required to perform a today yet rather unestablished practice creates a resistance. With time however, the linear business model will hopefully be replaced more and more by a circular approach and the resistance will decrease.

Furthermore, the literature review revealed quite many trade-offs and challenges connected to reuse of building materials. It is not surprising that a new business model meets resistance in the beginning. Change often takes effort and turning an entire sector in a different direction after decades following a linear business model will probably require both commitment and time. However, I believe that most problems will go away once the more circular model is established. For instance, when reusing old building materials is a more common practice, the resistance might fade and deconstruction for reuse will happen more naturally which will result in better supply. The quality checks might also be a more natural part of the deconstruction and construction process as well as the storing and logistics around it. It might also be possible that the costs for reusing materials, that according to the literature review is higher than using virgin materials, might decrease with time if it becomes a common practice. The requirements, regulations, and certifications, also stated as challenges in the literature, might also be a solution to implement reuse in the building sector. New requirements and regulations together with certifications focusing more on reuse can possibly have a high impact on companies and their work with material choices and deconstruction methods. It is for example possible to develop the climate declarations explained in section 2.4.2 in a direction that simplifies the declaration of reused materials. Furthermore, certifications such as LEED and BREEAM explained in section 2.4.1 can be adapted and have a stronger connection to reuse of building materials.

6.2 Discussion of the results from the case study

The main finding from the case study was that if materials are reused in Selma 2 Block 10 it will results in a significant reduction of the carbon footprint and total climate impact. If comparing the reference case with scenario 2, where the materials considered as reusable by the interviewees were modelled as reused in openLCA, the CO_2 eq. emissions were reduced by 76%. Even if only materials in the building parts with the highest climate impact were to be reused (as in scenario 3) there will still be a considerable reduction by 58%. Naturally, the fourth scenario, where all materials in Selma 2 Block 10 are reused from deconstructed buildings, results in the largest reduction, since the impact only comes from the transportation of the deconstructed materials. However, the fourth scenario is seemingly not probable in practice but is included to give a sense of the best-case scenario where no materials go to waste.

Investigating the climate impact reductions for the separate building parts further, it is apparent that the windows and doors have the largest reduction of CO_2 eq. emissions. The reduction is 99.94% but the round figure is 100%. I believe it is no surprise that the windows and doors have the highest reduction among the building parts, since all materials included in the windows and doors can be reused according to the interviewees. Other building parts with a high reduction in CO_2 eq. emissions are the facade and frame with a 93% respectively 92% reduction. Similar to the windows and doors, the facade and frame includes a large share of reusable materials which I consider the main reason for the reductions. The inner walls also have a considerable share of reused materials but does only get a 65% reduction. I suppose that some of the materials included in the inner walls that are not reusable have a rather high climate impact. Two building parts with rather low reduction of CO_2 eq. emissions are the roof and the foundation with a 34% respectively 7% reduction. The low reduction for the foundation is not surprising since most materials in the foundation are not reusable and the roof has a slightly lower share of reusable materials in comparison to the remaining building parts.

The interviews held as a part of the case study revealed what materials in Selma 2 Block 10 are reusable. I was surprised that the majority of the materials actually were reusable. Of course, there might be complications with dimensions and finding the right materials for the specific building project, but the interviews contributed with a valuable and optimistic viewpoint.

As the literature review revealed, the design stage is very decisive regarding the achievement of reducing the carbon footprint of a building. Since the design of Selma 2 Block 10 is already started and preliminary set, and due to the assumption that materials to reuse were accessible in the right dimensions and quality for Selma 2 Block 10, the result from the reuse case scenarios are possibly better than what are probable to be achieved in reality. Furthermore, finding materials without losing the climate benefits from too long transportation distances might be a problem if the market for old building materials is not very developed yet. This is something that has to be taken into consideration in the continuing planning of the building project.

Lastly, the results on building parts with the highest climate impact from this thesis corresponded to large parts with the results from the research report by Malmqvist et al. (2021) which gives credibility to the results. However, the comparison was made more difficult since not all building parts included in this thesis were included in the research report by Malmqvist et al. (2021) and vice versa. However, three of the parts with the highest impact, the frame, foundation, and facade, were included in both studies and were comparable. The comparison was also made more difficult due to differences in investigated building life cycle phases. The research report by Malmqvist et al. (2021) included phase A1-A5 while this thesis focused on phase A1-A4. This suggests that the results from the LCA calculations in this study should be slightly lower. Nevertheless, looking at Figure 7 illustrating an example of life cycle assessment results for a residential building in section 2.4.1, it is obvious that the contribution from phase A5 is rather low in comparison to the contribution from phase A1-A3.

6.3 Discussion of the methods and applied assumptions

The literature review has been used to investigate which building materials and parts that generally have the highest climate impact and what building materials are possible to reuse and to what extent. Furthermore, it investigated what trade-offs and challenges that are connected to the practice. I consider that the method has been successful in answering the first three research questions. However, investigating what building materials that have the highest climate impact could also have been answered by the LCA calculations in the case study and in that way be more adapted and specific to Selma 2 Block 10 when modelling the different scenarios. It is mainly scenario 3, where only the building parts with the highest climate impact include reused materials, that is affected. It is most likely probable that the results from the case study would be different if the third scenario was based on the case study rather than the literature review. The literature review stated the frame, foundation, facade, and roof as high contributors while the results from the LCA calculations in this thesis revealed that the frame, foundation, facade and windows and doors have the highest impact in Selma 2 Block 10. However, I believe that the order of magnitude for the different scenarios for the total impact would be the same, with scenario 1 as the highest, scenario 3 as the second highest, scenario 2 as the third highest and scenario 4 as the lowest, independent of if the scenarios are based on the literature review or the LCA calculations.

