CHALMERS
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Material Choices for a Fossil-Free Preschool

An Interview Study on How Materials are Chosen, and a Life Cycle Assessment of Hemp Insulation

Master's Thesis in the Master Programmes Structural Engineering and Building Technology & Design and Construction Project Management

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ABSTRACT

Many of the materials used for constructing a preschool today are not fossil-free. Therefore, the administration of premises of the City of Gothenburg (Lokalförvaltningen) has decided to construct a fossil-free preschool as a first step towards the goal of becoming fossil-free before the year 2030. Thus, the purpose of this thesis was to contribute to the development towards a fossil-free construction industry by identifying the process of material choices for a fossil-free preschool and to assess if the choice of insulation material in an exterior wall could be fossil-free. The assessment of insulation materials was performed by comparing the standard material mineral wool with hemp insulation as an alternative material.

A mixed methods research was conducted in this study. This included a qualitative interview study on actors in the industry and a quantitative life cycle assessment (LCA) of hemp insulation where GWP_{100} was assessed. Further, the global warming potential (GWP) of hemp insulation and mineral wool was compared.

From the interview study, a result was that some of the interviewees thought that the client makes the material choice and others thought everyone makes the choice. However, the results are coloured by the methodological choice to only interview ten actors. Regarding the definition of *fossil-free materials*, some thought it aimed to the raw material while some thought it aimed to the whole lifecycle of a material. Further, the interviewees also had multiple suggestions regarding how the material choices can be affected, e.g. by green public procurement.

The LCA was conducted on a cradle-to-gate basis. A result from the LCA was that the GWP of hemp insulation is -1.15 kg CO_2e per m^2 hemp insulation if biogenic CO_2 of -1 kg CO_2e per kg hemp plant is accounted for and if it would be produced in Sweden. Compared to mineral wool, hemp insulation would be superior since mineral wool has a GWP of 0.62 to 1.94 kg CO_2e per m^2 insulation.

From the results of the literature review, the interview study and the comparison, several conclusions were drawn. One conclusion was that it is important to state a clear definition and set boundaries of *fossil-free* to enable fossil-free materials to be chosen. Further, the actors in the construction industry have different opinions regarding actors' possibility to affect the material choices for a fossil-free preschool. Another conclusion drawn was that the methodological choices of an LCA, highly affect the results. The comparison between mineral wool and hemp insulation resulted in the conclusion that hemp insulation could be a better option for a fossil-free preschool than mineral wool.

Keywords: fossil-free, hemp insulation, LCA, material choice, mineral wool

Materialval för en fossilfri förskola
En intervjustudie angående hur material väljs och en livscykelanalys på hampaisolering

Examensarbete inom mastersprogrammen Konstruktionsteknik och byggnadsteknologi & Organisering och ledning i bygg- och fastighetssektorn

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SAMMANFATTNING

Många av de material som används för att bygga en förskola idag är inte fossilfria. Som ett första steg för Göteborgs Stad att nå målet att bli fossilfritt före år 2030, har Lokalförvaltningen i Göteborg beslutat att bygga en fossilfri förskola. Syftet med denna studie är således att bidra till utvecklingen mot en fossilfri byggindustri genom att klargöra materialvalsprocessen samt undersöka möjliga isoleringsmaterial för en yttervägg i en fossilfri förskola. De isoleringsmaterial som undersöktes var standardmaterialet mineralull och hampaisolering.

Metoden för denna studie var en mix av kvalitativ och kvantitativ metodik. Den kvalitativa delen bestod av en intervjustudie på olika aktörer i byggbranschen och den kvantitativ av en livscykelanalys (LCA) på hampaisolering där GWP_{100} undersöktes. Vidare jämfördes GWP för hampaisolering med GWP för mineralull.

Intervjustudien visade på att branschens aktörer har olika åsikter kring vem som gör materialvalen och när besluten ska fattas för att uppnå en fossilfri förskola. När det gäller definitionen av *fossilfria material* hade intervjuobjekten olika åsikter om vad det egentligen innebär. Några av intervjuobjekten ansåg att endast råmaterialet påverkade om ett material är fossilfritt medan andra ansåg att hela livscykeln behövde vara fossilfri. Vidare hade intervjuobjekten flera förslag kring hur materialvalen kan påverkas, till exempel genom grön upphandling.

LCA:n resulterade i att GWP för hampaisolering är -1,15 kg CO_2e per m^2 hampaisolering, om en biogen CO_2-lagring om -1 kg CO_2e per kg hampaplanta medräknas samt om den produceras i Sverige. Jämfört med mineralull skulle hampaisolering vara det bättre alternativet för en fossilfri förskola eftersom mineralullen har ett GWP på 0,62 till 1,94 kg CO_2e per m^2 isolering.

Från litteraturstudien, intervjustudien och jämförelsen mellan isoleringsmaterialen, kunde flera slutsatser dras. En slutsats är att det är viktigt att ange en tydlig definition och tydliga systemgränser för termen *fossilfritt* för att möjliggöra fossilfria materialval. Vidare har aktörerna inom byggbranschen olika åsikter om aktörernas möjlighet att påverka materialvalen för en fossilfri förskola. En annan slutsats från denna studie är att de metodiska valen för en LCA påverkar resultaten till en hög grad. Slutligen kunde en slutsats dras, utifrån jämförelsen mellan mineralull och hampaisolering, att hampaisolering kan vara ett bättre alternativ än mineralull som isoleringsmaterial i en fossilfri förskola.

Nyckelord: fossilfritt, hampaisolering, LCA, materialval, mineralull

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Acknowledgements

Material choices for a fossil-free preschool have been examined in this thesis. A mixed methods research was conducted where both an interview study and an LCA has been carried out.

This master thesis is a collaboration between the Department Sustainable Building at ÅF and the Division of Building Technology at Chalmers University of Technology during the spring term of 2018. The subject of the thesis was initiated by ÅF and developed throughout the collaboration. The thesis was supervised by Sjouke Beemsterboer, Doctoral Student at the Division of Building Technology at Chalmers, and Björn Rinde, Section Manager at the Department of Energy Management at ÅF. Holger Wallbaum, Full Professor in Sustainable Building at the Division of Building Technology, was the examiner of the thesis.

Firstly, we would like to thank our supervisor Sjouke Beemsterboer for his dedicated support during the study. The feedback given, with suggestions of how the work could be improved, was much appreciated.

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Gothenburg, May 2018

Karin Andersson and Ida Björhagen

Abbreviations and Definitions

Anthropogenic	Actions caused or produced by humans
Biogenic CO_2-storage	Absorption and storage of CO_2 in biomass
Ecoinvent 3.0	LCA database
EPD	Environmental product declaration
CO_2e	Carbon dioxide equivalents
Construction industry	Is in this thesis used in a broad context, including architect, consultancies, contractors, and property and real estate companies
GWP	Global Warming Potential
IVL	Swedish Environmental Research Institute
ISO	International Organisation of Standardisation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Inventory Assessment
Lokalförvaltningen	Builds and manages premises and housing for the City of Gothenburg operations
Lokalnämnden	The board of Lokalförvaltningen, comprise of politicians
LOU	Public Procurement Act of Sweden
Mineral wool	A common name for stone wool and glass wool insulation
PBL	Planning and Building Act of Sweden
PCR	Product Category Rules
Scutching	Process where the fibres are separated in fibrous plants
Simapro	LCA calculation software
The City of Gothenburg	A municipality in Sweden

1 Introduction

Since the 1990's, awareness of the climate change has increased worldwide (United Nations, 2018). The United Nations (2018) further states that the main cause of the climate change is a large amount of greenhouse gas emissions that yearly exploit the atmosphere. Because of the climate change, the nations of the world have several times since the year 1990 come together at conferences and agreed on common climate agreements (IPCC, 2018).

The result of the last conference, in Paris, was the *Paris Agreement* which will begin to apply at the latest in the year of 2020. In the Paris Agreement, the main goal is to keep the global temperature rise in this century well below 2 degrees Celsius and to pursue efforts to keep the changes at 1.5 degrees Celsius at most (United Nations, 2018). In order to fulfil this goal, the greenhouse gas emissions have to decrease in the coming years.

The greenhouse gas emission which humans have contributed to the most is carbon dioxide (Ciais, et al., 2013). The way greenhouse gases are emitted to the atmosphere is a complex process as seen in Figure 1.1. The emissions origin from both natural sources (marked with black arrows) and anthropogenic sources (marked with red arrows).

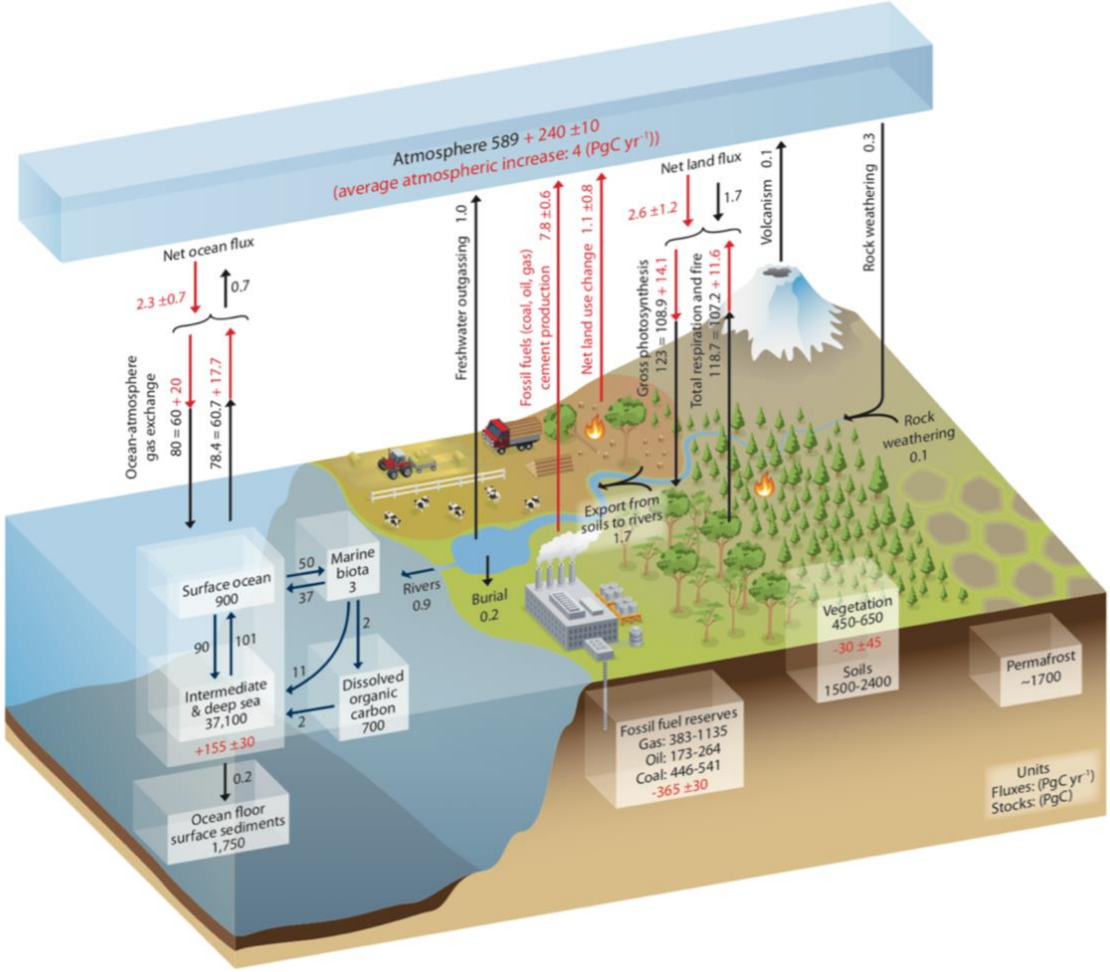


Figure 1.1. The cycle of carbon. The emissions from natural sources are marked with black arrows and anthropogenic emissions are marked with red arrows. The black numbers in the figure stand for the amount of carbon that was a part of the carbon cycle before the industrialization, and the red numbers stand for the extra carbon that has become active in the system since the industrialization. Retrieved from Ciais et al. (2013, p. 471).

The Swedish parliament has defined their own goals and visions in order to contribute to the global goals (Regeringskansliet Miljö- och energidepartementet, 2015). The Swedish parliament has also implemented a new climate policy framework for Sweden that contains new climate targets, a climate law and a climate policy council (Regeringskansliet, 2017). One part of the climate target is that Sweden by the year of 2045 should not have any net greenhouse gas emissions into the atmosphere and after 2045 achieve negative emissions. An example of negative emissions is if the operations in Sweden would emit less greenhouse gas than the amount of carbon dioxide absorbed by nature. With these ambitious goals, Sweden strives to be the first fossil-free welfare country in the world (Regeringskansliet Miljö- och energidepartementet, 2015). The term *fossil-free* indicates that no emissions should be emitted to the atmosphere from fossil resource.

The Swedish government also started the initiative *Fossilfritt Sverige* which is a platform where companies, municipalities and other actors who want to contribute to a fossil-free Sweden have the possibility to share their knowledge and progress (Fossilfritt Sverige, 2018a). Since the year of 2015, over 300 corporations have connected to the initiative and different industries, such as energy, transportation, construction, et al., are cooperating to reach the goals. The City of Gothenburg has decided to connect to the initiative and strive towards becoming fossil-free before the year of 2030 (Fossilfritt Sverige, 2018b).

From the goals and visions stated from the Swedish government, the City of Gothenburg has further formulated their goals. The goals have been divided into four large groups (klimat2030, 2018):

1. Construction should be fossil-free
2. Products and services should be fossil-free
3. All transportation should be fossil-free
4. The food production should be fossil-free

Regarding the first formulation, the first fossil-free construction work will be preschools, as preschools contribute to a major part of the construction work performed by the City of Gothenburg (Lokalnämnden, 2017). In order to obtain a fossil-free preschool, all stages in the lifetime of a preschool have to be fossil-free, which entails a lot of challenges for the construction industry (Lokalnämnden, 2017). One of the challenges is the material choice for the constructions.

In order to follow the development of the industry and be a leading company within fossil-free constructions, ÅF has decided to do a research work on the topic to gain knowledge of how this could be achieved. As a part of the research work, this thesis focuses on the material choices for a fossil-free preschool. In previous studies performed by ÅF and the administration of premises of the City of Gothenburg (Lokalförvaltningen), it has been concluded that the insulation used in the building, usually mineral wool, impact the buildings global warming potential (GWP) by 5%. A question to be answered would, therefore, be if there are any fossil-free materials available on the market. In earlier studies, it was identified that hemp insulation had a low GWP (Schiavoni, D'Alessandro, Bianchi, & Asdrubali, 2016; Murphy & Norton, 2008; Zampori, Dotelli, & Vernelli, 2013). Thus, hemp insulation was investigated in this study to see if it would be a suitable material to use in a fossil-free preschool in Gothenburg.

1.1 Aim and purpose

The purpose of this thesis is to contribute the development towards a fossil-free construction industry and further to a decrease of the anthropogenic greenhouse gas emissions. The aim of this study is to identify the process of material choices for a preschool building, while simultaneously evaluating the possibility to affect the material choices. The aim of the study is also to assess if the material choice of insulation in an exterior wall could be fossil-free by comparing the standard material used, mineral wool, with hemp insulation.

1.2 Delimitations

Some delimitations have been set for this study. The delimitations are stated and described in the subchapters below.

1.2.1 Definition of fossil-free

The definition of fossil-free used by the City of Gothenburg's board of the department of public facilities (Lokalnämnden) which is presented in subchapter 3.1.1, will be the one used as a starting point. Other definitions could have been used but this delimitation is implemented as one of the purposes of this thesis is that the results should be able to be used in Lokalnämnden's work with building a fossil-free preschool.

1.2.2 Achievement of a fossil-free preschool in Gothenburg

The study is delimited to the construction industry in Sweden since there are large differences between different countries such as legislation, public procurement, the market, energy sources and available products. The study focuses on Gothenburg. This delimitation affects the calculations in the life cycle assessment regarding, for example, transportation distance and material manufactures. This delimitation is set, since the pilot object of the fossil-free preschool is located in Gothenburg. Studying multiple countries and cities might not result in an accurate description of the conditions for a fossil-free preschool in Gothenburg.

1.2.3 The public client's perspective

Legislation differs between a private client and a public client, and this study is delimited to study the public client's perspective on the material choices when developing a preschool. Eighty percent of the children in Sweden attend a public preschool (Skolverket, 2016). Due to this, mainly the public sector develops and manages preschool buildings in Sweden. The goal to develop a fossil-free preschool is a goal from a public client and a result of researching both public and private clients might not give a correct description of the situation.

1.2.4 Evaluating the possibilities of fossil-free materials

The study focuses on evaluating the environmental performance of materials in the impact category Global Warming Potential (GWP). Other requirements on materials, such as functional and technical properties, are also considered when identifying replacement materials. Another focus could have been on the social or the economic parts of sustainability or other environmental indicators. However, to keep the focus on *fossil-free* the scope was limited to the GWP.

1.2.5 Life cycle assessment as a tool for evaluating materials

To evaluate the environmental performance of hemp insulation, a life cycle assessment (LCA) was performed with the focus on GWP. Other assessment methods with other impact categories could have been used. However, since the goal of the fossil-free initiative is to keep the temperature rise on the planet below two degrees Celsius and GWP is an indicator that considers more aspects of global warming than just CO_2, GWP was considered the most suitable measure. LCA is a tool that considers the building's lifecycle and since the goal is to achieve a fossil-free preschool, it was considered appropriate to study the lifecycle.

1.2.6 Evaluating replacement materials for mineral wool in a wall

Mineral wool is often used in preschools and is one of the standard materials used in walls because of its fire resistance. However, mineral wool is not assessed as a fossil-free material since it requires a lot of fossil fuels both for energy during the raw material extraction and the production and for the transportations. To achieve the goal of building a fossil-free preschool mineral wool needs to be replaced.

The choice was made to evaluate replacement materials for mineral wool. Other standard materials, and perhaps multiple standard materials, could have been examined for replacements to contribute to a wider aspect of the work. However, the choice was made to focus on one material that is used for a certain function in the building, since the requirements on the materials differ largely between different functions.

Insulation can be used in multiple elements in a building, however, the element focused on in this study is an exterior wall. Different element requires different properties from the insulation. The reason for studying insulation in an exterior wall is that it is the part of the building that often requires the most insulation and if it is possible to replace it would make the largest difference. Also, the thermal performance of an exterior wall greatly affects the energy performance of the building. Thus, the exterior wall plays a large part of the environmental performance of the building.

In order for a material to be considered as a possible replacement material, a requirement was set that the material needed to be an organic and a natural insulation material that preferably stores CO_2e. This delimitation was set since the goal is to become fossil-free and an organic material that stores CO_2e is more likely to fulfil the goal.

1.3 Research questions

In order to fulfil the aim and purpose of this study, two research questions were formulated. The questions are presented below:

1. *How can material choices be made when constructing a fossil-free preschool?*
2. *Which are the challenges and the advantages of replacing mineral wool with hemp insulation to achieve a fossil-free preschool in Gothenburg?*

1.4 Contributions

This thesis aims to fill a gap in how materials are chosen in public procurement in Sweden. By trying to replace the insulation material mineral wool, the study examines some of the complications that arise when replacing a standard material.

By identifying the performance of hemp insulation compared to mineral wool in an exterior wall of a preschool in Gothenburg, the thesis contributes towards the development of a fossil-free construction industry in Gothenburg. Another contribution of this study is to encourage actors to consider how they can contribute to a more sustainable and fossil-free society.

1.5 Disposition of the thesis

The second chapter comprises the methodology for this thesis. The third chapter comprise a literature review which includes the subjects; fossil-free construction, material choice for a fossil-free preschool and possible materials that could replace mineral wool. The fourth chapter in this thesis presents the results and the analysis of the interview study regarding material choice. In the fifth chapter, the life cycle assessment (LCA) of hemp insulation's GWP is presented. The results of the LCA is compared to mineral wool in Chapter 6. Chapter 7 presents the discussion and chapter 8 the conclusion of this study. Future works are suggested in Chapter 8.1.

2 Methodologies

In this chapter, the methodologies used in this thesis are described. In order to meet the aim and purpose of the study, a mixed methods research was conducted. The methodology was divided into four steps as illustrated in Figure 2.1.

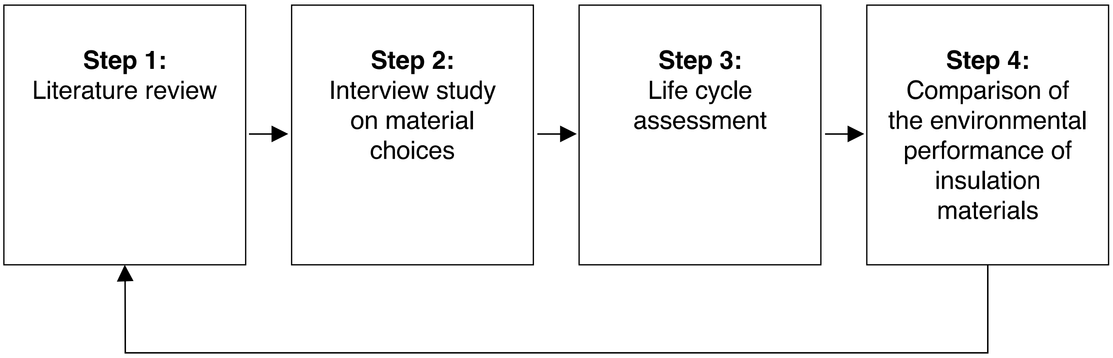


Figure 2.1. The iterative process of the method of this study.

In subchapter 2.1, the methodology for the literature review is described. The mixed method research approach is described in subchapter 2.2. The methodology for the interview study, the LCA and the comparison is described in the other subchapters.

2.1 Methodology for the literature review

To determine what has already been accomplished in the field, the literature review included a study of research articles, books, reports, web pages and framework agreements. The following subjects were studied:

- Definition of fossil-free materials.
- Material choices for a fossil-free preschool.
- Properties and requirements of insulation materials.

The result of the literature review is presented in Chapter 3. In this thesis, mainly first-hand sources were used. The literature review was mainly performed by using articles and books not older than 20 years available at Chalmers University of Technology’s library database. Reports available at governmental web pages such as National board of housing and Swedish Environmental Protection Agency was also studied in the literature review.

The literature review on *fossil-free* comprised of studying existing definitions of the term fossil-free as well as identifying what the meaning of the term is in the literature. The search was conducted mostly by researching Swedish and international governmental web pages for the term as well as the in reports published by IPPC. To study the material choices and how it could be affected, handbooks, books, web pages, and articles describing the building prosses and involved actors was studied. The search was conducted by using the terms: *construction process, construction process choice, environmental management, EPD, life cycle assessment, material choice, affect material choices, political instrument, green procurement.*

In the literature review, insulation materials and requirements on an insulation material were also studied. The material mineral wool was reviewed to examine which properties hemp insulation needs to fulfil. Both hemp insulation and mineral wool were studied by reviewing product declarations available from material suppliers as well as studying book covering the topic of insulation materials.

2.2 Mixed methods research

A mixed methods research was chosen to meet the aim and purpose of this thesis, which means that data is gathered by a mix of a qualitative and quantitative approach. The qualitative approach used was an interview study where data was gathered on how material choices are made today and how they could be made for a fossil-free preschool. A quantitative approach was used to gather information about the challenges and the advantages of replacing mineral wool with hemp insulation. The quantitative approach applied in this thesis was an LCA. A mixed methods research approach was chosen to gather information of the industries' opinions on material choices as well as assessing the challenges and advantages of replacing a standard material by using an LCA. The focus of the approaches has been equal. Further, the result of the interview study was used in the development of the LCA.

The challenge with a mixed methods research is that it requires skills, time and resources to perform a mixed methods research since it is more demanding (Cresweel & Plano Clark, 2011). Further, Cresweel and Plano Clark (2011) describe one of the challenges with a mixed methods research to be a duality in research between the two different approaches. Cresweel and Plano Clark (2011) continue to state that the advantages of using a mixed method research are that both qualitative and quantitative data is used and by mixing the approaches some of the weaknesses with the approaches can be avoided. Another advantage is that a mixed method research approach can be used as a bridge between two different aspects of one aim. This was considered suitable for this thesis since the aim of *material choice for a fossil-free preschool* both covers the qualitative part of how materials are chosen for as fossil free preschool as well as the quantitative part of how fossil free materials can be measured and compared.

2.3 Methodology for the interview study

For this thesis, an interview study was used to establish a greater understanding of how materials are chosen for a fossil-free preschool. The fossil-free preschool being developed by Lokalförvaltningen was treated as a reference project in this study, which means that the focus of the data collection was regarding this specific object. Lokalförvaltningen's project for a fossil-free preschool is within the preliminary study and partnering has been decided as the collaboration form. To collect data about the fossil-free material choices, semi-structured interviews were performed. The reason for performing interviews was to understand how individuals working in the industry describe the process of choosing materials.

May (2002) describes that if a new interview is more likely to just confirm previous discoveries, the right number of interviews has been reached. In this study, the time and interviewees' availability for interviewing was a constraint. Interviews were conducted to collect data from many different actors in the industry instead of focusing on one actor. This decision was made to accomplish the purpose of the study in order to identify how materials are chosen in the construction industry and how the interviewees think that the material choice could be more fossil-free.

The process of finding interviewees is essential to the result of the research (Seale, Gubrium, Gobo, & Silverman, 2013). Seale, Gubrium, Gobo, and Silverman (2013) describe that finding good interviewees sometimes happens on chance and sometimes by being recommended by previous interviewees. When choosing interviewees, the goal is to find interviewees who can describe the larger forces and processes under investigation (May, 2002).

In this study, interviewees were chosen based on recommendations from another interviewee. However, a draft about what kind of interviewee that could contribute to the research was identified during the literature review. These were: politician, architect, contractor, researcher, the client, structural engineer, fire consultant and controller. One requirement on the interviewees was that they should have worked with a public client previously, and preferably with preschools.

The first interview was conducted on Lokalförvaltningen's development manager to achieve a larger understanding of the project. This interview was also the starting point for recommendations for future interviews since the client's developer has a large network of contacts that could contribute to the study. The interviewees were all working for organisations which worked accordingly to an environmental management system. The list below presents the interviewees:

- *Client*
  The person interviewed as the *Client* has worked at Lokalförvaltningen with environmental management and project management for ten years. Further, the Client has a supporting role as project manager for the fossil-free preschool.
- *Fire Consultant*
  The person interviewed as the *Fire Consultant* has worked with assessing the fire safety in buildings for over six years. The Fire Consultant develops requirements for buildings' fire safety and consults regarding the design of buildings.
- *Structural Engineer*
  The person interviewed as the *Structural Engineer* has worked with evaluating and designing the structural system for buildings for twelve years.
- *HVAC & Energy Engineer*
  The person interviewed as the *HVAC & Energy Engineer* has worked as an engineer for three years. The HVAC & Energy Engineer works with coordination of buildings' technical systems and develops specifications and criteria for buildings.
- *Politician*
  The person interviewed as the *Politician* works as a full-time politician for the City of Gothenburg. The interviewed politician is a member of Lokalnämnden.
- *Researcher*
  The person interviewed as the *Researcher* has worked for a contractor with research and development for twenty years and is the head of the research and development department at one of the largest contractors in Sweden. The Researcher is also an Adjunct Professor in Construction Management
- *Architect 1*
  The person interviewed as *Architect 1* has worked as an architect for ten years at one of the largest architectural firms in Sweden. Architect 1 is an architect that works a lot with timber.
- *Architect 2*
  The person interviewed as *Architect 2* has worked as an architect for thirty-five years and has designed many preschools and schools.

- *Site Manager*
  The person interviewed as the *Site Manager* works as a site manager for one of the largest contractors in Sweden. The Site Manager has worked for the contractor for four years.
- *Controller*
  The person interviewed as the *Controller* (KMA in Swedish) works with coordinating the environmental work during a construction project and controls that the used materials fulfil the client's specifications. The Controller has worked as a quality, environmental and working environment coordinator for ten years.

Interviews held early in the study can provide unexpected insights, which can then be used to improve future interviews (May, 2002). All interviews were conducted within six weeks. Seale, Gubrium, Gobo, and Silverman (2013) state that this has both strengths and weaknesses. One weakness is that the interviewer develops knowledge and understanding by having more time to analyse each interview before continuing to the next. This can result in that the interviewer can gather more qualitative data. However, the interviews conducted later with higher knowledge might not correspond to the previous interviews. To fit an interview into the interviewee's schedule the time and place were determined after the preference of the interviewee. The requirements on the place were that the interviewee should feel secure to talk and that a conversation could be held without any disturbing noise, as recommended by Seale, Gubrium, Gobo, and Silverman (2013). The time for the interviews varied between 30 to 90 minutes dependent on the depth of the discussions. The interviews were conducted in Swedish and the results were later translated into English. This was chosen to minimize the language barrier and gain a more fluent discussion.

The questions used in the interviews were developed to help answer the research questions, and the questions were reviewed multiple times to ensure that they contributed to the study. The questions used can be found in Appendix I. In semi-structured interviews, some interview questions are fully decided on, whereas others might not be fixed, and the interviewer has the possibility to ask follow-up questions. According to Kvale (1996), semi-structured interviews are the ideal compromise since it encourages the interviewees to further articulate their thoughts on the subject and it both gives a structure to the interview and a flexibility. In this interview study, a majority of the questions prepared before the interview were open-ended questions. This was used to enable the interviewee to develop their own answers without being guided too much by the interviewers' opinions.

The interviewers' task is to draw out the relevant responses and to be neutral towards the topic but at the same time display interest. However, this requires skills because it can easily lead to bias (Seale, Gubrium, Gobo, & Silverman, 2013). To ensure that the questions were easy to understand, the questions were first tested in a test interview where a pretended roleplay of the interview was conducted with a test interviewee. The main questions were sent to the interviewees two days in advance of their interview to give the interviewees a possibility to prepare for the interview. The interviews started with introducing questions to get the interviewee on the right track and to demonstrate an interest in the subject.

2.3.1 Data documentation

The interviews were recorded with permission from the interviewee, to give a detailed record of the verbal interaction. When interviews are recorded it is possible to interact during the interview instead of having the focus on writing down answers (Seale, Gubrium, Gobo, & Silverman, 2013). However, Seale, Gubrium, Gobo, and Silverman (2013) continue to state that the recorder might affect the interview negatively since the interviewee might mistrust the researcher's use of the record. To prevent this, the interviewees' trust was established by describing how the data would be treated in this study.

2.3.2 Data analysis

To analyse the gathered data, the researchers listened to all the interviews and the answers and context for each question were written down. The data gathered were divided into five categories:

1. Definition of fossil-free.
2. The interviewees' participation of the sustainability work in the construction industry.
3. Material choices in the construction industry.
4. Fossil-free material choices in the construction industry.
5. Requirements and possible replacement material for mineral wool.

After the sorting of data, the answers were compared and translated from Swedish to English to generate the results presented in Chapter 4. The interviews were not transcribed.

2.4 Methodology for the life cycle assessment

To assess if the hemp insulation is fossil-free, a life cycle assessment (LCA) was performed. The LCA performed was a 'cradle-to-gate-with-options' LCA, with the stages A1-A4 included, as seen in Figure 2.2. The methodology for the LCA has been performed accordingly to the rules and guidelines in the product category rules (PCR) for insulation materials in Environdec (2014) and *The Hitch Hiker's Guide to LCA* by Baumann and Tillman (2004). Both Environdec (2014) and Baumann and Tillman (2004) are developed in line with the ISO-standards.

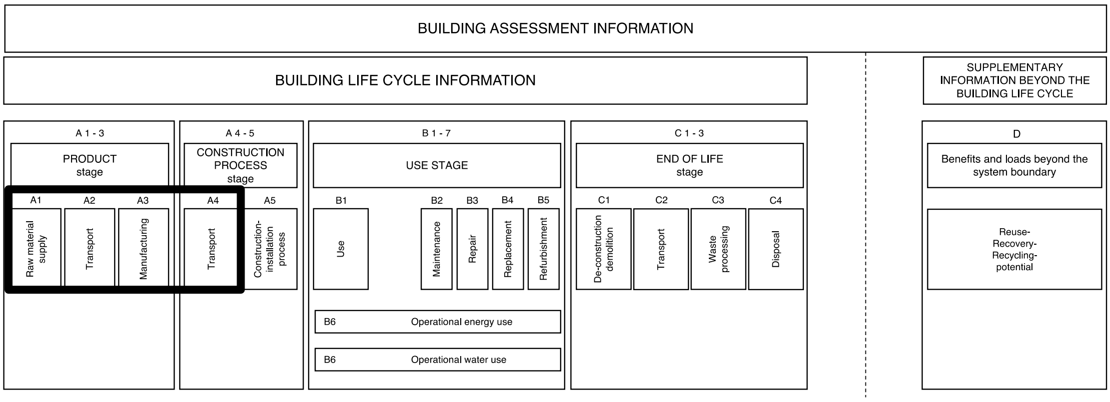


Figure 2.2. An illustration of the stages of a life cycle assessment from SS-EN ISO 15978:2011. The bold box encircles the parts included in the LCA carried out in this thesis.

Baumann and Tillman (2004) describe that the method for carrying out an LCA is a procedure as illustrated in Figure 2.3. Firstly, the purpose of the study is determined by the goal and scope. In the inventory analysis, the construction of the model and the calculation of the environmental impacts are performed. In the impact assessment, the results of the inventory analysis are put in relation to the environmental impacts. Continuously, during the procedure, decisions and results are interpreted and analysed.

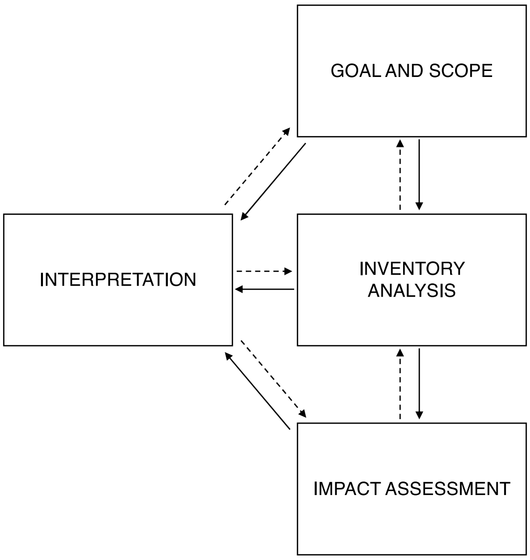


Figure 2.3. The LCA procedure. The boxes indicate procedure steps and arrows in the order the steps are performed. Brocken arrows indicate possible iterations. Adapted from (Baumann & Tillman, 2004).

During the life cycle inventory, several manufacturers of hemp insulation were contacted, in order to gather specific data, without success. When no specific data could be obtained, secondary sources such as articles and reports were used. However, one Swedish hemp farmer was reached and a discussion regarding the hemp cultivation and the insulation production was carried out, to verify the input identified in articles and reports. The information gathered from the Swedish hemp farmer can be found in Appendix II. The LCA was performed by using the LCA-software Simapro and the database Ecoinvent 3.0. The methodological choices for the LCA are further described in Chapter 5.1.

2.5 Methodology for the material comparison

The results of the LCA of hemp insulation were compared with certified environmental product declarations (EPD) data and generic data for mineral wool, both stone wool and glass wool. The EPD data was collected from the Swedish EPD database and the Norwegian EPD database, and the generic data was collected from the databases IVL and Ecoinvent 3.0. The functional unit for the comparison was 1 m^2 with R=1 m^2K/W. Further methodological choices are presented in Chapter 6.

2.6 Trustworthiness

This thesis has multiple delimitations which are discussed in Chapter 1.2. One of the goals with *Fossil-free Sweden* is to spread information on how improvements can be made in a transparent way. In this thesis, multiple assumptions are made and analysed in the LCA to gain a trustworthiness of the result.

To gain knowledge about how decisions are made when choosing materials for a preschool, interviews were held with multiple people who worked with different professions in the industry in Gothenburg. Since the majority of the interviewees were found based on recommendations from previous interviewees the results might be biased from the start. However, since a recommendation from a previous interviewee is a good way to start a collaboration, this method was still chosen. The choice to interview multiple actors in the industry instead of focusing on one actor was made in the methodology section. This is a delimitation of the thesis since one interviewee is not representative of all actors in that interviewees' field.

2.7 Ethical considerations

To avoid the risk of publishing and spreading sensitive material from the interviewees, all the interviewees are anonymous in this thesis but described generally, to gain trustworthiness of their statements. However, there are not so many project managers working with fossil-free preschools and the persons interviewed can probably still be identified with some effort. This, and how the gathered data would be used, were explained at the beginning of the interviews to make the interviewees aware of the situation. The interviews were recorded with permission from the interviewees and were deleted at the end of the study.

3 Literature Review

The literature review for this thesis is divided into three parts to meet the different aspects of the thesis' purpose and describe the procedure of material choices for a fossil-free preschool. The first part addresses what a fossil-free preschool is, the second describes the process of material choices for a fossil-free preschool and the third part is about insulation materials for a fossil-free preschool.

3.1 Definition of a fossil-free preschool

The concept *fossil-free* indicates that a product should be free from using fossil resources during its whole lifecycle, a fossil-free product. This results in that a fossil-free preschool should be a preschool that is free from using fossil resources during its whole lifecycle. A fossil resource is a resource that is derived from ancient plants and animal life, such as oil. A fossil resource can both be used as a fuel or as a part of a material. Burning a fossil fuel emits greenhouse gases and even though fossil resources are continually formed by natural processes, the resources are today being depleted much faster than they are being renewed (Miller & Spoolman, 2008). A product's lifecycle consists of all the stages from raw material extraction to the end of life (Baumann & Tillman, 2004). All stages of a building's lifecycle are presented in Figure 3.1.

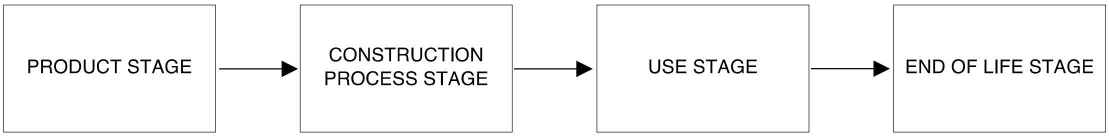


Figure 3.1. The lifecycle stages of a building.