To find the answer to what possible trade-offs and challenges that are connected to reuse, I find the literature very helpful. Nevertheless, I believe that the results would have benefited from more research on the topic. I imagine there is more to learn and understand from reports and journals that I did not have the possibility to investigate due to lack of time. The literature review I did, however, give me a deeper understanding for the practice of reuse and contributed to the acquaintance of the topic.

The case study contributed with a quantitative analysis of the CO_2 eq. emissions from the object at study, the residential building project Selma 2 Block 10. Given that LCA is stated as one of the best methods to calculate the environmental impacts from a building (Boverket, 2019c) the choice of tool feels suitable. Further, I believe that the results fulfilled the purpose of answering how many percentages the carbon footprint can be reduced with by reusing materials in Selma 2 Block 10.

It is relevant to discuss around what building life cycle phases that are included in the case study since not all building life cycle phases according to EN 15978 are included. As can be seen in Figure 7, phase B6 (operational energy use) have significant impact but is not considered in the case study of this thesis. As explained in section 5.2.6, only the phases A1-A4 are considered. Certainly, it is possible to include additional phases but that requires additional time for data collection and modelling. Phase A5, however, might be considered simple to include but is excluded since the construction will be the same for all four scenarios. I believe that additional phases would have contributed to a more in-depth analysis. An inclusion of the phase B4 (replacement) might for example have revealed if any materials and parts would have higher impact due to short lifetimes. Furthermore, it would have been interesting to investigate the end-of-life stage (C1-C4) of Selma 2 Block 10 to also assess for the impact that the materials have after the building’s lifetime. This includes to investigate whether or not the materials are reusable one more time after being used in Selma 2 Block 10.

It is also if interest to discuss how the chosen reference study period, set to 50 years for the study in this thesis, affects the results. Since the use stage and end-of-life stage are not included in the assessment, the lifetime of the building is of small importance. If including the use-stage and end-of-life stage, the results would probably change depending on if the lifetime were extended to 80 or 100 years. A longer lifetime of the building requires maintenance, repair and replacement. However, since those life cycle stages are not included, an extension of the lifetime will not make a difference in the current study.

The case study compares four different scenarios that are modelled with different inputs in openLCA. As explained in section 5.2.1, scenario 1 is a reference case and is supposed to represent today's linear business model. Scenario 2 is the first reuse case where the materials considered as reusable by the interviewees are modelled as reused. Scenario 3 describes the reusage of materials in the frame, facade, foundation, and roof while scenario 4 is modelled with all materials reused. I think the different scenarios contribute to valuable comparisons and conclusions especially for the total impact (hence Figure 20 and Figure 21). Even though it might be obvious that the CO_2 eq. emission reductions will be significant if all building materials in the project are reused from another deconstructed building, as in scenario 4, it is still of importance to clearly illustrate it. Hopefully, it can be seen as an inspiration to develop new methods in construction and deconstruction of building materials. Moreover, scenario 3 points out that a reduction of CO_2 eq. emissions can still be obtained even if not all reusable materials are reused in the building project. However, for the specific building parts, scenario 3 is not of equal importance since the results from scenario 3 is either the same as scenario 1 or scenario 2. It is, however, still included in the figures to not confuse the reader.

Additional scenarios could of course have been modelled. It would for example have been interesting to investigate the results from a scenario where only the most energy intensive materials were reused from a deconstructed building and see how many percentages the CO_2 eq. emissions would be reduced by then. Moreover, if a certain goal for the reduction of CO_2 eq. emissions from reuse were set, it would have been interesting to investigate what possible combinations and scenarios that would achieve that goal.

Further, it is relevant to discuss what building parts that are included in the case study. The included parts are the foundation, frame, roof, facade, inner walls, windows and doors. Parts that are not included are for example installations. The choice of included parts is partly based on the literature review but mainly based on what data that were available from Framtiden Byggutveckling. An inclusion of more building parts and components would result in a more comprehensive analysis. However, the literature review did not mention anything about for example installations. Maybe it is not a common included part of the assessment.

Two interviews with experts within reuse of building materials were made to base the assumptions on what materials could be reused in the different building parts of Selma 2 Block 10. Even though the interviewees were in agreement for most materials, the case study would still benefit from more interviewees to guarantee the results further. Nevertheless, I find the interviews to be a successful and effective method grounded in the object at study. General assumptions could have been done based on the literature review, but that method would probably not be as realistic as the interviews.

One way to address the complications with availability of building materials to reuse could have been to not assume that all materials were accessible but rather discuss with the interviewees around what materials that are probable to find on today's market for reusable products. The results from the reuse case scenarios would then probably be more representable of the actual possibilities.

However, it is not certain that the interviewees know exactly what materials are available on the market and furthermore, the design of the building project also needs to be based on the available products. Therefore, the case study has more a theoretical approach on what is possible.

The functional unit is a central part of LCA calculations. The functional unit is supposed to represent the function of the study and be a basis for comparison. Buildings are rather multifunctional and therefore it might be hard to choose a functional unit. The chosen functional unit for the case study in this thesis was *1 m^2 BTA*. It is hard to know if another functional unit would end in a different result. Surely, the actual numbers would change if divided by something else than the building area, but the proportions should still be the same.

Without further knowledge in other LCA calculation software, I find openLCA rather straight forward and transparent. With the ready-made LCIA methods it is simple to obtain and analyse the results. Ecoinvent used as the database for the LCA includes most materials that were required for the modelling of the building parts, even though some processes were missing, for instance roof felt and plastic vapour control layer. For those materials that were not included in ecoinvent version 3.8 I used as similar materials as possible and if no similar material was found in the database, an own process was made as for the case for the roof felt. The lack of materials in ecoinvent is a source of error and uncertainty. Furthermore, I have a concern about the processes not covering all building life cycle stages A1-A3. For some materials, as for example the *polystyrene foam slab for perimeter insulation*, it is clearly expressed that raw material extraction (A1), transportation (A2) and manufacturing (A3) are included in the process while for other materials, as for instance the *flat glass production*, it is not as clearly described. If not the raw material extraction (A1) and transportation (A2) are included in all processes, the results from the case study are affected since those building life cycle phases also have a significant impact. It is possible that another software and database available would generate different results and data from for example Boverket might be more representable for the Swedish conditions. Nevertheless, I believe that openLCA together with ecoinvent have provided relevant results that can guide the continuing work with Selma 2 Block 10.

6.4 Limitations and consequences of chosen methods

The study consists of a literature review and a case study with LCA calculations and interviews. A gain from using a mixed method research approach is that the questions are viewed from different viewpoints. The results on what building parts that have the highest climate impact from the literature review could partly be confirmed by the results from the sensitivity analysis in the case study. Nevertheless, there are also challenges with using a mixed method approach. For one thing, it is time demanding and for another there is a risk that neither method is given the in-depth focus required. The methods are however complementing each other where the literature review revealed what parts to focus on in the case study.

The literature review partly lacks quantitative results on degree of reusability which was supposed to guide the LCA calculations in the case study. Instead, interviews were held to fill this gap in information to make accurate assumptions regarding what materials to reuse in the building project. The limited number of reviewed literature might have affected the results of the literature review. Further research might possibly reveal further information on reusability of different materials. Furthermore, it was hard to distinguish what was actually possible in terms of reuse and what was made today.

Furthermore, the literature review only covered a limited number of studies on building materials and parts with high climate impact. The results would benefit from more extensive research that summarized several studies on the topic. Instead, the identification on what building parts that have the highest climate impact are based on what building parts were stated as high contributors in the literature analysed in the literature review. However, making a general conclusion was difficult due to rather general statements and conclusions in the literature. Different sources stated different parts as high contributors. This might not be surprising since it depends largely on what building materials are included in the part and how the analysis is performed. Therefore, the results on what building parts have the highest climate impact are limited and somewhat uncertain.

A limitation connected to the case study is that only the impact category climate change (GWP_{100}) is taken into consideration. The reason for that is the focus on CO_2 eq. emission reductions. Other impact categories such as acidification and eutrophication are interesting but not necessarily relevant for the scope of the study.

Both the literature review and the case study are focused on the environmental benefits from reusing building materials, hence the ecological dimension of sustainable development. It is however appealing to question if reuse of building materials can offer other values than environmental benefits. Is it possible that the practice can contribute to the economic and social sustainability? I find it reasonable that reuse should be less costly thanks to decreased costs for manufacture. At the same time the literature review revealed that there are challenges connected to the economy where the practice today involves additional expenditures from the deconstruction, storing and design process. Regarding social sustainability, it would be interesting to explore if buildings consisting of reused building materials offer the same well-being as buildings consisting of only new materials. Without being familiar with the subject, I cannot see why not.

The choice of data has most probably affected the results of the case study. Mostly generic data from ecoinvent version 3.8 and Boverkets klimatdatabas were used. Data from ecoinvent is primarily based on Swiss or European data, while Boverkets klimatdatabas is representing Swedish conditions. It is probable that Swiss or other European data differs from Swedish data which adds uncertainty to the results. However, with Sweden being a European country the uncertainties are probably assumably small and therefore the results from the case study are still considered relevant.

The case study does not give a universal answer to the climate benefits from reusing building materials. Nevertheless, the aim of the study, to investigate the possibilities and benefits of reusing building materials, is considered as fulfilled. The additional aim, to guide the entrepreneurs within the project towards beneficial decisions related to material choices, is also considered fulfilled.

6.5 Future studies

The reduction of the carbon footprint from reusing building materials in the residential building project Selma 2 Block 10 has been briefly described in this report. However, there are still endless possibilities to continue the research within this topic.

For the specific object at study, Selma 2 Block 10, future studies can include the possibilities to reuse the materials in Selma 2 Block 10 after the lifetime of the building. Circular economy is after all a concept based on minimizing the leakage of resources by reusing, repairing, recycling, sharing, and leasing resources in a closed loop (Ghosh, 2020) and the sustainability focus should not end after the construction of the building. This is connected to broader research on how many times building materials can be reused before having too poor quality and also, how to guarantee the structural strength over several lifecycles.

Another possible continuation of the analysis of Selma 2 Block 10 is to investigate what materials used in Selma 2 Block 10 that have the highest climate impact to understand the results better. It would for example be interesting to find out why the inner walls, which have a considerable share of reused materials, still have a slightly lower reduction of CO_2 eq. emissions compared to for example the facade and frame.

Other possible research questions are what difference the transportations have on the climate impact. It would for example be interesting to see what difference electric transportation might have on the climate impact. This kind of study could serve as support for putting pressure on the suppliers. Further ways to develop the analysis of Selma 2 Block 10 could be to accompany the LCA with social LCA (SLCA) and an economic LCA (LCC) to cover the entire field of sustainability.

Given that the design stage is a very important part of being able to reuse building materials, it would be interesting to investigate how design for deconstruction and reuse is done in the most efficient way. Furthermore, it would be gainful to investigate what building materials and products that are easy to reuse independent of the design of the building. Results from such a study could contribute to increasing the reuse of products in all types of building projects, not only projects that focus on reuse from the start of the design process.