The mission to build a fossil-free preschool in Gothenburg is a goal set to develop a more sustainable construction industry (Lokalnämnden, 2018). Sustainability is a term that means different things to different people and organisations. A 'sustainable development' can be defined as a development that leads from a less sustainable state to a more sustainable state (Ashby, 2015). A commonly used definition of sustainable development is the Brundtland Commission definition:

> *"Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs"*
>
> \- *The Brundtland Report* (WCED, 1987)

Sustainability is often described as consisting of three pillars: economic, environmental and social (Ashby, 2015). Baker (2006) argues that sustainable development has different meanings attributed to the concept and can be described as a ladder with different meanings on the different steps. One of the steps is strong sustainability which is when the environmental limit is constraining the economic and social aspect. The relation between the parts of sustainability is that economies are constrained by social limits and both social and economic are constrained by environmental limits. Fossil-free is a measurement of strong sustainable development since the environmental aspect is in focus and no trade-offs between the economic and environmental aspects are allowed.

Fossil-free can be seen as a way of communicating a sustainable aim of reducing the use of fossil resources and by doing this, reducing the emission of greenhouse gases in a simplified term. Mulder, Ferrer, and Van Lente (2011) describe that a complex term such as sustainability often is simplified to easily communicate it to the public. Mulder, Ferrer, and Van Lente (2011) continue to argue that by using simplified terms it can result in a difficulty of seeing the whole picture and might result in that one problem is solved and other problems are ignored.

To compare the environmental impact of two alternative materials in a material choice for a fossil-free preschool the measurement Global Warming Potential (GWP) could be used. GWP is a measurement of greenhouse gases' contribution to the global warming by measuring the amount of heat a gas traps in the atmosphere (IPCC, 2007). IPCC (2007) describes that the relation between the gases is relative and compares the effect of a gas with the effect of the same mass of carbon dioxide. The comparison is based on i.a. the lifespan of the gas in the atmosphere. Different gases have different lifespans in the atmosphere which has resulted in that the GWP commonly is expressed in years as well e.g. GWP_{100}. Apart from fossil-free, there are multiple articulations of sustainability that often are measured in GWP such as; carbon neutral, zero emissions and climate neutral.

3.1.1 The city of Gothenburg's definition of a fossil-free preschool

The administration of premises of the City of Gothenburg (Lokalförvaltningen) is the department of public facilities in Gothenburg that both administrate, manage and build the facilities for the municipality (Lokalnämnden, 2017). The facilities mainly consist of preschools, schools, retirement homes and offices. In Sweden, 80% of the children attend a public preschool (Skolverket, 2016) and, thus, Lokalförvaltningen builds approximately 20 preschools a year. The mission to build a fossil-free preschool is a pilot project presented in the goal- and target document for Lokalförvaltningen for the year 2017 (Lokalnämnden, 2018). Lokalnämnden, which works as the board of Lokalförvaltningen, assigned the goal which was developed from the City of Gothenburg's goal to become a fossil-free municipality to the year 2030. The goal was first included in the municipality's budget which is the governing document for the municipality.

According to Lokalnämnden (2018), a fossil-free preschool should be fossil-free at all stages and for all materials. Included in their definition are raw material via transport and manufacturing to the construction site and the completed building. Therefore, the concept fossil-free, according to Lokalnämnden, includes raw materials, fuels in all vehicles (transportation and work equipment) and energy (heat and electricity) at the manufacturing stage and at the construction site. The focus is thus on the lifecycle stages presented in Figure 3.2. However, the operation of the preschool will be taken into consideration by energy efficiency and local energy production. Lokalförvaltningen's normal energy consumption standard is likely to apply with 45 kWh/m and year. The energy supply will be district heating from Göteborg Energi. Göteborg Energi has the goal to be fossil-free at the latest 2035. Process-related greenhouse gas emissions such as cement production will also be included in the assessment of fossil-free (Lokalnämnden, 2018).

The ambition is that the greenhouse gas emissions should be as low as possible, and the emissions that cannot be avoided should be compensated in the most appropriate way to achieve net zero.

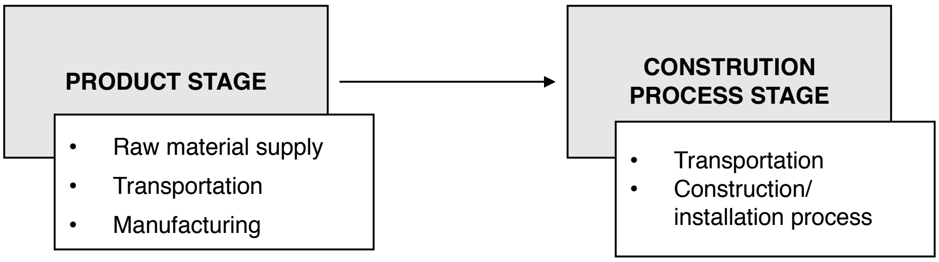


Figure 3.2. Lifecycle stages included in Lokalförvaltningen's definition of fossil-free

3.1.2 Compensation methods to achieve a fossil-free preschool

When investigating the GWP and if a process is fossil-free, carbon dioxide compensations can sometimes be accounted for. A CO_2-compensation is a process that removes CO_2e from the atmosphere or removes a CO_2-emitting process from the society (Metz B. , et al., 2005). Metz et al. (2005) further present Carbon Dioxide Capture and Storage (CCS) as a possible compensation method. CCS is a process where CO_2e is captured by separating it from industrial and energy-related sources. Further, the CO_2e is transported to a storage location, usually far down in the ground or under the ocean floor, where it will be isolated from the atmosphere for a long time.

Another compensation method is biogenic CO_2-storage in plants (Harris, Millner, & Taylor, 2018). Harris, Millner, and Taylor (2018) further describe that the principle behind biogenic CO_2-storage in plants is that plants absorb CO_2e from the atmosphere during their growing phase and the CO_2e is then stored in the plant. Lokalnämnden (2018) has proposed to plant trees in connection with the preschool to have a local biogenic CO_2-storage mechanism as a compensation method. However, this compensation method has not been assessed.

Further, a compensation method that is used is that a company can "pay" for the CO_2-emission they emit (Romson, 2008). The payment is done by taxes which i.a. are used to remove coal plants in developing countries and replace it with renewable energy sources.

Another method that can be used is Clean Development Mechanism (CDM) origin from the Koyoto Protocol (Metz, Davidson, Bosch, Dave, & Meyer, 2007). It entails that companies invest in projects that work with emission reductions in developing countries and contributes to a sustainable development in those countries.

Regarding if compensation methods can be accounted for or not, is a political and institutional uncertainty (Metz B. , et al., 2005). Thus, it is not always seen as an option in order to reach a climate neutral result such as fossil-free.

3.2 Material choices in the construction process

To gather information about the first research question *"How can material choices be made when constructing a fossil-free preschool?"*, the research question was divided into the following sub-questions:

- *Where in the construction process are the material choices made?*
- *Who makes the material choices?*

Construction processes differ between both projects and clients. To describe where materials commonly are chosen in the construction process the description of the process from (Sveriges Byggindustrier, 2017) is applied.

The construction process comprises the design phase and the construction phase and is often preceded by a preliminary study followed by a use phase combined with facility management. The decision to build is part of an operation plan and requires an internal project management from the organisation. The construction of a new building needs to follow regulations. If the client does not have all required resources for constructing a building, the client need to procure those resources. Figure 3.3 illustrates the different phases of the construction process and the parts required to develop a new building.

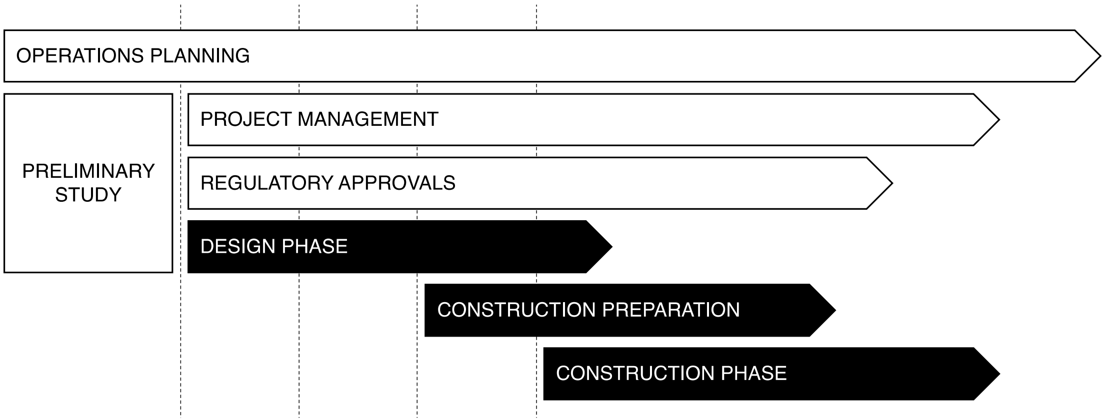


Figure 3.3. The construction process for a new building is illustrated with black boxes and other required parts in the construction process is illustrated with white boxes. The illustration is adapted from Sverige Byggindustrier (2017).

3.2.1 Material choices with regard to procurement

If a client does not have all the required resources for constructing a building, the client need to procure those resources. The client has the main responsibility for the project and is the one who decides the contracting strategy (Potts & Ankrah, 2014). The chosen contract strategy affects the allocation of risk, the project management requirements, the design strategy and the procurement of consultants and contractors. Potts and Ankrah (2014) describe that the contract strategy has a major impact on the timescale and the ultimate cost of the project. Further, Potts and Ankrah (2014) describe that the following should be considered when choosing the strategy; payment mechanism, project delivery system, bidding procedures and criteria in the contract. The criteria in the contract can affect the material choices since the chosen material need to fulfil the criteria. The payment mechanism for the contract that is used can be price based, cost-based or other incentives based (Potts & Ankrah, 2014).

Management and coordination of the project are often transferred from the client through different forms of contracts. In Sweden there are mainly two different forms of project delivery systems (Upphandlingsmyndigheten & Konkurrensverket, 2017), these are:

- *Design-bid-build*
  In design-bid-build, the client procures and has the responsibility for the design team.
- *Design-build*
  In design-build, the client procures a contractor that is responsible for procuring the design team (Sveriges Byggindustrier, 2017).

In Sweden, standard agreements are often used for procurement. The purpose of standard agreements is to reduce the transaction costs and the risk and to increase the predictability of the contents of a specific agreement (Sveriges Byggindustrier, 2017).

In Sweden, the contract delivery system can be combined with different forms of collaborations. Partnering is a form of collaboration where the parties involved in the project are systematically strengthening and developing their collaboration in order to reach the project's aim (Kardefors & Dwulf, 2012). Kardefors and Dwulf (2012) further describe that the parties involved are working with common interests, goals and open-book accounting. For material decisions, partnering results in flexibility which leads to that decisions can be made later in the process (Potts & Ankrah, 2014). In Sweden there are two types of partnering; project partnering and strategic partnering. In project partnering the procurement point can vary in time and in strategic partnering, the client has established a long-term relationship with the supplier and later in the process develop a project specific contract. Kardefors and Dwulf (2012) describe that the procurement in partnering project often is performed based on soft criteria instead of absolute values such as price.

In Sweden, a clear difference between a public client and a private client is that only the public client is subjected to the Swedish Public Procurement Act, 1 chap. 2 § LOU. The aim of LOU is to guarantee that the public client uses public funds to finance public purchases in the best possible way by seeking out and taking advantage of market competition in the relevant market to get a good deal (Konkurrensverket, 2018).

The fundamental principles for public procurement are specified in 4 chap. 1 § of LOU and apply to all procurement of products, services and works. One of the fundamental principles of public procurement is '*The principle of non-discrimination*' which states that it is not possible for the public client to select suppliers on grounds of nationality. This result in that the client may not include requirements on the materials resulting in that only Swedish companies can leave tenders or give preference to a local company.

3.2.2 Material choices with regard to the design phase

The purpose of the design phase is to transform the client's vision of a building to building documents. The design phase can be divided into the program stage, the system document stage and the building document stage (Sveriges Byggindustrier, 2017). Depending on the project delivery system, the client and the contractor have a different amount of involvement in the design phase. Sveriges Byggindustrier (2017) describes the stages as; in the program stage the conditions for the project and questions regarding, location, form, structural system, alternative materials and technical supply system are evaluated and tested. This stage results in technical specifications which restricts the possible materials to choose from. In the system document stage, the building is furthered developed by coordinating a holistic picture of the system included in the building. The system documents are used for applying for a building permit.

Decisions regarding which materials to use and not to use are made in all of these stages but many of the specific decisions are described in Sveriges Byggindustrier (2017) as being made in the system document stage. In the building document stage, the design is even further clarified and developed, and the results of this stage are drawings, specifications, listings for the construction process. Figure 3.4 illustrates the stages, what is decided in the stages and which documents that result of the stages. Besides the client, different consultants are involved in the design phase and assist the client in making the decisions.

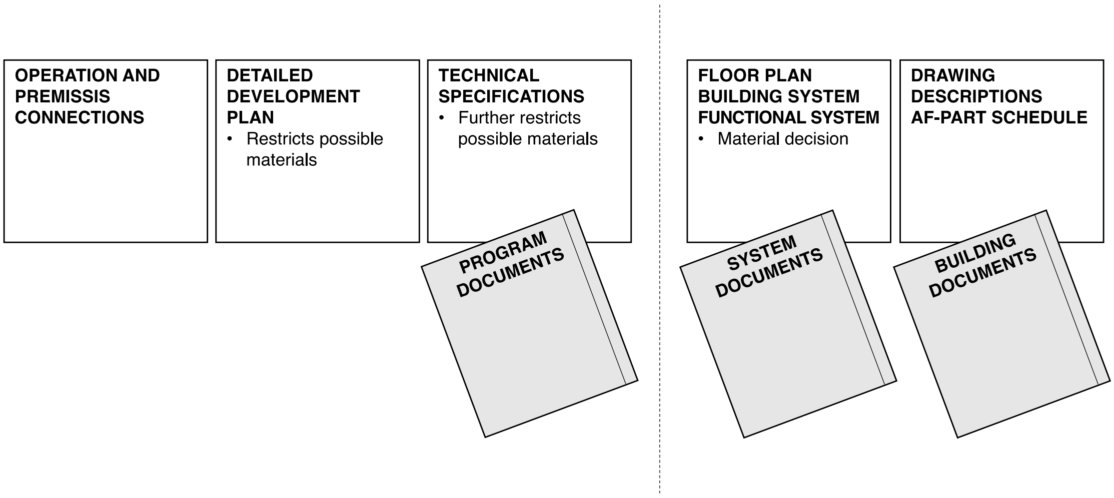


Figure 3.4. The design phase and relating documents. Modified from Sveriges Byggindustrier (2017).

As described, many of the decisions regarding materials are performed in the design phase of the construction process. Depending on which delivery system the client uses the client has a different amount of involvement in the design phase and therefore different amount of involvement in the material choices. However, even if the contractor has the responsibility for the design phase, it is still the client's responsibility that the materials used in the construction are suitable (Boverket, 2018b).

3.2.3 Material choices with regard to the construction phase

During the construction phase the building is constructed and the materials are ordered from the suppliers and built into the building. Due to LOU, the client cannot prescribe specific material suppliers for a project. However, it is possible to limit the contractor's choice of materials and material suppliers in the specifications developed in the design phase. In the construction phase the requirements described in the design phase need to be fulfilled and according to Erlandsson (2006), it is very important that the requirements can be verified.

3.2.4 Actors in the construction industry's role in the material choices

The different actors in the construction industry have different roles in the material choice process and the role of the actors varies between projects. The list below describes the general role the different actors have in the material choice process.

- *Politician*
  Politicians in the parliament and the government set the goal for environmental development in Sweden (Regeringen, 2018). The politicians in Lokalnämnden sets the goal for the development of Lokalförvaltningen (Lokalnämnden, 2018). Due to this, the politicians can lead the development toward fossil-free material choices if this is a specified goal.

- *Client*
  The client procures the building and has the main responsibility for choosing suitable materials. By demanding and paying for the use of fossil-free materials, the client can ensure the use of fossil-free products in the building. The client often hires a project manager to the construction process (Sveriges Byggindustrier, 2017).

- *Architect*
  An architect plans and designs the building and aims to develop a building that is both aesthetical and functional. Thus, the architect suggests different designs and solutions to the client and, together with the other consultants in the project, the architect develops the documents in the design phase. Multiple factors are often considered by the architect when evaluating the various categories of building materials and trade-offs between the factors are needed to make the decisions (Ogunkah & Yang, 2012).
- *Structural engineer and other consultants*
  A structural engineer ensures the structural performance of the building and is commonly suggest solutions for the buildings structural system to the client. Other consultants give suggestions and advice about their area. Together with the architect, the consultants develop the documents in the design phase.
- *Controller*
  The controller shall, according to 10 chap. 9-10 § PBL, have the knowledge, the experience and the suitability required for controlling that the project fulfils the requirements of the building legislation.
- *Contractor*
  The contractor performs the building and orders the materials from the suppliers (Sveriges Byggindustrier, 2017). As a result of the law of public procurement, 4 chap. § 1 LOU, the client cannot specify a specific supplier which results in that the contractor is the one selecting the supplier.

3.3 Different mechanisms' effect on the material choices for a fossil-free preschool

From the first research question *"How can material choices be made when constructing a fossil-free preschool?"*, the sub-question *"How can different mechanisms affect the material choices?"* was developed to gather information on how material choices can be affected. In this subchapter, some of the mechanisms that can be used to affect the material choices towards a fossil-free material are described.

3.3.1 Political instruments' effect on the material choices

When the resources are not used optimally on the free market, different instruments can be used to regulate the market (Naturvårdsverket, 2012). An instrument gives an incentive to increase or decrease the use of a product or service. To reach an environmental goal, different instruments can be used. Boverket (2016) describes that there are four different types of instruments to affect the environmental performance of materials which are; administrative, economic, informative and research and development.

Today, the most commonly used economic instrument in the construction process is carbon dioxide tax (Boverket, 2018). Boverket (2018) describes that the cost of greenhouse gas emissions is included in the price the client pays for e.g. building materials. This results in that the client already is paying for a large part of the climate emissions that occur during the construction phase and to add an extra tax on the greenhouse gas emissions from the completed building could result in double taxing.

Boverket (2018) gives four proposals of instruments that could be used to increase the environmental sustainability in the construction industry. These four proposals are listed below:

- *Proposal 1: Information about life cycle assessment of buildings*
  The aim is to increase knowledge about climate calculations in the design phase and increase the demand for specific information about climate emissions from construction materials. Another aim is that the guidance will remove the gap between the client's and the manufacturers' awareness about the construction materials' climate impacts.
- *Proposal 2: Climate declaration of buildings*
  One purpose of requiring a climate declaration of a building is to decrease the impact on the climate by raising awareness and the knowledge about building materials' environmental impacts.
- *Proposal 3: The government's efforts to reduce the greenhouse gas emissions from a building's lifecycle*
  Boverket (2018) proposes that all public clients in the construction sector, which develops or uses buildings, should lead the movement of increasing knowledge on buildings' environmental lifecycle impacts. This knowledge could later be spread to other actors in the industry. This could, for example, be knowledge about alternative materials that could be used instead of the standard materials.
- *Proposal 4: Develop criteria for green public procurement*
  Finally, the last proposal is to develop criteria for green procurement that can be a complement to the existing optional environmental criteria. This is further described in subchapter 3.3.2.

Boverket (2016) concludes in the report that an instrument should be implemented as close to the source of the problem as possible, to get the most desired effect. It is also important to examine a new instrument's relation to existing instruments so that they do not have negative effects on each other. One example given regarding this is that a requirement of a CO_2e-emission allowance on building materials, regulated by legislation, might not get the desired effect. The reason for this is because it already exists carbon dioxide taxes on both transportation and different materials in the European trade agreement.

3.3.2 Green procurement's effect on the material choices

Setting criteria demanding fossil-free materials in the procurement is called green procurement. Green public procurement could be a mechanism used to affect the material choices. Green public procurement is an administrate political instrument which has the purpose of guiding towards a more sustainable development (Naturvårdsverket, 2010). The total value of public procurement in Sweden for the year 2015 was 642 billion SEK which represents about one-sixth of the Swedish GDP (Upphandlingsmyndigheten & Konkurrensverket, 2017, p. 8). Green public procurement aims to create an incentive for suppliers to develop more environmentally beneficial products, and in the long run lead to a more sustainable consumption and production (Naturvårdsverket, 2010). One of the benefits of green public procurement compared with environmental taxes, is that it can affect foreign suppliers that import materials to Sweden as well (Lundberg, Marklund, & Brännlund, 2009).

One part of an organisation's environmental work can be to improve the environmental capabilities of the organisation's supply chain by requiring specific green criteria in the procurement (Lee & Klassen, 2008). In the building sector, this can be done when consultants, contractors, subcontractors and material suppliers are selected. Naturvårdsverket (2010) has identified three key factors that seem to determine if environmental criteria are included in the procurement:

- *Political interest*
  Political interest is a formalized support through a well-established and implemented environmental policy.
- *Insecurity of which criteria to include*
  In relation to LOU, there are an insecurity of which criteria to include and a concern that the contract will be reviewed and get an appeal.
- *Individual commitment*
  Individual commitment is identified as the last key factor and means that individual enthusiasts are pushing for environmental requirements.

High cost and insufficient monitoring of environmental criteria is a problem with green public procurement (Erlandsson, 2006). Erlandsson (2006) continues to describe that the criteria must have a clear connection to an established environmental problem and that the tendering document must describe how the criteria will be evaluated in the tendering process to follow the principle of equal treatment in 4 chap. 1-2 § LOU. Fewer environmental requirements with a focus on the most significant environmental aspects that can easily be verified is a solution to this problem presented by Varnäs, Balfors, and Faith-Ell (2009). Another barrier to green procurement is lack of environmental data that can be verified and a solution to this problem could be to use a life cycle assessment (Varnäs, Balfors, & Faith-Ell, 2009). No alternative product available or that the available products are more expensive and have differences in quality or fitting, is also a problem to overcome (ICLEI/Öko-Institut, 2007). One of the drawback with green public procurement mentioned by Lundborg, Marklund, and Brännlund (2009) is that when setting an absolute value as criteria for green procurement the suppliers will all meet this criterion and might not work towards an improved solution.

3.3.3 Environmental management systems' effect on the material choices

Environmental management is a management practice of reducing environmental impacts of organisations which includes practices such as waste reduction, recycling, reuse and adoption of cleaner technologies (Wong, Lai, & Cheng, 2015). Wong, Lai, and Cheng (2015) states that an environmental management systems (EMS) play a key role in developing environmental management practices. Organizations implement EMS to maintain compliance with environmental regulations, reduce environmental costs, reduce risks, train employees, develop indicators of impact and improve environmental performance (Christini, Fetsko, & Hendrickson, 2004). The actors in the construction industry could use an EMS to develop their practice to be fossil-free.

EMS was originally designed for permanent organisations and not project-based organisations, which is common in the construction industry (Gluch, 2005). However, many companies in the construction industry work in accordance with an EMS and the number is increasing (Gluch, et al., 2014). Gluch et al, (2014) states that the most common way to use EMS in the industry is to establish an environmental policy.

Many companies in the industry set environmental goals but have problems to follow them up. Implementing EMS in the construction industry shows no trend of increasing short-term profit, productivity or market share. However, other benefits such as company image, satisfied personnel and management, product image and recruitment, has an increasing trend after implementing an EMS (Gluch, et al., 2014).

3.3.4 Standards' effect on the material choices

Boverket (2017) describes that there are standards for almost everything in the construction industry and usually standards are divided depending on function. AMA is a criteria-standard commonly used by consultants and clients voluntarily when procuring and setting requirements on projects. Using already developed criteria reduce the transaction cost and structured construction documents and calculable requests that reduce the risk of misinterpretation and expensive mistakes. By including sustainability criteria to AMA, Upphandlingsmyndigheten (2015) aims to make them more accessible to the procurers. Today there are no standardised AMA-codes for fossil-free requirements (Upphandlingsmyndigheten, 2018).

3.3.5 Life cycle assessments effect on the material choices

A life cycle assessment's (LCA) purpose could be to support the material choice process and documentation of the environmental performance of a building or a material (Swedish Standards Institute, 2011). To increase the use of LCA and to simplify the tool is one of the changes proposed by Boverket (2018) that could increase the sustainable development of the construction industry. A trend for environmental management in Sweden identified by Gluch et al, (2014) is that companies perform activities, often LCA, that aims to transfer environmental information and accountability between the actors involved in the construction process. An LCA could both be used to evaluate the environmental performance of different materials and also to verify if the goal of fossil-free is reached or not. The Swedish Standards Institute (2011) describes that even if the assessment is developed on realistic scenarios, the result may not fully reflect the actual and future performance of the building.

Baumann and Tillman (2004) describe that the strength of an LCA is that it helps to determine which action is more "environmentally friendly". It also studies a whole product system and thus, sub-optimisations are avoided. Johnsen and Løkke (2012) state that transparency in how the procedure for the LCA is carried out is important since the results are largely affected by the methodological choices for the LCA and the result can, therefore, be both controversial and inexact.

3.3.6 Environmental product declarations' effect on the material choices

An environmental product declaration (EPD) is a verified registered document that gives transparent and comparable data about a product's environmental impacts (Environdec, 2018). Further, Environdec (2018) states that the main purpose of an EPD is to communicate the environmental impacts of different products. An EPD for a specific material can be developed from Product Category Rules (PCR). If two EPDs are developed from the same PCR, the LCA behind the EPD is developed after the same rules, which makes them more comparable. Availability of information on the environmental impact of different materials from different suppliers is one thing that could affect the sustainable development (Boverket, 2018).

3.3.7 Byggvarubedömningen's effect on the material choices

One of the requirements that a client can specify is to get the building certified or that the materials and products used in the building should be listed in a specific database. Lokalförvaltningen has their own requirements for the development of a building, which shall complement laws, regulations and practices (Göteborgsstad, 2018). One of the requirements is that the used material should be listed in the material database Byggvarubedömningen (Göteborgs stad, 2018). Byggvarubedömningen (2018) is a database that evaluates construction materials' environmental performance. If a material is listed in Byggvarubedömningen it has a minimum level of environmental performance and needs to be re-certified every third year (Byggvarubedömningen, 2018). The main criterium for the certification is that the product should be non-toxic, but some consideration is also made with regard to a product's emissions during its lifecycle. To gather information regarding if a material is fossil-free the information found in Byggvarubedömningen is not yet sufficient.

3.3.8 Building certification systems' effect on the material choices

To assess and classify buildings from an environmental perspective there are several international and national systems. The first commercially available environmental assessment system was the Building Research Establishment Environmental Assessment Method (BREEAM) from the UK (Thuvander, Femenias, Norling Mjörnell, & Meiling, 2012). Thuvander et al. (2012) further list some other certification systems available; Leadership in Energy and Environmental Design (LEED) from the US, Miljöbyggnad that was developed as a Swedish environmental rating tool and the Nordic eco-label Svanen. In the certification systems, a building's performance is evaluated and assessed from different indicators such as energy consumption, material usage and indoor climate. Depending on how well the building fulfils the criteria in the indicators the building can receive certifications to verify the performance.

3.4 Thermal insulation materials for a fossil-free preschool

The first part of this subchapter describes the cycle of building materials and the energy consumption and carbon dioxide processes when producing a building material. The other part describes the properties of an insulation material and different types of insulation materials.

3.4.1 The cycle of building materials

Today, the building industry is the second largest consumer of raw materials on earth. By studying the environmental impacts of materials in a building project, there are a few things that initially can be said about materials according to Berge (2009). First of all, the resources can be divided into two groups, renewable resources and non-renewable resource. The non-renewable materials are the ones that can only be harvested ones, and some of these resources that are used the most in the world are becoming scarce. Thus, it is not sustainable to keep harvesting these materials since the assets from the earth eventually will run out. A more sustainable use of the resources would be to use the renewable resources and also to recycle and re-use the used non-renewable materials. Figure 3.5 illustrates the cycle of materials according to Berge (2009).

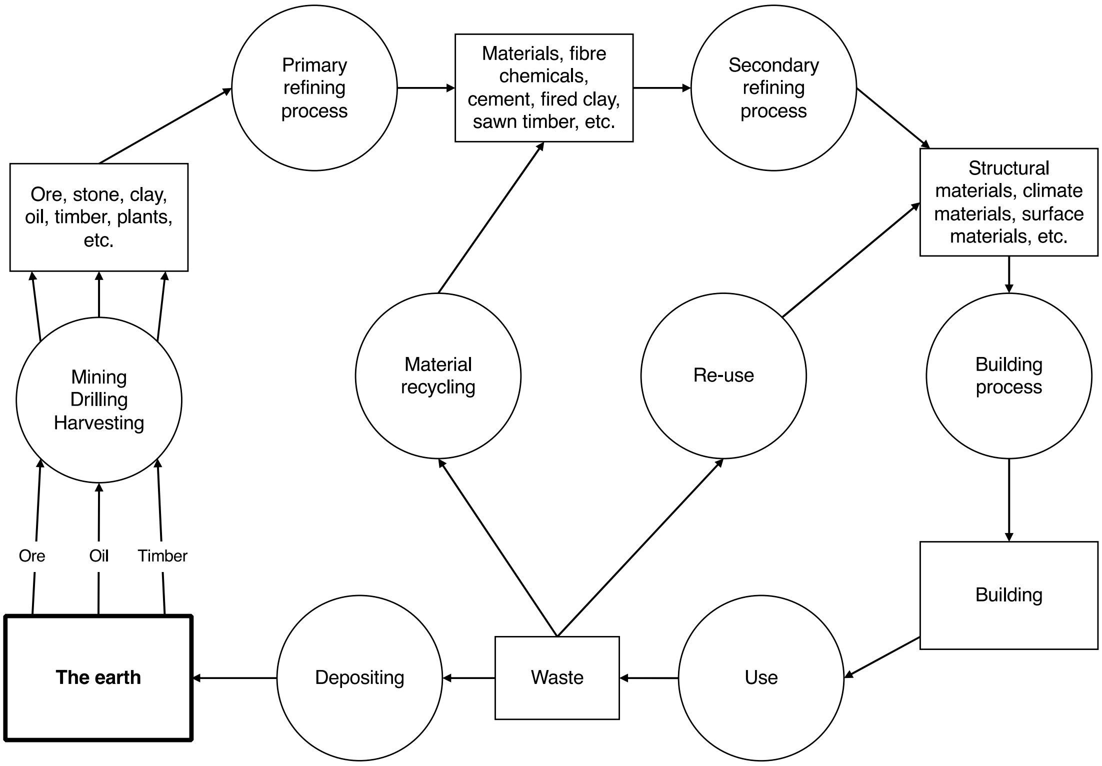


Figure 3.5. The cycle of materials according to Berge (2009). The rectangles represent an object or a product from the previous step and the circles represent a process or something that is done with the previous box.

Another way to make the construction of a building more sustainable is to reduce the material use of the building (Berge, 2009). Activities that can reduce the material use can be to make more adaptable buildings that can be used for many different activities. This can be made by three principles; implement separate layers, make it possible to disassemble each layer within the layer or using standardized mono-material components.

3.4.2 Energy consumption of building materials

Today, fossil resources are to a great extent used for energy. In Europe today, the construction sector stands for 40% of the energy use (Schiavoni, D'Alessandro, Bianchi, & Asdrubali, 2016). In this percentage, construction, operation and demolition are included. Further, the energy that is directly related to the materials used in the building usually stands for 10 to 25% of the energy use in a building (Kram, 2001). The largest part of the energy consumption is due to the operational energy use. According to Thormark (2007), a building's energy demand over a 50-year period can vary a lot between different buildings. The main reason for the large differences is due to the materials used in the building (Berge, 2009). This is both because the process of producing a material in itself requires a large amount of energy, and also because the performance of the material, durability and heat capacity, is connected to the operational energy use. However, when constructing low energy buildings, the operational energy use is a lot smaller because of the massive walls, and therefore the materials can stand for as much as 50% of the total energy consumption (Berge, 2009). Thus, it is just as important to find better alternatives for the materials as for the energy source.

The energy used for a material is defined as embodied energy (Berge, 2009). A product's embodied energy includes all energy used during the manufacturing process; extraction the raw materials, refining process, processing, and all the transports to the final product. A material's feedstock is also a part of the embodied energy which is the raw material's incineration value. Of the total energy input in a building construction, the materials' embodied energy usually is between 85 to 95% according to Berge (2009). The remaining 5 to 15% of the total energy input is used for; transporting the final product to the construction site, the energy consumption on the building site, the maintenance of the building and finally the energy required for the demolition of the building.

3.4.3 Carbon processes in building materials

During the lifecycle of a material, a material can both emit and absorb CO_2e and the process differ between different materials (Berge, 2009). Some of the processes that usually emits CO_2-emissions are (Statistiska centralbyrån, 1999):

- The raw material extraction.
- The production method from raw material to finished product.
- The construction method and installation process.
- The transportation from the resource to the factory and from the factory to the construction site. Locally extracted resources are better and also locally produced products. This also depends on the type of transport mode.

Organic materials, such as timber, absorb CO_2e during its growth by transforming it to carbon (Naturvårdsverket, 2017a). Thus, when using building materials made of organic compounds, the building materials will store CO_2e during its entire lifetime (Gustavsson, 2010). Further, Gustavsson (2010) states that, when extracting timber, new plants are usually replanted which will further take up more CO_2e from the air, and the total stock of plant-based products will increase in the whole system. Therefore, construction materials made from plants will reduce the CO_2-concentration in the atmosphere and will contribute to a reduction of the global warming and the climate change. However, the waste treatment of an organic material affects the outcome of the total CO_2-emissions and need to be considered.

3.4.4 Properties of insulation materials

The insulation in a building plays a major role in the energy consumption of a building. The main reason why the insulation affects the energy consumption during the building's lifespan is mainly that the operational energy consumption and the heat demand is related to the building envelope (Pfundstein, et al., 2012). Beside that it affects the operational energy use of the building, the process of producing and installing the product requires energy and is consequently emitting greenhouse gases. The most used insulation material in the year 2011 was mineral wool which stands for 52% of the used insulation materials (Hera, et al., 2016).

The main purpose of an insulation material is that the thermal performance should be as good as possible (Pfundstein, et al., 2012). The thermal performance depends on the thermal conductivity which is a measure of a material's ability to transport thermal energy. Thus, an insulation material should have a low thermal conductivity as it should prevent the heat inside to travel out through the building envelope. Thermal conductivity is usually noted as λ and is measured in the unit W/mK.

A thermal insulation material usually has a thermal conductivity between 0.030-0.050 W/mK and can in that range be regarded as good (Pfundstein, et al., 2012). The thermal conductivity depends on a lot of parameters such as the raw material, the density, the microstructure and nature of the solid components, the content of moisture, the temperature, the cell gases and the fineness of fibres and their orientation if it is a fibrous material. Besides the thermal conductivity, there are other important characteristic properties of an insulation material (Pfundstein, et al., 2012):

- *Temperature stability*
  Insulation materials should ensure that the indoor temperature is stable. Thus, maximum values for the service temperature is often specified by the manufacturer.

- *Dimensional stability and temperature induced changes in length*
  Due to temperature changes, moisture content variation and loads, all materials undergo dimensional changes that are specific to certain materials and these are divided into reversible and irreversible changes. Therefore, the product standards specify minimum requirements for dimensional stability.

- *Water vapour diffusion resistance*
  All building materials have a certain resistance against moisture that strives to distribute themselves evenly into the air. This resistance is called water vapour diffusion resistance. Manufacturers usually specify minimum and maximum values for their products. Fibrous materials are usually limited resistant to diffusion.

- *Water absorption*
  Water absorption is when water absorbs into the building material and this is in general not desirable for any building material. However, insulation materials are often not hygroscopic which means that they do not absorb moisture from the air and they usually do not suck up capillary water. Maximum and minimum values are defined in the product standards. If the moisture content in an organic insulation gets too high during a long time, there is also a risk for mould.

- *Sound impedance*
  Sometimes, the thermal insulation material should also improve the acoustics in the room and in those cases, the sound impedance should be as low as possible.

- *Fire safety resistance*
  According to BFS 2011:6, *"Buildings shall be designed with a fire protection that ensures that the fire safety is satisfactory".* Thus, regardless of the fire performance of an insulation material, a building should be designed accordingly. However, different insulation materials can have different fire resistance.

3.4.5 Types of thermal insulation materials

Insulation materials are usually classified according to their raw material into two main groups; inorganic and organic. Inorganic materials usually consist of minerals and organic materials consists of carbon and origin from a once-living organism (Pfundstein, et al., 2012). Further, the insulation materials within each group, inorganic and organic, are subdivided to synthetic and natural materials depending on how the raw material is processed, assembled and produced. Organic materials usually contain additives in order to resist e.g. fire and moisture, and those additives are generally not organic. Therefore, for an organic material to be classified as organic, it cannot contain more than 25% of inorganic additives (Berge, 2009).

Further, different insulation materials can be used in different parts of a building. Some materials are developed to be used in a roof, a wall or a floor slab. In Table 3.1 to Table 3.3, classifications of insulation materials that can be used in an exterior wall are presented (Pfundstein, et al., 2012).

Table 3.1. Inorganic insulation materials, subdivided into synthetic and natural.

Inorganic insulation materials	
Synthetic	Glass wool
	Rock wool
	Cellular glass
	Foamed glass
	Calcium silicate foam
Natural	Expanded perlite
	Exfoliated vermiculite
	Expanded clay
	Insulating clay bricks

Table 3.2. Organic insulation materials, subdivided into synthetic and natural.

Organic insulation materials	
Synthetic	Polystyrene, expanded
	Polystyrene foam, extruded
	Polyurethane rigid foam
	Polyurethane in-situ foam
	Phenolic foam
Natural	Wood wool
	Wood fibres
	Insulation cork board
	Cellulose fibres
	Hemp
	Sheep’s wool
	Cotton
	Flax
	Cereal granulate
	Reeds
	Coconut fibres

Table 3.3. Organic insulation materials, subdivided into synthetic and natural.

Unclassified new development materials	
Synthetic	Nano cellular foams
	Vacuum insulation panel

3.4.6 The standard insulation material mineral wool

Mineral wool is a general term for glass wool and rock wool and is one of the most commonly used insulation materials (Hera, et al., 2016). The reason that it is such a popular insulation material in the building industry is due to its properties; good insulating capacity, resistance against mould, vermin and rot, prohibit good sound insulation and has a good resistance to fire (Berge, 2009). However, it requires a lot of energy during the production (Širok, Blagojevic, & Bullen, 2008). Table 3.4 presents the materials' properties.

Table 3.4. Specific properties for mineral wool, (Berge, 2009) if nothing else is stated.