The results from the literature review are mostly qualitative even though some quantitative data was found on the embodied energy and impact reduction from reuse. However, I think that it would have been interesting to find more quantitative results on to what extent building materials are reused today.

From the realization that there is a lack of data on what is required in terms of treatment to make a material reusable after deconstruction, there is also great possibilities to investigate this topic. Due to lack of time, there were no possibilities to investigate it in this thesis. However, knowledge within this field is both relevant and important for the future implementation of the practice.

Lastly, in LCA calculations of this study it was assumed that all environmental loads from the deconstructed materials were allocated to the deconstructed buildings. However, if it is desired to allocate the environmental loads to the new building project instead, methods on how to model reuse in openLCA is required.

7 CONCLUSIONS

This last chapter will present the conclusions from the thesis. It is structured in four stages where the research questions are revisited one by one.

RQ1: Which building materials (e.g., wood, steel, and concrete) and parts (e.g., foundation, facade, and roof), generally have the highest climate impact in building projects?
Different materials have different embodied energy (EE) and embodied greenhouse gas emissions (EG) and with that also different climate impacts. EE and EG-intensive materials mentioned in the literature are steel, aluminium, concrete, glass, brick, and stone wool where steel, aluminium and concrete are explained as strong contributors to the climate impact. The Swedish reference values list concrete (both prefabricated and cast-in-place), steel, insulation, and gypsum as materials with high climate impact.

Regarding building parts, most climate impact comes from the frame, facade, foundation, and roof according to the literature. However, the climate impact from building parts is highly affected by the materials used in the constructions. Nevertheless, building materials and parts are hard to classify as either good or bad. The use context needs to be considered and sometimes an EE or EG-intensive material is the most environmentally friendly choice, if other materials require larger amounts or similar.

RQ2: Which building materials are possible to reuse, and to what extent can they be reused?
The literature review revealed that there are possibilities to reuse both structural and non-structural building products even though the practice is not too widespread yet. Below follows a summary of 8 common building materials and how they can be reused.

- *Concrete* can be crushed and reused as road base material and aggregate in new concrete. It is also possible to reuse entire concrete frames in new buildings.
- *Wood* in good condition can be reused in furniture and interior panelling. Furthermore, flooring made of wood is possible to reuse, likewise cross-laminated timber if they are possible to deconstruct from an old building.
- *Brick* can be reused if the tiles are separated from the mortar which is possible with today’s methods.
- *Sheet* can be reused if not destroyed by rust or other.
- *Steel* is today highly recycled but additional environmental benefits can be achieved if reused. Steel is suitable to reuse due to the standardized dimensions.
- *Gypsum* is in theory possible to deconstruct and reuse but it is not a common practice today.
- *Mineral wool* is 100% reusable and *glass wool* can be reused if dry and packaged.
- *Glass* in buildings is often replaced before it is needed which opens up for reuse. However, there is a risk that old windows do not meet the requirements regarding energy and U-values.

RQ3: What possible trade-offs and challenges needs to be taken into consideration when reusing building materials?

Even though reuse is nothing new, there are still trade-offs and challenges connected to the practice. Listed below are ten trade-offs and challenges found in the literature.

- *Culture, norms, and traditions* can result in resistance towards the practice due to associations with poor quality, old-fashionedness, lack of aesthetics and risk.
- *Quality and performance* are questioned, and the lack of quality controls results in fear of reusing materials. The materials can also be damaged if the deconstructed buildings are not designed to be deconstructed.
- *Offering of goods* is considered a problem since the market for products to reuse is yet rather unestablished. An additional problem is that consumers often require a large amount of the same type of product at the same time as the market is unpredictable due to uncertainties regarding available quantities, qualities, size, and price.
- *Knowledge,* or rather the lack of knowledge, hinders reuse of building materials. The lack of experience among companies together with few successful methods and studies affect the practice in a negative way.
- *Storing and logistics* can become more expensive as the time required to store the materials increase when the materials need to be purchased in an early stage. Moreover, the storing needs to be located close to the building site to avoid additional emissions from transportation.
- *Time* is required to deconstruct, sort the building materials, design the building based on available products and to perform quality controls.
- *Economy* is a central part of all building projects and reusing materials and components can result in additional cost from deconstruction, sorting, storing, and designing.
- *Flexibility* is important since the design is dependent on available materials to reuse. The design process is required to be kept flexible which requires extra effort.
- *Requirements, laws, and regulations,* or rather the lack or requirements, laws and regulations, contributes to the continuation of the linear business model.
- *Certifications* have a vague connection to reuse, and it can be argued that certifications result in a moderate sustainability effort if the focus is to achieve the minimum requirements.

RQ4: With how many percentages can the carbon footprint be reduced by reusing building materials in comparison to using only new materials in the residential building project Selma 2 Block 10?

By reusing materials in Selma 2 Block 10, it is possible to reduce the carbon footprint by 76% for the building life cycle stages A1-A4. If only reusing materials in the foundation, frame, roof, and facade, it is possible to reduce the climate footprint by 58%. If reusing all materials in Selma 2 Block 10 it is possible to achieve a reduction of 99%. These results presumes that all environmental loads from the deconstructed materials reused in Selma 2 Block 10 are allocated to the already deconstructed buildings. The results also presumes that there are available materials on the market to reuse. The reductions of the carbon footprint for the specific building parts are summarized in Table 19 below.