	Stone wool	**Glass wool**
Raw material:	Non-renewable Diabase, dolomite, limestone	Non-renewable Quartz sand, soda, dolomite, lime and recycled glass
Thermal conductivity:	0.035 – 0.045 W/mK	0.031 – 0.045 W/mK
Fire resistant:	Euro class A1 Building material class A1	Euro class A1 Building material class A1
Sound impedance:	Yes	Yes
Density:	20-200 kg/m^3	20-110 kg/m^3
Moisture/mould:	Not sensitive	Not sensitive
Lifespan:	40 years (Erlandsson & Holm, 2015)	40 years (Erlandsson & Holm, 2015)
Price:	770 SEK/m^3 (Byggmax, 2018)	360 SEK/m^3 (Byggmax, 2018)

Širok, Blagojevic and Bullen (2008) describe that the first step in the production process of stone wool is that the raw material is melted at approximately 1300-1600°C in a cupola which is a place for melting magma rocks and supplements. The most commonly used energy source here is coke, otherwise, electricity and gas furnace are used. The next step is fiberisation by spinning the melt into fibres in a centrifuge. An organic binder is mixed with the fibres and produces the wool which is then collected and spread into a thin layer on a conveyor belt. The spread is then transported to a curing oven and after that, it is cut into the final product.

The production process of glass wool starts with mass being melted and drawn out into thin fibres in a powerful oil burner and glue is then added to the loose wool (Berge, 2009). The wool is then heated to form sheets or matting in a kiln. The fibres should be as small as possible to get a high thermal insulation. Emissions from the production are limited to formaldehyde and dust in addition to energy pollution, describes Berge (2009).

Berge (2009) describes that the raw materials are abundant for the main constituents of glass wool and stone wool. Waste can go back to the first step in the production of mineral wool, although the industry is so centralized that this form of recycling is economically unrealistic (Berge, 2009).

3.4.7 Alternative insulation materials for a fossil-free preschool

One of the research questions in this thesis is "*Which are the challenges and the advantages of replacing mineral wool with hemp insulation to achieve a fossil-free preschool in Gothenburg?*". To be able to answer the question, possible replacement materials need to be identified. Further, as a part of this study, one material will be assessed in an LCA. Thus, the most suitable insulation material for a fossil-free preschool is identified as hemp in this subchapter.

As this thesis aims to investigate alternative insulation materials for mineral wool in order to decrease the CO_2e-emission and improve the environmental performance, the alternative replacement materials should;

- function as an insulation material in a wall,
- have a low GWP value,
- preferably bind and store carbon dioxide,
- consist of renewable raw materials,
- be able to be produced in Sweden close to Gothenburg.

Schiavoni, D'Alessandro, Bianchi, and Asdrubali (2016), Murphy and Norton (2008) and Asdrubali, D'Alessandro, and Schiavoni (2015) has performed comparative analyses of the global warming potential of several thermal insulation materials. The materials that had the lowest GWP, can be used in an exterior wall, are renewable and can be produced in Sweden, are presented in Table 3.5 together with the GWP for the mineral wools; stone wool and glass wool. The studies vary due to the difference in functional unit (f.u) and the boundaries. Thus, those parameters are also specified.

Table 3.5. GWP for some insulation materials. CTGA=cradle-to-gate, CTGR=cradle-to-grave.

Material	Functional unit	GWP [kg CO_2e f.u]	System boundary	Reference
Stone wool	1 m^2, R=1 m^2K/W	1.45	CTGA	(Schiavoni, D'Alessandro, Bianchi, & Asdrubali, 2016)
Glass wool	1 m^2, R=1 m^2K/W	9.89	CTGA	(Schiavoni, D'Alessandro, Bianchi, & Asdrubali, 2016)
Hemp and cotton	1 m^2, R=1 m^2K/W	0.17-0.26	CTGR	(Schiavoni, D'Alessandro, Bianchi, & Asdrubali, 2016)
Hemp	1 m^2, U=0.16 W/m^2K	0.345	CTGA	(Murphy & Norton, 2008)
Sheep wool	1 m^2, U=0.16 W/m^2K	-0.323	CTGA	(Murphy & Norton, 2008)
Rock wool	1 m^2, R=1 m^2K/W	2.77	CTGA	(Asdrubali, D'Alessandro, & Schiavoni, 2015)
Sheep wool	1 m^2, R=1 m^2K/W	1.457	CTGR	(Asdrubali, D'Alessandro, & Schiavoni, 2015)

As can be seen in Table 3.5, hemp insulation and sheep wool insulation are two possible replacement materials for mineral wool. The negative GWP-value for sheep wool is due to the boundaries in the study where the emissions from the sheep are excluded and uptake of CO_2e is included (Murphy & Norton, 2008). However, if the sheep farming would be included in the study the environmental impact would have been much higher (Berge, 2009). Some pros and cons of the two materials are stated in Table 3.6.

Table 3.6. Summary of the pros and cons of hemp insulation and sheep wool described by Berge (2009).

	Pros	**Cons**
Hemp insulation:	• Grow fast • Renewable resource • Stores CO_2e • Low embodied energy • Can grow without pesticides • Suitable for wood constructions • Good moisture performance	• Can be expensive • The yearly harvest depends on the weather • Contains plastics
Sheep wool:	• Consist of waste material that would • Good moisture performance • Good sound properties	• Can be expensive • Emissions from the sheep farming contribute to the global warming • Contain borates which are a hazardous substance • Contains plastics

Due to the outcome of the pros and cons in Table 3.6, hemp insulation is assessed to be more sustainable and is therefore investigated further.

3.4.8 Hemp insulation as an alternative material for a fossil-free preschool

Hemp insulation is an organic natural insulation material made out of the shives and fibres from the hemp plant *Cannabis Sativa* (Pfundstein, et al., 2012). The plant can grow in Sweden and is harvested when it is 1.5-4 meters high (Karlsson, 2013). After the hemp plant is harvested it is windrowed on the field for two to three weeks (Ingrao, et al., 2015). After the windrowing process, the hemp fibres are separated by scutching in specific machines.

Depending on the supplier, different additives such as bicomponent fibres, water glass, potato starch and a flame retardant are added (Pfundstein, et al., 2012). The product from the shives can be used directly as loose insulation and the fibres can be processed into insulation. About 10% polyester fibres are added to the insulation to improve the stability, flexibility and resilience (Pfundstein, et al., 2012). The obtained fibres are then formed into insulation blocks. The energy required for producing hemp fleece is generally low, or at least lower than for other insulation materials (Berge, 2009). Berge (2009) continues to state that the installation process of hemp insulation is rather simple, as it can be cut with a hand or power saw.

In the year 2013, the production of hemp in Sweden were 51 hectares in total (Karlsson, 2013) and no numbers have been found for the production of hemp for the year 2018. Therefore, hemp insulation would have to be imported from countries outside of Sweden at an early stage.

One advantage of hemp insulation is that it in the end-of-life stage can be recycled or composted (Berge, 2009). However, if additives such as polyester fibres are added, the process gets more complicated. If the products were separated, the hemp could either be reused or composted and the polyester could be recycled. The hemp insulation could also be treated as combustible waste.

Another advantage of hemp is that it binds CO_2e during it's growing phase and can capture 1-2.9 kg CO_2e per kg harvested hemp plant (Zampori, Dotelli, & Vernelli, 2013). The absorbed CO_2e will be stored in the hemp plant for its total lifespan.

Hemp insulation has both good thermal and sound insulation properties and the material allows vapour diffusion. The material is not useful where it is exposed to large moisture loads and compression and has a limited resistance to alkalis and acids. However, the plant is resistant to mould as it does not contain any proteins that attract insects and other organisms (Berge, 2009). Table 3.7 presents the properties of hemp insulation.

Table 3.7. Specific properties for hemp insulation, (Berge, 2009) if nothing else is stated.

	Hemp insulation
Raw material:	Renewable Hemp
Thermal conductivity:	0.040 - 0.050W/mK
Fire resistant:	Euro class E Building material class B2
Sound impedance:	Yes
Density:	20-60 kg/m^3
Moisture/mould:	Not sensitive
Lifespan:	40 years (Erlandsson & Holm, 2015)
Price:	1184 SEK/m^3 (Hampavaruhuset, 2016)

4 Results and Analysis of the Interview Study

To answer the research questions, *"How can material choices be made when constructing a fossil-free preschool?"* and *"Which are the challenges and the advantages of replacing mineral wool with hemp insulation to achieve a fossil-free preschool in Gothenburg?",* ten interviews were conducted with different actors from the construction industry that was identified to have a role in the material choice process for buildings. A more specific description of the interviewees can be found in subchapter 2.3.

The interviews were conducted to collect information from the different actors' point of view on how material choices are made in the industry and how more fossil-free materials can be chosen. All the answers and citations in the result are translated from Swedish to English by the authors. The questions used in this interview study can be found in Appendix I.

This chapter contains the results of the interview study together with an analysis and is divided into five subchapters. The first part describes how the different interviewees describe the term *fossil-free*, the second on how they work with sustainability, the third on how they perceive materials to be chosen, the fourth how the material choice can be affected and the fifth what requirement a replacement material for mineral wool should fulfil.

4.1 The interviewees' perception of the term *fossil-free materials*

Regarding the term *fossil-free materials*, the interviewees had different interpretations of the term. The Researcher, the Client, the Politician and the HVAC & Energy Engineer all said that a fossil-free material for them is when no fossil fuels or fossil resources have been used during the materials lifecycle. The Client and the Politician also included that no other global warming emissions should be emitted during the lifecycle. However, the Client explained that the end-of-life stage is excluded from the definition for the pilot project *fossil-free preschool* since it is impossible to predict what will happen with the waste in the future and the client also believed that the waste disposal will be fossil-free in the future.

That no global warming emissions should be emitted during the lifecycle of a material, was what the Site Manager focused on when describing a fossil-free material. Architect 2 and the Controller described a fossil-free material as a material free from containing any fossil resources. Architect 1 focused on that a fossil-free material is a renewable material that preferably binds CO_2e. The Researcher mentioned that the concepts *fossil-free* and *climate neutral* are both difficult to comprehend and separate. When the Politician was asked why the concept fossil-free was chosen as a goal for the preschool, no answer was given.

Regarding if the raw material stone is a fossil-free material, the interviewees had different opinions. The Site Manager, the HVAC & Energy Engineer and the Politician all considered stone to be a fossil-free material. However, the Politician also claimed that stone is not the material for the future. Architect 1 and the Researcher did not consider stone to be a fossil-free material since it is not renewable and requires a lot of energy to quarry.

No one of the interviewees believed that it would be possible to build a fossil-free preschool today without using compensation for the greenhouse gas emissions. The Client mentioned that the project would be considered as a success if the GWP per built square meter floor area was reduced from 350 to 100 kg CO_2e. The Client also described that they might, in some today unknown way, account for that Lokalförvaltningen has started a change in the industry as a compensation. The Researcher described that compensations can be a good solution, but also compared it to putting on a band-aid when you have cut yourself; it would be preferable if you had not been cut from the beginning. To start the development towards a fossil-free construction industry is the goal of the project, and not to build one preschool that is fossil-free, described the Politician. A rhetorical question asked by the Politician was:

> *"Sweden together with Norway is one of the world's richest countries, Gothenburg is one of Sweden's richest municipalities; if a fossil-free preschool can't be built here, where can it then be built?"*
>
> *-The Politician*

4.2 The interviewees' part of the construction industry's sustainability work

This subchapter presents the interviewees' answers to how they work with sustainability in their respective organisation and what part they think their discipline play or should play in the development towards sustainability.

When asked how the company works with sustainability, the Researcher described the organisational structure of the sustainability team at the company and how the sustainability work is implemented in the company through different goals. According to the Researcher, the Research and Development department's part in sustainability work is to develop new solutions and implement changes. The Controller described that their part in the sustainability work is to ensure that the requirements from the client are fulfilled. A controller does not affect the sustainability of a building since they only control what has already been decided by the client, continued the Controller.

Architect 1 expressed that architects have a large role in the industry's development towards sustainability and the only drawback is that they cannot decide as much as they want. What Architect 1 work with, is to give sustainable suggestions to the client and be a bit firm in that the new solution is a good solution. Architect 2 described that they have sustainability as a focus in their company and that they want to work towards a sustainable society. More specifically what they do is to work with sustainable materials and sustainable shapes. Sustainable shapes are for example how much surface is required for a specific area. Since the industry has many different actors and architects cannot do exactly what they want, it is a limitation in Architect 2's work.

To have one person on the structural engineering team that has the speciality of being updated on current sustainability trends is how the Structural Engineer described their sustainability work. The Structural Engineer continued to describe that, by designing the building structure in a sustainable manner, by for example using less material or choosing an insulation material so the building gets a low energy demand, is a way that the structural engineer can affect the sustainability in the construction industry. However, the Structural Engineer described that since the contractor chooses the specific material supplier, it makes it hard for a structural engineer to affect the sustainability of a building largely.

The Site Manager described that they cannot affect much of how sustainable the building materials used in the construction are since almost everything is decided in the design phase of the construction process. The Politician described that they are a large client of premises and by using their client-power they can develop the industry to become more sustainable. Requiring fossil-free materials and creating a demand for fossil-free specific products is one of the ways that they work with sustainability. Trying to identify fossil-free materials for installation system is one of the ways the HVAC & Energy Engineer described their work with sustainability. The HVAC & Energy Engineer continued to explain that their systems do not affect the total amount of emissions for a building's lifecycle much and that the largest contributor to the emissions is concrete.

By trying to travel by train or not travel at all is how the Fire Consultant described their sustainability work. The Fire consultant tries to consider the requirements and wishes of the client and the other consultants and come with new environmentally beneficial solutions. However, the lack of knowledge and the fact that fire safety is a requirement that has a higher priority than the environmental interest is a drawback in their sustainability work explained the Fire consultant.

4.3 The interviewees' perception of the material choice process

Three of the actors, the HVAC & Energy Engineer, the Site Manager and the Structural Engineer, said that who chooses the material depends on the purpose of the material, the project and the contracting form. They described that different consultants and architects decide materials in the design phase for their respective field. The Structural Engineer explained that a structural engineer decides the material in the structural system, but the line between what a structural engineer decides and what an architect decides is often diffuse and a close collaboration is often needed. That everyone except the site manager chooses and are responsible for the material choices, is something that the Site Manager stated. With 'everyone' the site manager meant the consultants, the architect, the client and the procurer. The Politician described that everyone's decisions need to change to achieve a fossil-free construction.

The Researcher, the Client, Architect 1, Architect 2, the Fire Consultant and the Controller all thought it is the client that choose the materials for the building, both through setting the requirements and through controlling and approving the suggestions given by the consultants and architects. All of these actors, except Architect 2, also thought that the client is responsible for the decision. However, Architect 2 described that consultants and architects also are responsible for the choice since they are responsible for their suggestions. The Fire Consultant also described that the architect chooses the materials for a building. The HVAC & Energy Engineer explained that the government and BBR are responsible for the choice of materials since they are the ones that set the restrictions on the society. The Structural Engineer described that the ones giving the suggestions on solutions are responsible for the material choices, but the client needs to approve the suggestion. The Politician stated that everyone that makes the choice are responsible for the choice and that everyone in the construction industry are responsible for the fossil-free development. Table 4.1 illustrates a summary of who the different actors think makes the material choice and who they think is responsible for the choice.

Table 4.1. The grey boxes illustrate which actor the different interviewees think chooses the materials and the ♦ illustrate who they perceive to be responsible for the choice.

	Client	Fire consultant	Structural engineer	HVAC & energy engineer	Researcher	Architect	Site manager	Controller	Government	Procurer
Client	▨ ♦									
Fire Consultant	▨ ♦					▨				
Structural Engineer	▨		♦			▨				
HVAC & Energy Engineer	▨		▨	▨		▨			♦	
Researcher	▨ ♦									
Architect 1	▨ ♦									
Architect 2	▨ ♦					♦				
Site Manager	▨ ♦	▨	▨	▨		▨		▨		▨
Controller	▨ ♦									

The Client described that they want to make the material choices as late as possible in the construction process for the fossil-free preschool, preferably just before the material needs to be constructed into the building. The reason for this is that they want to be able to use the best the market has to offer at that specific moment. All the other interviewees except the Politician thought the material choices needed to be taken as early in the process as possible to be able to adapt the working process to the changed material.

4.4 The interviewees' thoughts on how fossil-free material choices can be achieved

The Site Manager, Architect 1, Architect 2, the Politician, the Client, the Structural Engineer, the HVAC & Energy Engineer, the Researcher and the Fire Consultants all described that materials are chosen out of habit and if no incentive is given to change the material the same material will be used. The Researcher explained that the construction industry often is perceived to be conservative and unchanging, but that this is not true and that many changes happen each year; people just do not notice them much. Economy of scale is another reason resulting in that the same material is used. This means that when larger quantities are used the price goes down and the materials become cheaper, explained the Researcher.

A way to develop a fossil-free building, mentioned by the Site Manager, Architect 1, Architect 2, the Politician, the Client, the Structural Engineer, the HVAC & Energy Engineer, the Researcher, the Controller and the Fire Consultant, was that the client should set the requirement of *fossil-free* and pay for it. The Structural Engineer explained that if the client does not ask or pay for a change, no one will change. Also mentioned by the Structural Engineer was that if the goal to become fossil-free came from the consultancy firm, and not from the client, it could be a conflict of interest with some clients which could result in a lower profit. That the client includes environmental requirements on fossil-free materials in the procurement is something that all interviewees thought was a good solution to increase the use of fossil-free materials.

The HVAC & Energy Engineer think that if AMA updated their codes to include more environmental aspects, it would be easier for clients and consultants to specify and require more environmental products. The Politician described that it is important for a public client to demand change in order for the industry to develop. To build low energy buildings is a change in the industry that was developed this way explained the Politician. By creating a demand in the market for fossil-free products, by setting fossil-free as a requirement, is a way to speed up the development of fossil-free products, explained the Client. Multiple suppliers that the Client has been in contact with have expressed that they are surprised that fossil-free materials have not been required earlier.

The Controller does not detect any problems with controlling if the building meets any type of criteria, but it would be helpful if the database Byggvarubedömningen included fossil-free as an indicator as well. That Byggvarubedömningen could be a useful tool for assessing if materials from a supplier meet the set requirements is also mentioned by Architect 2, the HVAC & Energy Engineer, the Client, the Politician and Site Manager. The Controller mentioned that the drawbacks with Byggvarubedömningen are that the suppliers need to recertify their products every third year to stay in the database and since being certified costs, some suppliers do not want to pay the extra cost.

With the increased use of different building certification systems, such as Miljöbyggnad, BREEAM and Svanen, the extra cost of being updated with licenses has made it harder for the smaller actors in the industry, explained the Site Manager. The Client described that if it was mandatory for suppliers that sell products in Sweden to present an EPD for the products, it would solve the problem with information available regarding products environmental properties. To have one person, an ‘environmental coordinator’, responsible for the environmental aspect of a building during the whole construction prosses, was suggested by Architect 1 as a way to maintain the environmental perspective throughout the entire construction project. Architect 1 mentioned that it was common to use an environmental coordinator together with a building certification system. The Controller described that the only way environmental coordinators can become more common in projects is if the Client decides to pay for them.

The Site Manager gave the suggestion that it would be good if the materials were stamped so the information regarding the material and its environmental properties could be easy to control. Using BIM as a tool could be a clear way to illustrate and document what materials a building contains and the materials environmental impact, was another suggestion given by the Site Manager. The Researcher described that controlling that a building fulfils the requirements are an important part of the development, to ensure that no contractor promise more than they can fulfil.