Table 19 Overview of the reduction in carbon footprint for both the total impact from Selma 2 Block 10 and the different building parts included in the case study.

	kg CO_2 eq./m^2 BTA scenario 1	Reduction potential scenario 2	Reduction potential scenario 3	Reduction potential scenario 4
Total impact	**254.9**	**-76%**	**-58%**	**-99%**
Foundation	44.1	-7%	-7%	-99%
Frame	131.6	-92%	-92%	-99%
Roof	3.4	-34%	-34%	-98%
Facade	24.5	-93%	-93%	-99%
Windows and doors	35.2	-100%	0%	-100%
Inner walls	16.0	-65%	0%	-98%

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APPENDIX I – Inventory: pre-existing data on Selma 2 Block 10

Table 20 Materials and quantities preliminary set in Selma 2 Block 10 used as the basis for the LCA calculations.

Building part	Preliminary set building materials in Selma 2 Block 10	Simplified building material name used in thesis	Quantity (kg)
Foundation			
	Insulation, EPS, L = 0.035 W/mK, 38 mm, 0.57 kg/m^2, 15 kg/m3 (Bewi, Jackon, Styrolit, Sundolitt)	EPS insulation	330
	Ready-mix concrete, low-strength, generic, C12/15 (1700/2200 PSI), 0% recycled binders in cement (220 kg/m3 / 13.73 lbs/ft3)	Ready-mix concrete C12/15	99880
	Plastic vapour control layer, 0.2 mm (Tommen Gram)	Plastic vapour control layer	167.98
	Self levelling mortar, for floors, walls and overhead appl., 3-50 mm, 1400 kg/m3, Pericret (PCI Augsburg)	Self-levelling mortar	25424
	Insulation, EPS, L = 0.035 W/mK, 38 mm, 0.57 kg/m^2, 15 kg/m3 (Bewi, Jackon, Styrolit, Sundolitt)	EPS insulation	4358.4
	Fabriksbetong, husbyggnad klimatförbättrad C30/37, C30/37, 2350 kg/m3	Concrete C30/37	263697
	Fabriksbetong, husbyggnad klimatförbättrad C30/37, C30/37, 2350 kg/m3	Concrete C30/37	341408
	Reinforcement steel (rebar), generic, 90% recycled content, A615	Reinforcement steel	17161
Frame			
	Konstruktionsstål, obearbetad, skrotbaserad, 7850 kg/m3	Steel	47509
	Aggregate, from stationary crushing plant, Rock fines 0/2, Rock fines 0/4, Crushed rock 0/8, Macadam 2/5, Macadam 4/8, Macadam 8/11, Macadam 8/16, Macadam 11/16, Macadam 16/22, Stenmjöl, Bergkross, Makadam (NCC)	Aggregate	544800
	Gipsskiva, standardskiva, 710 kg/m3	Gypsum board	40292.5
	Glasull, ljudisolering, 14 kg/m3	Glass wool insulation	1461.88
	Korslimmat trä, u 12%, barrträ, 465 kg/m3, moisture content 12%	Cross-laminated timber	569997
	Gipsskiva, golvskiva, 1120 kg/m3	Gypsum board (floorboard)	66102.4
	Spånskiva, 700 kg/m3	Fibreboard	69916
	Limträ, u 12%, gran, 434 kg/m3, moisture content 12%	Cross-laminated timber	40090
	Ready-mix concrete, normal-strength, generic, C30/37 (4400/5400 PSI), 10% (typical) recycled binders in cement (300 kg/m3 / 18.72 lbs/ft3)	Ready-mix concrete C30/37	76800

	Ready-mix concrete, normal-strength, generic, C30/37 (4400/5400 PSI), 10% (typical) recycled binders in cement (300 kg/m3 / 18.72 lbs/ft3)	Ready-mix concrete C30/37	223200
	Ready-mix concrete, normal-strength, generic, C30/37 (4400/5400 PSI), 10% (typical) recycled binders in cement (300 kg/m3 / 18.72 lbs/ft3)	Ready-mix concrete C30/37	29526
	Reinforcement steel (rebar), generic, 90% recycled content, A615	Reinforcement steel	3232
	Reinforcement steel (rebar), generic, 90% recycled content, A615	Reinforcement steel	9315
	Reinforcement steel (rebar), generic, 90% recycled content, A615	Reinforcement steel	13080
Roof			
	Plastic vapour control layer, 0.2 mm (Tommen Gram)	Plastic vapour control layer	185
	Gipsskiva, standardskiva, 710 kg/m3	Gypsum board	8875
	Sågad vara, u 16%, barrträ, 455 kg/m3, moisture content 16%	Wood scantling	10010
	Takspapp, enskiktstätning, 1410 kg/m3	Roof felt	7050
	Sågad vara, u 16%, barrträ, 455 kg/m3, moisture content 16%	Wood scantling	2048
	Sågad vara, u 16%, barrträ, 455 kg/m3, moisture content 16%	Wood scantling	2336
	Limträ, u 12%, gran, 434 kg/m3, moisture content 12%	Cross-laminated timber	6591
	Cellulosafiber, återvunnet papper, lösull	Cellulose fibre (loose wool)	20100
Facade			
	Gipsskiva, standardskiva, 710 kg/m3	Gypsum board	27663.38
	Plastic vapour control layer, 0.2 mm (Tommen Gram)	Plastic vapour control layer	576.65
	Plastic vapour control layer, 0.15 mm (Tommen Gram)	Plastic vapour control layer	288.84
	Sågad vara, u 16%, barrträ, 455 kg/m3, moisture content 16%	Wood scantling	4170
	Sågad vara, u 16%, barrträ, 455 kg/m3, moisture content 16%	Wood scantling	6510
	Cellulosafiber, oanvänt papper, skivor	Cellulose fibre (boards)	40224
	Fasadtegel	Brick	397417.5
Windows and doors			
	Multifunctional steel door, product group 1, 1000mm x 2125 mm, H 3 D, H 3 OD, H 3 VM, H 3 KT, RS 55, D 65 OD, D 65 (Hörmann)	Steel door	783
	Aluminium profile for windows and doors, 2600 kg/m3, Al Profile (Saray)	Aluminium profile for windows and doors	247
	Float glass, single pane, generic, 3-12 mm (0.12-0.47 in), 10 kg/m^2 (2.05 lbs/ft2) (for 4 mm/0.16 in), 2500 kg/m3 (156 lbs/ft3)	Float glass	5500