The Politician stated that the requirements set on materials today will not be less strict, it is more likely that they will be complemented with new restrictions. Continuing speaking about the material requirements, the Politician mentioned that the requirements are developed around the market today.

The Fire Consultant and the Researcher believed that it is important to include all actors in the material choices, so all actors' knowledge can be considered and used to realize the goal of choosing more fossil-free materials. To reach a fossil-free construction industry, the Researcher described, is the responsibility of all actors in the industry and all actors' commitment is needed for the success of the project. The Fire Consultant also mention that the client should hold workshops with all actors early in a project, to get everyone involved in the goal. Architect 1 described that to change how materials are chosen it is good to surround yourself with other people who are dedicated to change and dare to test new solutions. Architect 1 also thought that doing mock-ups of the buildings elements early in the design phase was a good way to link the project to the reality.

To increase focus on social and environmental values, and not just focus on economic development, was important according to the HVAC & Energy Engineer. By starting as early as possible with educating children in preschools and explain the importance of the environment is something needed to get a change in the values of the society according to the HVAC & Energy Engineer. One of the problems with a fossil-free industry described both by the Researcher and the Politician, is that changing from a standard material to a new material can affect existing suppliers of non-fossil-free materials negatively, which could lead to other challenges such as unemployment.

One of the problems with reaching a fossil-free construction industry, described by the Structural Engineer, is that many of the material suppliers are chosen by the contractor on site. The Client's suggestion for solving this problem was to set a requirement on how much CO_2e a specific material is allowed to emit. If the contractor then finds an alternative material that can uphold this requirement, the environmental goal will still be reached. The Researcher explained that it is very important not to sub-optimize the building by setting specific CO_2e-requirements on materials but to regard a building as a whole system. Architect 1 thought it was hard to assess the environmental effect of changing a material and thought a simplified LCA tool might be useful to be able to quantify the effect of changes in the building design.

The Structural Engineer described that it is a large risk for the consultants to suggest a change of material if the change would lead to a problem. Architect 2 mentioned a project where the material for a façade was changed successfully even though the client was sceptical to the change at the beginning of the project. Architect 2 also described that by testing the façade material's resistance against the environment in a backyard, Architect 2 was well prepared for the counter-arguments from the client and could convince the client that the façade material would be great for the project.

4.5 The interviewees' opinion on requirements on replacement material for mineral wool

During the interviews, the interviewees were asked; what properties they thought a replacement material for mineral wool should have, if they have knowledge about any challenges or opportunities with replacing the standard material, and if they had tested or researched on any alternative materials.

All the asked interviewees described that a replacement material should meet the client's requirements on insulation materials and have technical properties that are similar to mineral wool. The Fire Consultant described that one of the main reasons stone wool and glass wool is used in buildings is because of their good fire resistance, where stone wool has better properties than glass wool. However, if an insulation material was used that does not have the same fire properties as stone wool, the Fire Consultant do not see any problem with achieving the fire safety requirements in an alternative way by for expel using fire retardants, sprinklers or a fire-resistant gypsum board.

The Site Manager mentioned that it is important that the material is easy to transport, both to the construction site and at the construction site. The material should fit into elevators used at the construction site and not required any extra storage on the site compared to mineral wool. Both the Researcher and the Site Manager mentioned that the material also should be effective to install and that it is important that the material is non-hazardous and safe to handle for the construction workers. The Researcher also described that it is important that the material keeps its shape during the lifecycle and that the materials properties should not change drastically during the lifecycle of the product.

Architect 1 said that the insulation does not need any aesthetical properties since it is hidden in the structure. However, according to Architect 1, it is important to consider if a change in insulation material would increase the thickness of the walls. The Controller described that the most important aspect is that the material has the same price as the material that it is going to replace. The Structural engineer described that it is important that the replacement material is inorganic to resist mould.

Architect 2 had used cellulose insulation in one earlier project and thought it performed well. However, this was ten years ago and Architect 2 think that the market for cellulose insulation is much smaller today. Architect 1 has not worked with wood fibre insulation but thinks that the material could be a replacement material for mineral wool. The HVAC & Energy Engineer has done research on some replacement materials for thermal insulation and has identified hemp to be possible replacement material.

5 Life Cycle Assessment of Hemp Insulation

In this chapter, a life cycle assessment (LCA) for hemp insulation is performed. The LCA was performed to enable a comparison between the GWP of hemp insulation compared to the GWP of mineral wool.

First, the goal and scope are described, including i.a. the options to model, system boundaries and assumptions. Secondly, a life cycle inventory analysis (LCI) is made where all parts of the system boundary are analysed. Thirdly, a life cycle impact assessment (LCIA) was performed where the results of the base scenario of hemp insulation are presented. Finally, an interpretation is made on the whole LCA to assess the result and the choices made in the scope.

5.1 Goal and scope

In this subchapter, the goal and scope of the life cycle assessment of hemp insulation are presented. As stated previously in this thesis, hemp insulation was chosen to be studied in this LCA. The investigated hemp insulation consists of hemp fibres, ammonium sulphate and polylactide granulate, which directly implies that it will not be completely fossil-free.

5.1.1 Goal

The goal of this life cycle assessment is to investigate to what extent hemp insulation fossil-free is if it would be produced for a fossil-free preschool in Gothenburg in the year of 2018. This LCA is also conducted to clarify the challenges when replacing a standard material with a new one. In Chapter 6, the results of this LCA is compared with EPDs for both stone wool and glass wool. To make the results comparable with other materials, the hemp insulation will be analysed separately and not in a wall, since the assessed hemp insulation has comparable physical properties to mineral wool.

Similar LCAs have been conducted by other parties before, but this LCA was conducted specifically with the assumption that the product would be used in a preschool in Gothenburg.

This study is primarily conducted as a foundation for the development of fossil-free buildings in Gothenburg and the results will mainly be used for educational purpose. The results of the LCA were also used in a comparison with stone wool and glass wool. The results could also be used as a foundation for future development of hemp insulation and indicate the possibilities of producing it in Sweden. Finally, the results are also meant to be used to start a dialogue of the material and its potential.

In order to reach the goal of the study, some questions should be answered in the LCA:

- What is the GWP of hemp insulation during the cradle-to-gate stages of its lifecycle?
- What is the GWP for hemp insulation if it would be produced in Sweden?
- Which activities in the lifecycle of hemp insulation contribute the most to the GWP?
- In what way could hemp insulation be produced to reach a lower GWP?

5.1.2 Scope

The rules and guidelines in the PCR for insulation materials in Environdec (2014) and *The Hitch Hiker's Guide to LCA* (Baumann & Tillman, 2004), were used to develop this LCA. The scope includes the parts; options to model, initial flowchart and product system, functional unit, impact categories and method for impact assessment, type of LCA, system boundaries, data quality requirements and assumptions.

The software used for the inventory and the impact assessment of this LCA was Simapro with the implemented database Ecoinvent 3.0. Ecoinvent 3.0 is an LCA database and a non-profit association founded by institutes of the ETH Domain and the Swiss Federal Offices (Ecoinvent, 2018). Ecoinvent is described to be a transparent LCA inventory database where the data behind the result are presented (Ecoinvent, 2018).

5.1.2.1 Options to model

In the market today, the number of hemp insulation manufacturers is rather low. However, the base scenario investigated in this LCA was an average of three different identified hemp insulation products available on the market. The data collected from the different products were also verified against each other to ensure reliable values. Thus, the data used for the base scenario of this LCA are an average of the data presented in Table 5.1.

Table 5.1. Information about the products used for the base scenario used in this LCA

	NatuHemp	**Thermo Hanf**	**Naturtherm CA**
Manufacturer	Black mountain	Thermo Natur	Manifattura Maiano
Reference	(Black Mountain, 2018)	(Thermo Natur, 2018)	(Manifattura Maiano, 2018)
Country	United Kingdom	Germany	Italy
Density [kg/m^3]	30	30-42	30
Thermal conductivity [W/mK]	0.039	0.038	0.038
Hemp fibre content [%]	95	82-85	90
Polylactide granulate content [%]	4.5	10-15	10
Ammonium sulphate content [%]	0.5	3-5	-

An approximation of the average of the data from Table 5.1 constitutes the properties for the base scenario which is presented in Table 5.2.

Table 5.2. The data for the base scenario studied in this LCA.

The base scenario of hemp insulation	
Density [kg/m^3]	30
Thermal conductivity [W/mK]	0.038
Hemp fibre content [%]	88
Polylactide granulate content [%]	9
Ammonium sulphate content [%]	3

5.1.2.2 Initial flowchart and the product system

In Figure 5.1, the initial and general flowchart of the lifecycle of hemp insulation is presented.

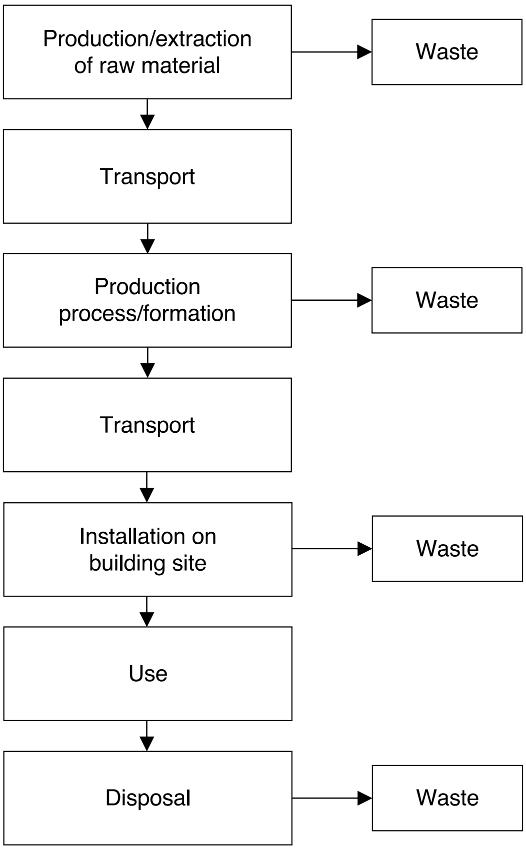


Figure 5.1. A general and initial flowchart of hemp insulation's lifecycle.

5.1.2.3 Functional unit

The primary function of an insulation material is to thermally insulate, and secondary functions are; moisture performance, sound impedance, fire resistance, durability and stability. To be able to compare hemp insulation with mineral wool, the performance of the insulation materials need to be the same. The functions that mainly varies between hemp insulation and mineral wool is the thermal conductivity and the fire resistance.

According to Environdec (2014), the functional unit for insulation materials used in EPDs should be 1 m^2 insulation board with a thermal resistance R=1 m^2K/W. Thus, in order to make the results in this LCA comparable with other insulation materials, the functional unit for this LCA was 1 m^2 insulation with a thermal resistance of R=1 m^2K/W. To consider the difference in fire resistance, the fire protection for the hemp insulation was improved by adding gypsum board on the surface in the parametrical study, see subchapter 5.4.2.4.

To get functional input values for Simapro, the hemp insulation needed to be defined by mass. Thus, the mass for the functional unit was calculated in Appendix II.

5.1.2.4 Impact categories and method for impact assessment

As the goal is to investigate how fossil-free hemp insulation is, the global warming potential (GWP) is used as an indicator to assess how fossil-free hemp insulation is. Thus, GWP_{100} was investigated in this LCA as GWP_{100} is the impact category recommended in Environdec (2014), to make it comparable with other EPDs. However, it could be argued that it would be more suitable to use GWP_{20} since Sweden has the goal to become fossil-free or fossil neutral before 2045, which is within 100 years. Thus, both GWP_{100} and GWP_{20} were investigated for the base scenario. The substantial LCI parameters included in the GWP are stated in Table 5.3.

Table 5.3. The impact category investigated in the LCA (IPCC, 2007).

Impact category	Substantial LCI parameters	Unit of category indicator
Global Warming Potential	CO_2, CH_4, N_2O, C_2F_6, CF_4, CCl_4	kg CO_2e

5.1.2.5 Type of LCA

The type of LCA carried out was an accounting LCA with a parametrical study within the system. The varied parameters are described in subchapter 5.4.2.4.

5.1.2.6 System boundaries

The LCA was made on a cradle-to-gate basis with the stages A1-A4 included based on the stages described in SS-EN ISO 15978:2011, see Figure 5.2. Stage A5 was excluded from the system boundaries since the installation process of mineral wool and hemp insulation basically is the same. All insulation material boards require the same transportation on the construction site and have a quite low density and, thus, be lifted by hand (Pfundstein, et al., 2012).

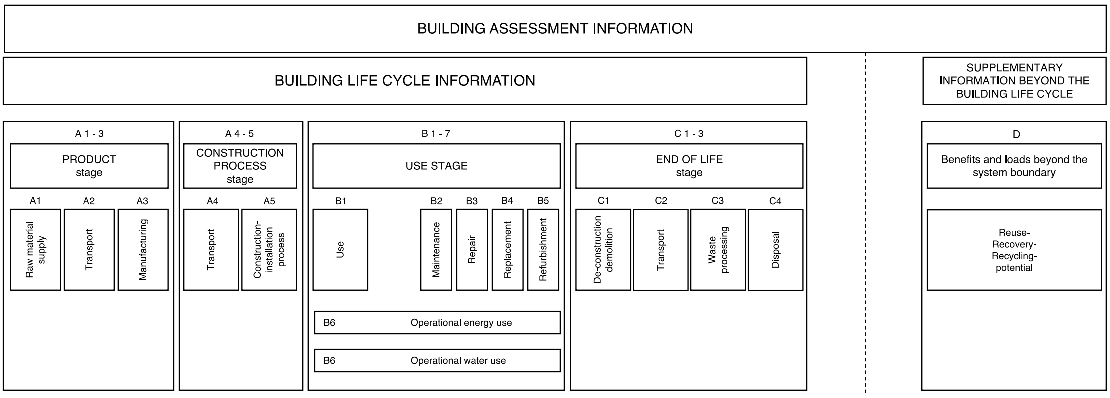


Figure 5.2. An illustration of the stages included in a lifecycle from SS-EN ISO 15978:2011.

A cradle-to-gate study was made because:

- The use phase is assumed to be similar for all insulation materials since the U-value of the building envelope would be the same regardless of the insulation material and, thus, not relevant to investigate.
- The hemp insulation is assumed to have a lifespan of 40 years. Therefore, it is complicated to determine what will happen with the material after such long time as the waste scenarios can look very different depending on the existing technology. Also, there are predictions that the waste treatment will be fossil-free in 40 years according to the interviewee 'Client'. Thus, the end-of-life stages are excluded from this LCA.

In Figure 5.3, a flowchart for the cradle-to-gate lifecycle for hemp insulation is presented together with the natural and the technical system boundaries. The technical system is the system in which products and processes are developed and produced by recourses originating from the natural system.

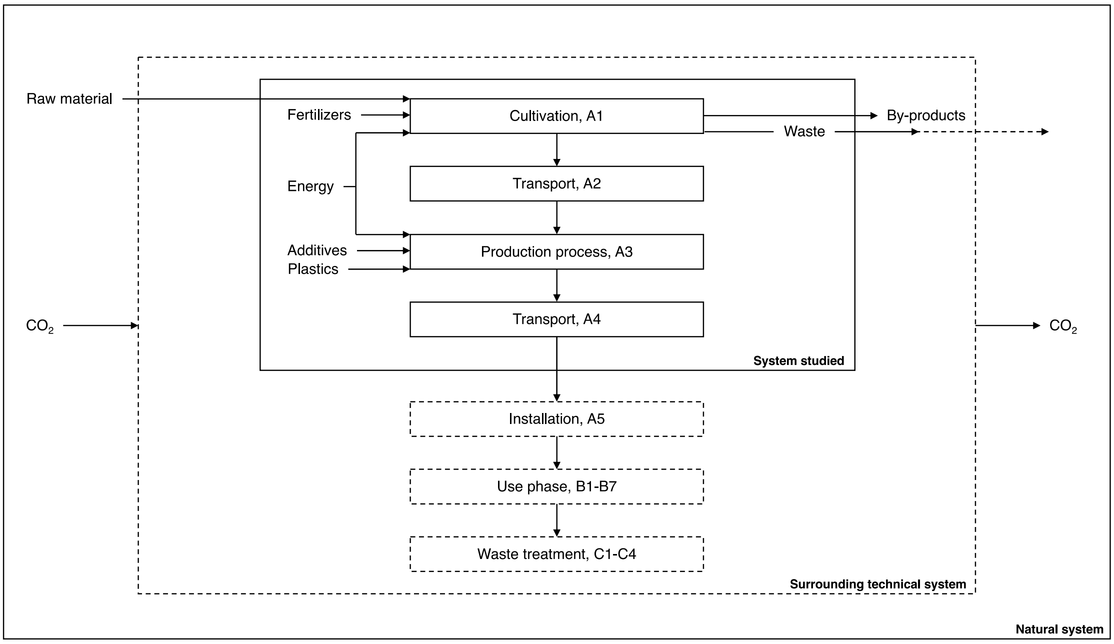


Figure 5.3. Flowchart of the system of hemp insulation with natural and technical systems.

Boundaries in relations to natural systems

The LCA for the hemp insulation starts when the cultivation of the hemp plants starts. Thus, the hemp seeds are in the natural system and outside the system boundaries of this LCA. The waste produced in stage A1 can according to Berge (2009) be composted and the waste produced in stage A3 is assumed to be reused within the system.

Geographical boundaries

Hemp plants are today cultivated in i.a. the United Kingdom, Germany, Italy and Sweden. The inputs for the location of the cultivation were therefore varied between Global and Swedish inputs for the electricity, heat and transportation, where the Global conditions was an average of the products from the United Kingdom, Germany and Italy for a usage in Gothenburg. The production of hemp insulation is today located in the same countries as the cultivation, except for in Sweden. However, if the demand for hemp insulation increased, a manufacturer could establish production in Sweden.

Therefore, the inputs for the production of hemp insulation was also varied between Global and Swedish inputs on electricity, heat and transportation where the Global conditions was an average of the products from the United Kingdom, Germany and Italy for a usage in Gothenburg. The cultivation and the insulation panel production were assumed to be within the same country.

Cut-off criteria and boundaries in relation to production capital and personnel

The general idea with LCA is to make it as inclusive as possible and at the same time make the data collection feasible and relevant to the goal of the study. Thus, some parts of the system have been cut-off, as recommended by (Baumann & Tillman, 2004). The production capital, such as approximations of machinery and buildings, are included in the LCA for the hemp insulation and the personnel required are excluded as recommended in (Baumann & Tillman, 2004).

Boundaries in relation to other products' lifecycle and allocation

According to SS-EN ISO 14044:2006 allocation shall be avoided if possible by dividing the process into subprocesses that can be assigned to the different products. Allocation in this study cannot be avoided since multiple products are produced of hemp fibres. When deciding on the basis of allocation for this study the recommendation from the SS-EN ISO 14044:2006 was followed. Thus, the allocation was based on economic values. However, in the PCR for insulation materials (Environdec, 2014), the allocation should be based on physical properties when allocation cannot be avoided. Thus, a comparison of the result was made in the interpretation where the allocation was based on mass. The allocation is further described in subchapter 5.2.5.

System subdivision

A flowchart for the system with the background system and the foreground system is presented in Figure 5.4.