	Float glass, single pane, generic, 3-12 mm (0.12-0.47 in), 10 kg/m^2 (2.05 lbs/ft2) (for 4 mm/0.16 in), 2500 kg/m3 (156 lbs/ft3)	Float glass	5500
	Float glass, single pane, generic, 3-12 mm (0.12-0.47 in), 10 kg/m^2 (2.05 lbs/ft2) (for 4 mm/0.16 in), 2500 kg/m3 (156 lbs/ft3)	Float glass	5500
	Wooden decking, cladding and planed timber for joinery applications, 540kg/m3, Moistr. 3-5%, Accoya Scots Pine (Accsys Technologies PLC)	Wooden decking, cladding and planed timber	35532
Inner walls			
	Korslimmat trä, u 12%, barrträ, 465 kg/m3, moisture content 12%	Cross-laminated timber	71675.1
	Korslimmat trä, u 12%, barrträ, 465 kg/m3, moisture content 12%	Cross-laminated timber	71675.1
	Gipsskiva, brandskiva, 830 kg/m3	Gypsum board (fireproof)	56657.46
	Gipsskiva, brandskiva, 830 kg/m3	Gypsum board (fireproof)	56657.46
	Gypsum plaster board, regular, generic, 6.5-25 mm (0.25-0.98 in), 10.725 kg/m^2 (2.20 lbs/ft2) (for 12.5 mm/0.49 in), 858 kg/m3 (53.6 lbs/ft3)	Gypsum board	37967.74
	Gypsum plaster board, regular, generic, 6.5-25 mm (0.25-0.98 in), 10.725 kg/m^2 (2.20 lbs/ft2) (for 12.5 mm/0.49 in), 858 kg/m3 (53.6 lbs/ft3)	Gypsum board	37967.74
	Sågad vara, u 16%, barrträ, 455 kg/m3, moisture content 16%	Wood scantling	11476
	Cellulosafiber, oanvänt papper, skivor	Cellulose fibre (boards)	35532

APPENDIX II – Inventory: transportation data

Table 21 Selection of transportation data from Boverkets klimatdatabas, retrieved (2022).

KATEGORI, MATERIAL OCH MEDELVÄRDE	**TRANSPORTSTRÄCKA MED LASTBIL (km)**
Trävaror	
Spånskiva	640
Hyvlat virke, u 16 %, barrträ	190
Korslimmat trä, u 12 %, barrträ	440
Limträ, u 12 %, gran	440
Sågat virke, u 16 %, barrträ	190
Medel	**380**
Återanvänd byggprodukt	40
Betong	
Fabriksbetong, husbyggnad C30/37	35
Medel	**35**
Återanvänd byggprodukt	40
Isolering	
EPS, expanderad polystyren, tryckhållfasthetsklass 80	440
Glasull, ljudisolering	440
Cellulosafiber, oanvänt papper, lösull	440
Cellulosafiber, oanvänt papper, skivor	440
Medel	**440**
Återanvänd byggprodukt	40
Tätskikt	
Plastfolie, ångspärr	640
Medel	**640**
Återanvänd byggprodukt	40
Stål och andra metaller	
Armeringsstål, obearbetad, skrotbaserad	1040
Konstruktionsstål, alla sorter, primär råvara (exkl. objektsanpassningar)	1040
Medel	**1040**
Återanvänd byggprodukt	40
Bruk och bindemedel	
Avjämningsmassor < 17 % cement	340
Medel	**340**
Återanvänd byggprodukt	40
Byggskivor	
Gipsskiva, brandskiva	290
Gipsskiva, standardskiva	290
Medel	**290**
Återanvänd byggprodukt	40
Tätskikt	
Takspapp, enskiktstätning	440

Medel	**440**
Återanvänd byggprodukt	40
Murbruk och tegel	
Tegelsten	640
Medel	**640**
Återanvänd byggprodukt	40
Fönster, dörrar och glas	
Ytterdörr, stål, massiv	540
Fönster, trä/aluminium, inåtgående, 3-glas	540
Medel	**540**
Återanvänd byggprodukt	40

Table 22 Selection of transportation data from the EPD library (International EPD system), retrieved (2022).

KATEGORI, MATERIAL OCH MEDELVÄRDE	**TRANSPORTSTRÄCKA MED LASTBIL (km)**
Aggregate	
Från Eskilstuna (Kjula)	376
Från Sundsvall (Råsta)	722
Från Stockholm (Rotebro)	463
Från Norrköping (Skärlunda)	305
Från Göteborg (Tagene)	9.2
Från Lund (Södra Sandby)	272
Från Falun (Falukrossen)	462
Från Umeå (Bjurholm)	973
Från Östersund (Ljusberget)	779
Från Gävle (Sälgsjön)	512
Från Ramnaslätt	60.7
Medel	**449**

APPENDIX III – Inventory: ecoinvent input data

Table 23 Input data explaining the chosen processes, quantities, transportation types and distances.