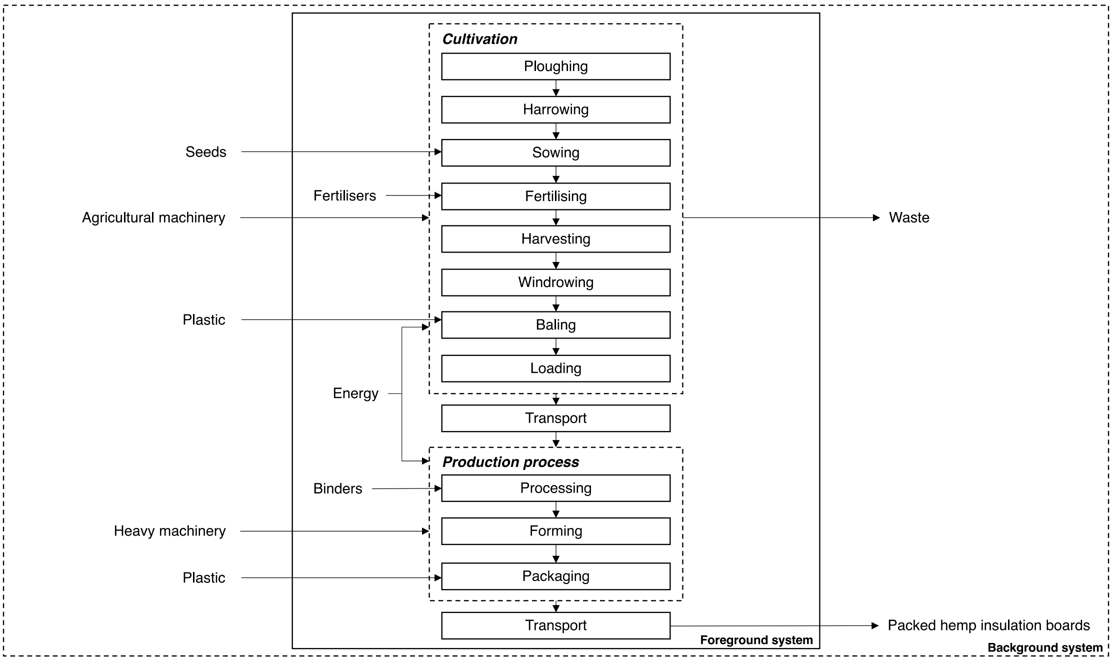


Figure 5.4. Background system and foreground system for this LCA.

5.1.2.7 Data quality requirements

The quality requirements of the data used in the study greatly affect the workload and the quality of the results of the study (Baumann & Tillman, 2004). The quality of data gathered in this study varies due to the restriction of time, economic founds and data availability. The sources of the data in the foreground system are specified in the LCI to increase the transparency of the study.

The database Ecoinvent 3.0 and primary data collected from the manufacturers for the products described in Table 5.1 has mainly been used for the inventory and implemented in the software Simapro. Secondarily, when data that was not available in Ecoinvent or from the manufacturers, data was collected from earlier studies and sector organisations.

5.1.2.8 Assumptions made in the LCA

In the list below, the assumptions made in the LCA are listed:

- The location of the cultivation and production of hemp insulation in Sweden is assumed to be close to the city Skövde, since hemp cultivation exists there today (Hampaprodukter, 2018).
- The packaging process for the hemp insulation is assumed to be the same as described for mineral wool in Ecoinvent 3.0.
- The amount of fertilization required for hemp plant production is based on Swedish recommendations, both for the Swedish and the Global conditions.
- A bale of hemp weights 700 kg according to the standard size of a bale in Ecoinvent 3.0.
- For inputs and processes that could not be established, similar processes' input from Ecoinvent 3.0 were assumed for the hemp insulation.
- The cultivation and the insulation panel production were assumed to be within the same country.
- Transportation distances are based on distances in Google maps. The distribution of road transportation, rail transportation, and water transportation was for the Global conditions based on Naturvårdsverket's data (Naturvårsverket, 2017b). For the Swedish conditions, the distribution of road transportation and rail transportation was based on Transportstyrelsen's data (Transportstyrelsen, 2016).
- For the electricity used in the LCI, a low voltage was assumed (Elektroskandia, 2018).

5.2 Life cycle inventory analysis

In this chapter, the life cycle inventory analysis is described for the base scenario. A complete list of the inventory can be found in Appendix IV. The inventory of hemp insulation was made in the LCA-software Simapro, built on the database Ecoinvent 3.0. The white boxes in Figure 5.5 represent processes already available in Simapro from the database Ecoinvent 3.0 and the grey boxes represent the unit processes developed in Simapro.

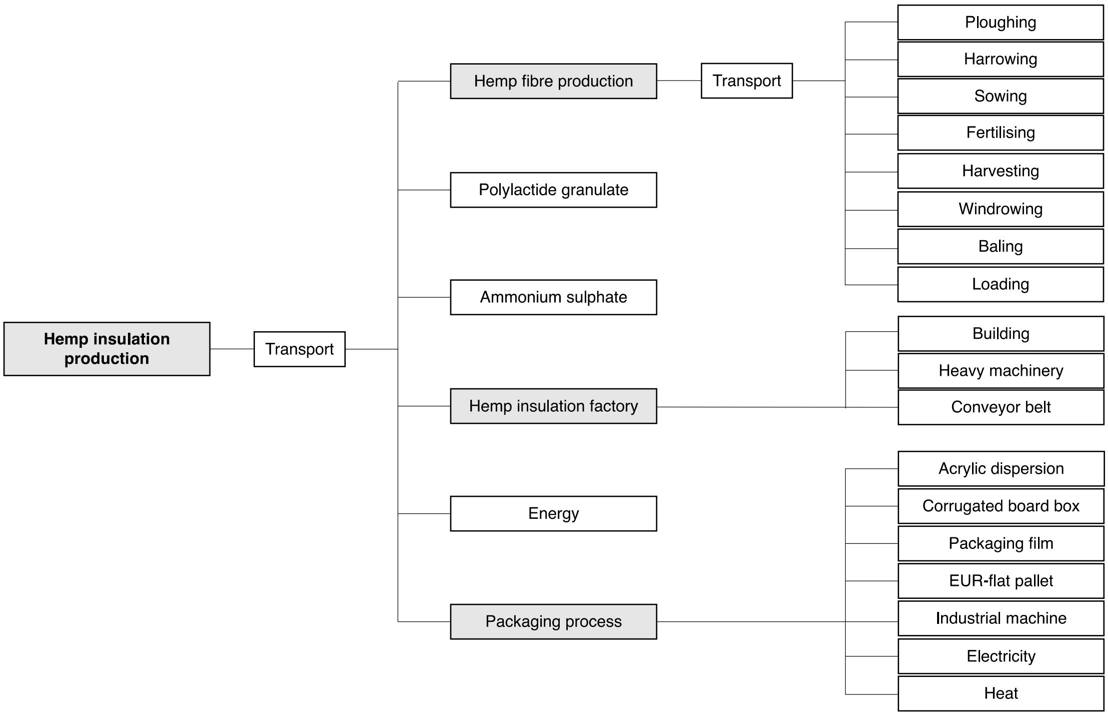


Figure 5.5. Flowchart of the production of hemp insulation.

The product was modelled for two conditions, *Global conditions* (GLO) and *Swedish conditions* (SE). The parameters that differed were the type of heat and electricity, and the transportation distances and modes. However, the transportation distance in stage A2 was the same for both the Global and Swedish conditions. As the existing products identified comes from the United Kingdom (UK), Germany (DE) and Italy (IT), an average of the inputs from these three countries was used for the Global conditions.

For the Global conditions, the transportation distance between the factory and the building site was based on an average distance between the UK and Gothenburg, Germany and Gothenburg, and Italy and Gothenburg. Estimations of the transportation distances for the Global conditions were measured in Google maps, see Table 5.4.

Table 5.4. An estimation of the distances for the global conditions

Transportation (GLO)	**Distance [km]**
From the United Kingdom to Gothenburg	1500
From Germany to Gothenburg	1300
From Italy to Gothenburg	2000
Average:	**1600**

All transportation distances are compiled in Table 5.5. The distance from the cultivation to the factory was estimated to be the same for both the Global and the Swedish conditions, as it was assumed that the cultivation and the hemp insulation factory were located within the same area. Therefore, it was assumed that the transportation distance between the factory and the field was 3 km. For the Swedish conditions, the distance between the factory and the building site was based on the assumption that the hemp production would be placed in Skövde and the construction site in Gothenburg.

Table 5.5. All transportation distances used in this LCA.

Transportation	Distance [km]
From cultivation to factory	3
From the factory to the building site (GLO)	1600
From the factory to the building site (SE)	160

The distribution of transportation modes in a global perspective was assumed according to Naturvårdsverket (2017b) and are presented in Table 5.6 with corresponding distances for each mode.

Table 5.6. The rate of the used transportation modes in the Global conditions.

Transportation mode (GLO)	Rate	Distance [km]
Road	49%	780
Water	33%	520
Rail	19%	300

The distribution of transportation modes in Sweden was assumed according to Transportstyrelsen (2016) and are presented in Table 5.7 with corresponding distances for each mode.

Table 5.7. The rate of the used transportation modes in the Swedish conditions.

Transportation mode (SE)	Rate	Distance [km]
Road	67%	107
Rail	33%	53

For the Global conditions, the electricity and heat required for the subprocesses are allocated as a third each from the United Kingdom, Germany and Italy. In the subchapters below, the unit processes, marked with a grey box in Figure 5.5, are described and inventoried.

5.2.1 Hemp fibre production

The data for the hemp plant cultivation was collected from Jordbruksverket (Rosenqvist, 2017) and from a hemp-farmer in Skövde (Appendix III). Hemp plant production is made through agricultural cultivation. First of all, the land is ploughed and harrowed before the sowing can begin. Since hemp is a rather easy plant to cultivate, no irrigation is required during the tillage. However, fertilisation is necessary to get a good yield. The fertilisations necessary are nitrogen, phosphate and potassium. The plant grows for 100 to 120 days until they are harvested and windrowed on the field. After two to three weeks of windrowing the harvest is baled and transported to a storage area (González-García, Hospido, Feijoo, & Moreira, 2010). The unit process for the hemp plant production is presented in Figure 5.6.

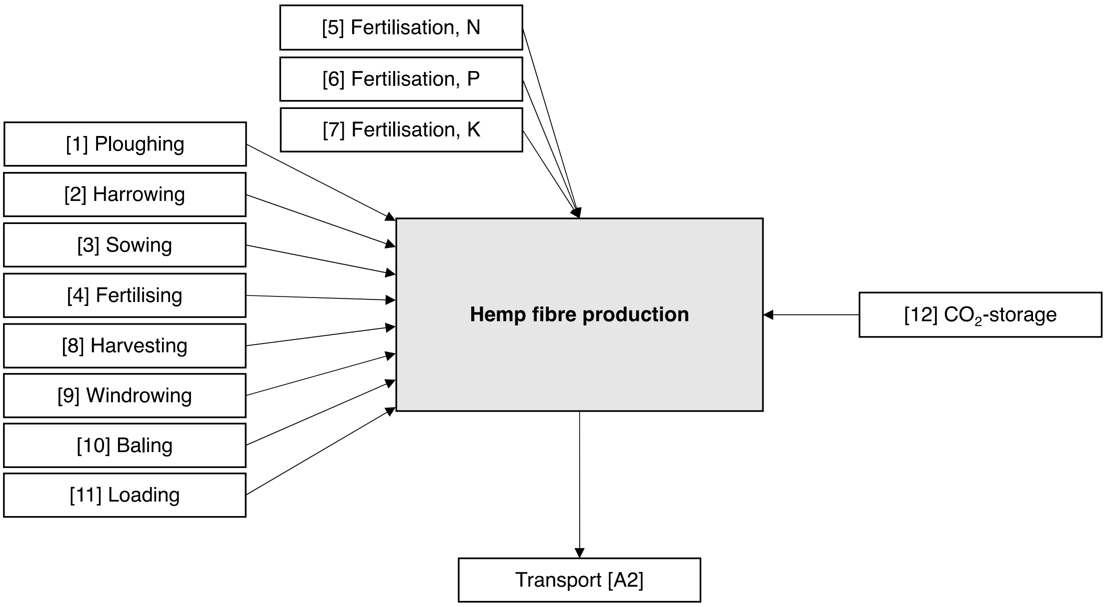


Figure 5.6. Hemp plant production unit process for cradle-to-gate. The numbers are referred in Table 5.9.

According to Rosenqvist (2017), the average mass of hemp produced on one hectare of farmland is 6.5 tonnes dry substance. For simplicity, the inventory for the hemp plant production was made for 1 tonnes hemp which correspondingly requires 0.1538 hectares of farmland. Thus, the processes that are executed on the farmland (ploughing, harrowing, sowing, fertilising, and harvesting) is calculated for 0.1538 hectares.

The amount of fertilisation required for 1 tonnes hemp is based on values recommended by Jordbruksverket (Rosenqvist, 2017) and the credibility of the values was consulted with hemp farmer, see Appendix III. The amount of fertilisation is presented in Table 5.8.

Table 5.8. The amount of fertiliser recommended using for hemp cultivation

Fertilisation	Amount for 1 ha	Amount for 1 tonnes
Nitrogen (N)	97 kg	15 kg
Phosphate (P)	13 kg	2 kg
Potassium (K)	26 kg	4 kg

The baling process and bale loading are specified in the unit ‘pieces of bales’ and are calculated with the assumption that one bale weights 700 kg.

When hemp plants grow, they absorb between 1 kg to 2.9 kg CO_2e per kg harvested hemp plant (Zampori, Dotelli, & Vernelli, 2013). These values correspond with the values given by the Swedish hemp farmer. If this storage is accounted for in the LCA, the stored CO_2e would result in a lower total GWP_{100}. The result in the impact assessment is presented both with and without CO_2-storage with a storage of 1 kg CO_2e per kg hemp plant.

In Table 5.9, the inputs for the different sub-processes for the unit process ‘Hemp fibre production’ are presented together with the source of the amount and type of input.

Table 5.9. Inventory of the processes in the hemp plant production unit process for cradle-to-gate.

	Process	Value for producing 1 tonne dry substance hemp	Source for input data
1	Ploughing	$1.54*10^{-1}$ ha	(Rosenqvist, 2017)
2	Harrowing	$1.54*10^{-1}$ ha	(Rosenqvist, 2017)
3	Sowing	$1.54*10^{-1}$ ha	(Rosenqvist, 2017)
4	Fertilising	$1.54*10^{-1}$ ha	(Rosenqvist, 2017)
5	Urea, as fertilisation N	15 kg	(Rosenqvist, 2017)
6	Fertilisation, P	2 kg	(Rosenqvist, 2017)
7	Fertilisation, K	4 kg	(Rosenqvist, 2017)
8	Harvesting & windrowing	$1.54*10^{-1}$ ha	(Rosenqvist, 2017)
10	Baling	1.43 p	(Ecoinvent 3.0)
11	Bale loading	1.43 p	(Ecoinvent 3.0)
12*	Biogenic CO_2-storage	1000 kg	(Zampori, Dotelli, & Vernelli, 2013)

*Biogenic CO_2-storage is optional.

5.2.2 Hemp insulation factory

One process that is common for all insulation materials modelled in Ecoinvent 3.0, is that they include a factory consisting of a building, heavy machinery, and a conveyor belt. Similar to the other insulation materials, the hemp insulation production also requires heavy machinery and a conveyor belt. Therefore, a unit process was made for the hemp insulation factory, see Figure 5.7. This factory is an estimation based on the process for the stone wool factory in Ecoinvent 3.0 since no data for a hemp insulation factory was available or possible to obtain from a manufacturer. Assumptions were made that only a third of the heavy machinery used in a stone wool insulation factory is required for a hemp insulation factory.

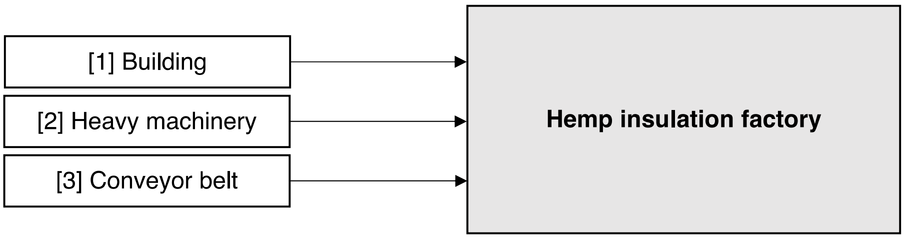


Figure 5.7. Hemp insulation unit factory unit process for cradle-to-gate. The numbers are referred in Table 5.10.

In Table 5.10 the inputs for the different sub-processes for the unit process 'Hemp insulation factory' are presented together with the source of the amount and type of input.

Table 5.10. Inventory of the hemp insulation factory unit process for cradle-to-gate.

	Process	**Value for producing 1 hemp insulation factory**	**Source for input data**
1	Building	$2.55*10^{6}$ kg	(Ecoinvent 3.0)
2	Heavy machinery	$1.00*10^{4}$ m	(Ecoinvent 3.0)
3	Conveyor belt	$8.40*10^{3}$ m^{2}	(Ecoinvent 3.0)

5.2.3 Packaging process

The packaging process is assumed to be the same as for the mineral wool insulation process in Ecoinvent 3.0. This is because the products will be produced in the same format and can, therefore, be packed in the same way. The packaging process thereby consists of acrylic dispersion, corrugated board box, packaging film, EUR-flat pallet, industrial machine, electricity and heat, see Figure 5.8. Both the electricity and the heat are varied in the Global and the Swedish conditions.

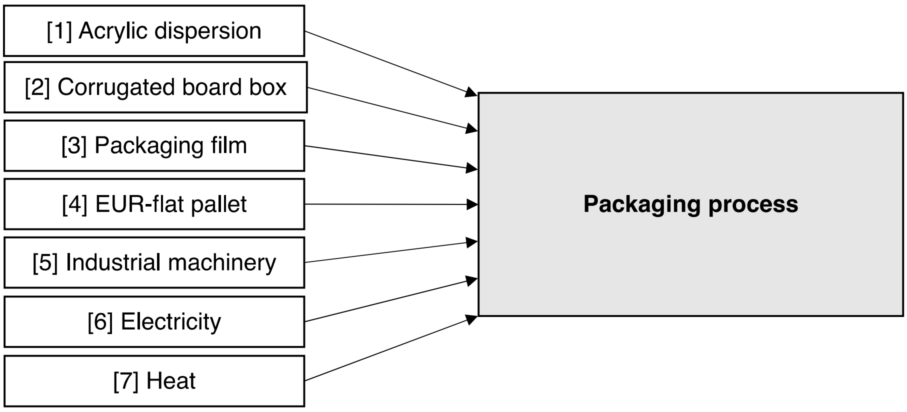


Figure 5.8. Packaging unit process for cradle-to-gate. The numbers are referred in Table 5.11.

In Table 5.11 the inputs for the different sub-processes for the unit process ‘Packaging process’ are presented together with the source of the amount and type of input.

Table 5.11. Inventory of the processes for the packaging unit process for cradle-to-gate.