	Ecoinvent input data openLCA						
A1-A4	***A1-A3 process***	***Quantity (kg)***	***A4 Transportation type***	***km S1***	***km S2***	***km S3***	***km S4***
Foundation							
EPS insulation	polystyrene foam slab for perimeter insulation | polystyrene foam slab for perimeter insulation | Cutoff, U	4688.4	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	440	40	40	40
Ready-mix concrete C12/15	unreinforced concrete production, with cement CEM II/A | concrete, normal | Cutoff, U	99880	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	35	35	35	40
Plastic vapour control layer	packaging film production, low density polyethylene | packaging film, low density polyethylene | Cutoff, U	167.98	transport, freight, lorry 3.5-7.5 metric ton, EURO5 | transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cutoff, U	640	640	640	40
Self-leveling mortar	cement mortar production | cement mortar | Cutoff, U	25424	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | Cutoff, U	340	340	340	40
Concrete C30/37	concrete production, 30MPa, ready-mix, exposure class XC3 | concrete, 30MPa | Cutoff, U	605105	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	35	35	35	40
Reinforcement steel	reinforcing steel production | reinforcing steel | Cutoff, U	17161	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	1040	1040	1040	40
Frame							
Steel	steel production, converter, unalloyed | steel, unalloyed | Cutoff, U	47509	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	1040	40	40	40
Aggregate	gravel production, crushed | gravel, crushed | Cutoff, U	544800	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	449	40	40	40
Gypsum board	gypsum plasterboard production | gypsum plasterboard | Cutoff, U	40292.5	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	290	290	290	40
Glass wool insulation	glass wool mat production | glass wool mat | Cutoff, U	1461.88	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	440	40	40	40
Cross-laminated timber	cross-laminated timber production | cross-laminated timber | Cutoff, U	610087	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	380	40	40	40
Gypsum board (floorboard)	gypsum plasterboard production | gypsum plasterboard | Cutoff, U	66102.4	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	290	290	290	40
Fibreboard	medium density fibreboard production, uncoated | medium density fibreboard | Cutoff, U	69916	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	380	40	40	40
Ready-mix concrete C30/37	concrete production, 30MPa, ready-mix, exposure class XC3 | concrete, 30MPa | Cutoff, U	329526	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	35	40	40	40

Reinforcement steel	reinforcing steel production | reinforcing steel | Cutoff, U	25627	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	1040	1040	1040	40
Roof							
Plastic vapour control layer	packaging film production, low density polyethylene | packaging film, low density polyethylene | Cutoff, U	185	transport, freight, lorry 3.5-7.5 metric ton, EURO5 | transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cutoff, U	640	640	640	40
Gypsum board	gypsum plasterboard production | gypsum plasterboard | Cutoff, U	8875	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	290	290	290	40
Wood scantling	structural timber production | structural timber | Cutoff, U	14394	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	380	40	40	40
Roof felt	Roof felt, production (own process)	7050	transport, freight, lorry 3.5-7.5 metric ton, EURO5 | transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cutoff, U	440	440	440	40
Cross-laminated timber	cross-laminated timber production | cross-laminated timber | Cutoff, U	6591	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	380	40	40	40
Cellulose fibre (loose wool)	cellulose fibre production | cellulose fibre | Cutoff, U	20100	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	440	40	40	40
Facade							
Gypsum board	gypsum plasterboard production | gypsum plasterboard | Cutoff, U	27663.38	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	290	290	290	40
Plastic vapour control layer	packaging film production, low density polyethylene | packaging film, low density polyethylene | Cutoff, U	865.49	transport, freight, lorry 3.5-7.5 metric ton, EURO5 | transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cutoff, U	640	640	640	40
Wood scantling	structural timber production | structural timber | Cutoff, U	10680	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	380	40	40	40
Cellulose fibre (boards)	cellulose fibre production | cellulose fibre | Cutoff, U	40224	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	440	40	40	40
Brick	clay brick production | clay brick | Cutoff, U	397417.5	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	640	40	40	40
Windows and doors							
Steel door	door production, outer, wood-aluminium | door, outer, wood-aluminium | Cutoff, U	783	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | Cutoff, U	540	40	540	40
Aluminium profile for windows and doors	window frame production, aluminium, U=1.6 W/m^2K | window frame, aluminium, U=1.6 W/m^2K | Cutoff, U	247	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | Cutoff, U	540	40	540	40
Float glass	flat glass production, uncoated | flat glass, uncoated | Cutoff, U	16500	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | Cutoff, U	540	40	540	40

Wooden decking, cladding and planed timber	structural timber production | structural timber | Cutoff, U	35532	transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | Cutoff, U	540	40	540	40
Inner walls							
Cross-laminated timber	cross-laminated timber production | cross-laminated timber | Cutoff, U	143350.2	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	380	40	380	40
Gypsum board	gypsum plasterboard production | gypsum plasterboard | Cutoff, U	113314.92	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	290	290	290	40
Gypsum board (fireproof)	gypsum plasterboard production | gypsum plasterboard | Cutoff, U	75935.48	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	290	290	290	40
Wood scantling	structural timber production | structural timber | Cutoff, U	11476	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	380	40	380	40
Cellulose fibre (boards)	cellulose fibre production | cellulose fibre | Cutoff, U	35532	transport, freight, lorry >32 metric ton, EURO5 | transport, freight, lorry >32 metric ton, EURO5 | Cutoff, U	440	40	440	40

APPENDIX IV – Climate impact assessment results

Table 24 Summarized results from openLCA in kg CO_2 eq. and kg CO_2 eq./m^2 BTA for the four different scenarios.

	Scenario 1		**Scenario 2**	
	GWP		***GWP***	
A1-A4	***kg CO_2 eq.***	***kg CO_2 eq./m^2 BTA***	***kg CO_2 eq.***	***kg CO_2 eq./m^2 BTA***
Total impact	1414670.0	254.9	337459.0	60.8
Foundation	244867.0	44.1	226740.0	40.9
Frame	730334.0	131.6	57779.8	10.4
Roof	19122.9	3.4	12684.1	2.3
Facade	136197.0	24.5	8897.8	1.6
Windows and doors	195171.0	35.2	115.4	0.02
Inner walls	88978.4	16.0	31242.4	5.6
	Scenario 3		**Scenario 4**	
	GWP		***GWP***	
A1-A4	***kg CO_2 eq.***	***kg CO_2 eq./m^2 BTA***	***kg CO_2 eq.***	***kg CO_2 eq./m^2 BTA***
Total impact	592721.0	106.8	12655.5	2.3
Foundation	226740.0	40.9	2871.6	0.5
Frame	57779.8	10.4	6237.9	1.1
Roof	12684.1	2.3	325.7	0.1
Facade	8897.8	1.6	1728.5	0.3
Windows and doors	195171.0	35.2	127.3	0.02
Inner walls	88978.4	16.0	1364.6	0.2

APPENDIX V – Modelling in openLCA

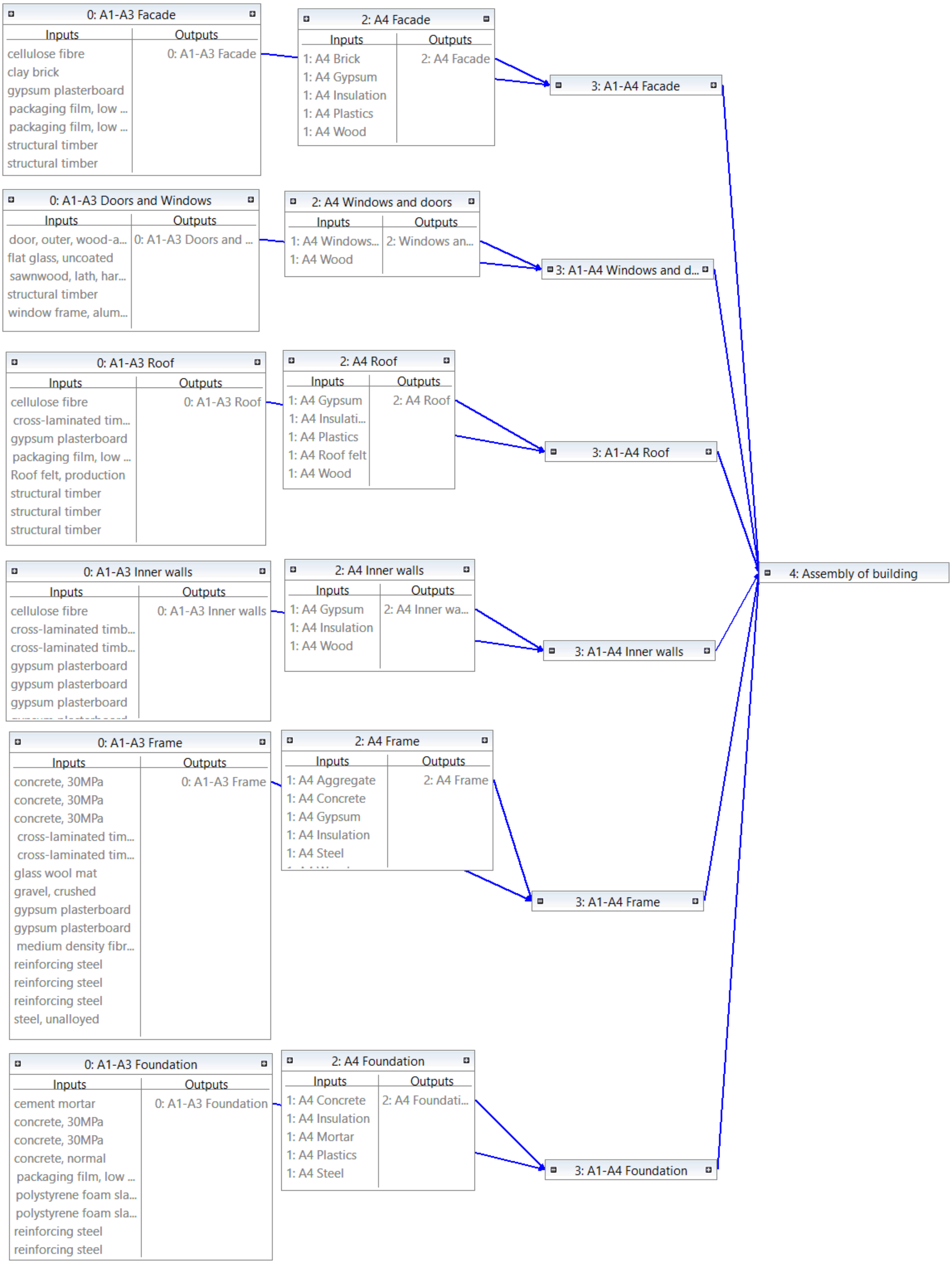

Figure 33 Example of a modelled product system in openLCA.

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
DIVISION OF BUILDING TECHNOLOGY
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
www.chalmers.se