	Process	**Value for production of 1 kg hemp insulation**	**Source for input data**
1	Acrylic dispersion	$5.85*10^{-3}$ kg	(Ecoinvent 3.0)
2	Corrugated board box	$9.86*10^{-4}$ kg	(Ecoinvent 3.0)
3	Packaging film	$6.51*10^{-3}$ kg	(Ecoinvent 3.0)
4	EUR-flat pallet	$1.24*10^{-3}$ p	(Ecoinvent 3.0)
5	Industrial machinery	$2.21*10^{-6}$ kg	(Ecoinvent 3.0)
6	Electricity	$3.09*10^{-3}$ kWh	(Ecoinvent 3.0)
7	Heat	$1.524*10^{-1}$ MJ	(Ecoinvent 3.0)

5.2.4 Hemp insulation production

The hemp is delivered to the factory in bales where the hemp first is dried to the desired humidity and sorted into short and long fibres (Idler, Pecenka, Fürll, & Gusovius, 2011). The long fibres are used for insulation and are, after the sorting, blended with the ammonium sulphate (the fire-retardant) and the polylactide granulate (PLA). After that, the mass is formed into a fleece material with several layers put on top of each other, which are finally pressed into a board and cut to the right size. The insulation panels are packed in plastic film and stacked on EUR-flat pallets. The production process is divided into two parts, the first part is when the fibres are separated, and the second part is when the insulation boards are produced. The reason behind this is because during the first part, a co-product (the short fibres) are produced and an allocation of the emissions are performed. During the production, either electricity or gas can be used as an energy source (Murphy & Norton, 2008). In Figure 5.9, the subprocesses included in the hemp insulation unit process are presented.

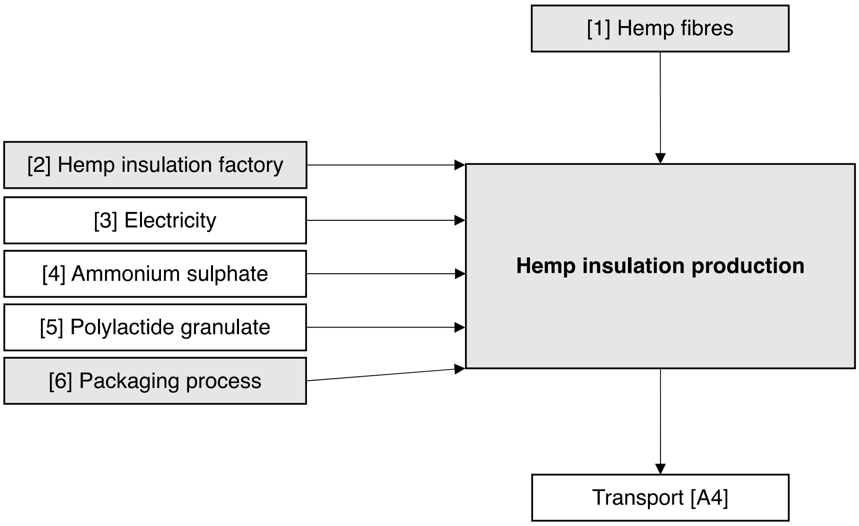


Figure 5.9. Hemp insulation production unit process for cradle-to-gate. The numbers are referred in Table 5.12.

In Table 5.12 the inputs for the different sub-processes for the unit process 'Hemp insulation production' are presented.

Table 5.12. Inventory of the hemp insulation production for the packaging unit process for cradle-to-gate.

	Process	Value for producing 1 kg hemp insulation	Source for input data
1*	Long hemp fibres	0.88 kg	Input for base scenario
2	Hemp insulation factory	$2.21 \cdot 10^{-10}$ p	(Ecoinvent 3.0)
3a	Electricity, fibre separation	2.38 kWh	(Murphy & Norton, 2008)
3b	Electricity, board production	2.47 kWh	(Murphy & Norton, 2008)
4	Ammonium sulphate	0.03 kg	Input for base scenario
5	Polylactide granulate	0.09 kg	Input for base scenario
6	Packaging process	1 p	Input for base scenario

* The hemp fibres are sorted into long fibres, short fibres and dust. Only the long fibres are used for the insulation.

5.2.5 Allocation calculations

As mentioned in the scope, the allocation in this study is based on economic values. The relation between the mass of the long fibres, the short fibres and the dust are; 75% short fibres, 20% long fibres and 5% dust (Zampori, Dotelli, & Vernelli, 2013). This relation is illustrated in Figure 5.10.

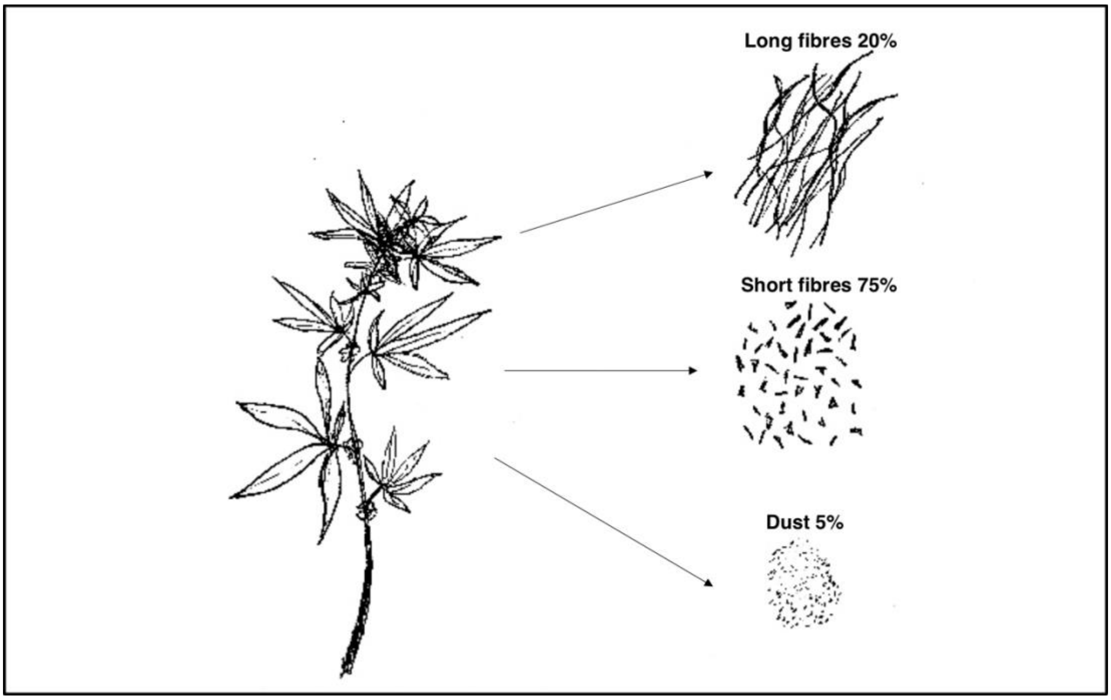


Figure 5.10. The relation between the mass of the long fibres, the short fibres and the dust from the hemp plant.

Hemp insulation is produced from long fibres and co-products can be produced from the short fibres. The hemp farmer (Appendix II) described that the short fibres usually are used as rabbit pellets.

The price for the short fibres is 5 SEK/kg and the long fibres 17.80 SEK/kg (Hampaprodukter, 2018). The allocation of the emissions of the long fibres is calculated with Equation 3.

$$a_l = \frac{P_l * m_l}{P_l * m_l + P_s * m_s} = \frac{17.8 * 0.2}{17.8 * 0.2 + 5 * 0.75} = 48.7\% \qquad \text{(Equation 3)}$$

a_l – Allocation of the emissions of the long fibres

P_l – Price for the long fibres, 17.80 SEK/kg

P_l – Price for the short fibres, 5 SEK/kg

m_l – Percentage long fibres of the mass from hemp, 20%

m_s – Percentage short fibres of the mass from hemp, 75%

The allocation results in 48.7 % long fibres and 51.3% short fibres. The allocation of the fibres is performed in the life cycle inventory after the fibres are separated.

5.3 Life cycle impact assessment

In this subchapter, the environmental impact of hemp insulation is assessed. The environmental indicator investigated in this LCA was GWP_{100}. As a reference, GWP_{20} was analysed for the whole LCA, cradle-to-gate. The result of GWP_{100} and GWP_{20} for the base scenario is presented in Figure 5.11.

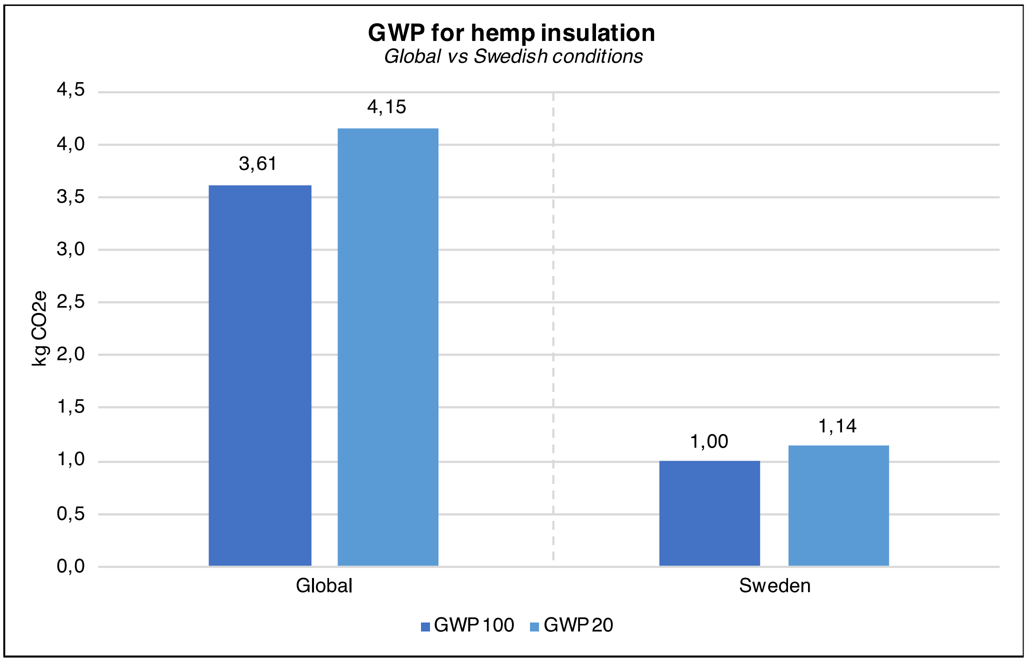


Figure 5.11. GWP_{100} and GWP_{20} of hemp insulations for the global and the Swedish conditions.

One reason for investigating hemp insulation is because it absorbs and stores CO_2e. Thus, the absorption of the CO_2e is accounted for in the results presented in Figure 5.12.

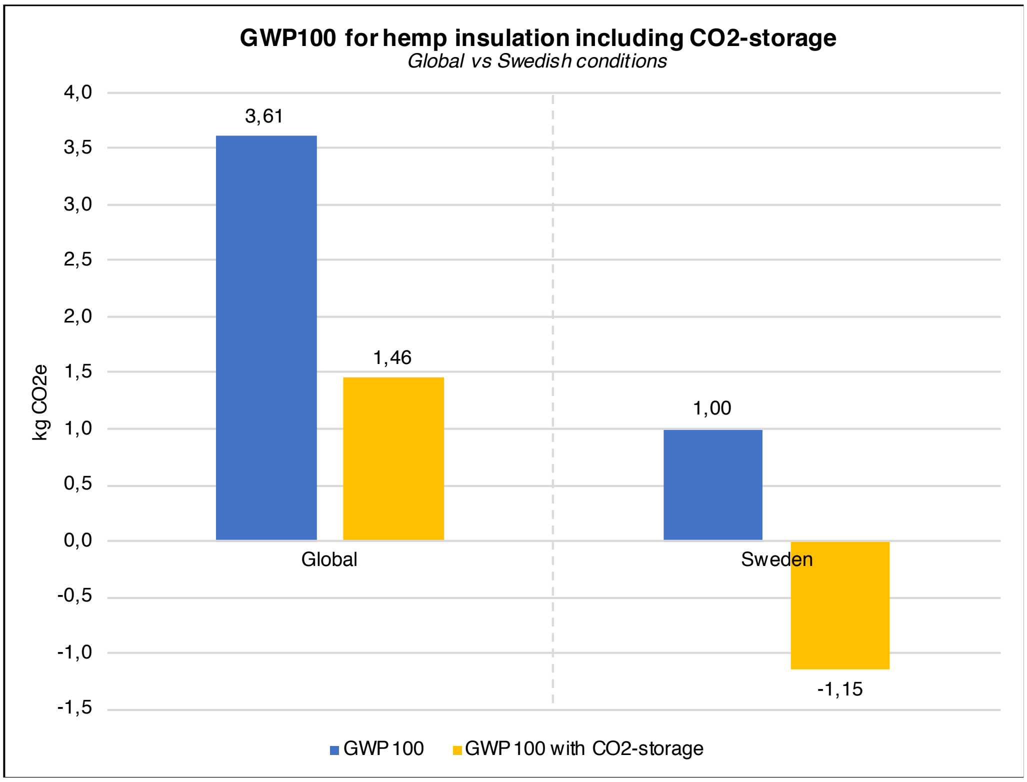


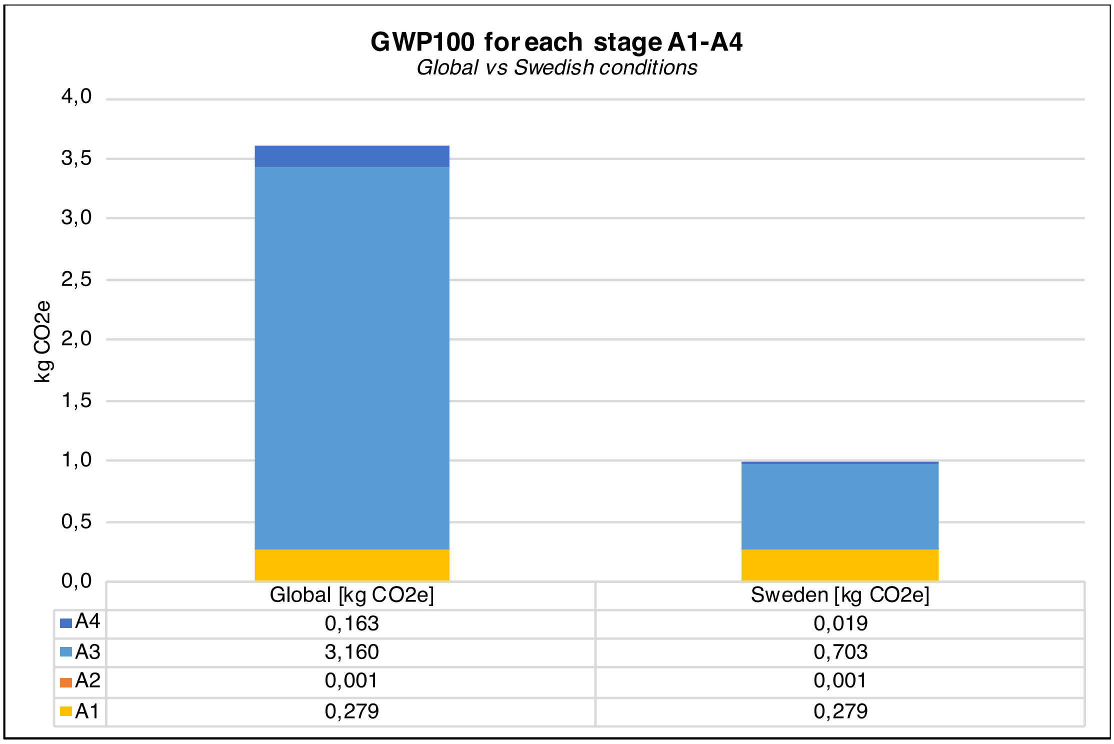
Figure 5.12. GWP_{100} of hemp insulation including biogenic CO_2-storage in the GWP.

5.4 Interpretation

In this chapter, the life cycle assessment is analysed, interpreted and verified. A sensitivity analysis is performed as a parametrical study presented in subchapter 5.4.2.4.

5.4.1 Identification of significant issues

In order to identify the significant issues in this LCA, a dominance analysis is performed. The result of how much the stages in the LCA emit is presented in Figure 5.13.



	Global [kg CO2e]	Sweden [kg CO2e]
■ A4	0,163	0,019
■ A3	3,160	0,703
■ A2	0,001	0,001
■ A1	0,279	0,279

Figure 5.13. GWP100 for each stage, A1-A4, in the LCA for global and Swedish conditions.

The main activities affecting the result are presented in Figure 5.14 for the scenario with the Global conditions and in Figure 5.15 for the scenario with the Swedish conditions. The activities affecting the scenario with the Swedish conditions with at least 3% was presented in the figure and the same activities are shown for the scenario with the Global conditions.

In Appendix V, all processes responsible for more than 1% of the total emissions are listed for both the Global and the Swedish conditions. The electricity and the polylactide granulate (PLA) affected the result the most for both of the scenarios. However, electricity had a much larger impact on the scenario with Global conditions than the Swedish conditions. The reason for this can be because Swedish electricity consists of more renewable energy sources (Liljenström, et al., 2015).

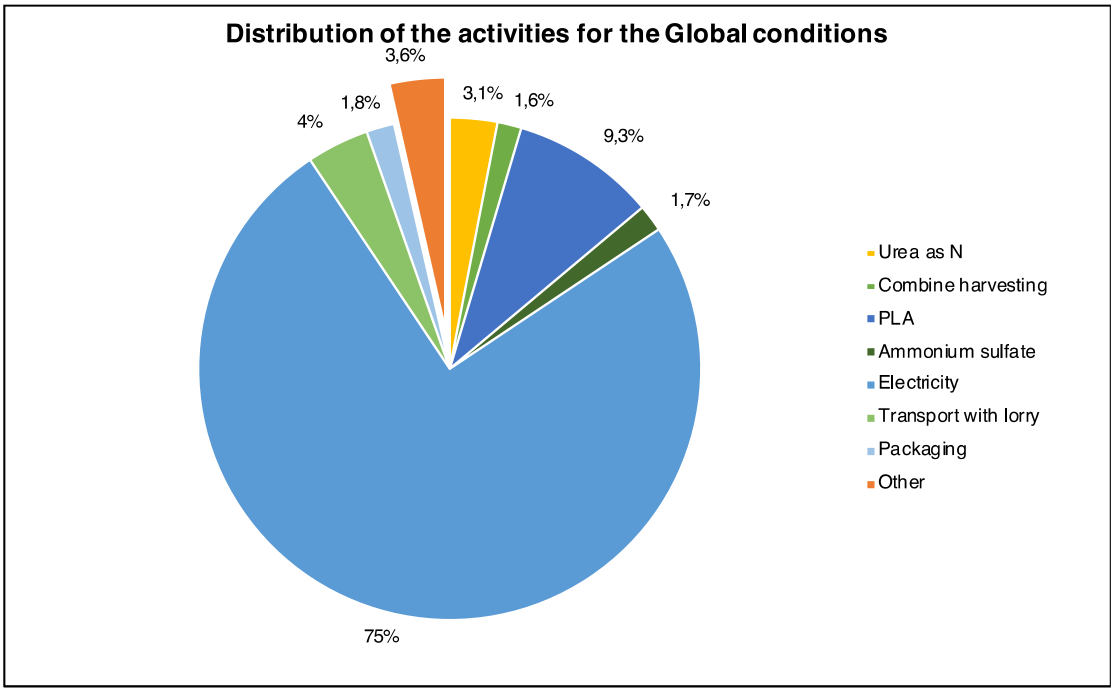


Figure 5.14. The distribution of the activities affecting the result the most on the scenario with the Global conditions.

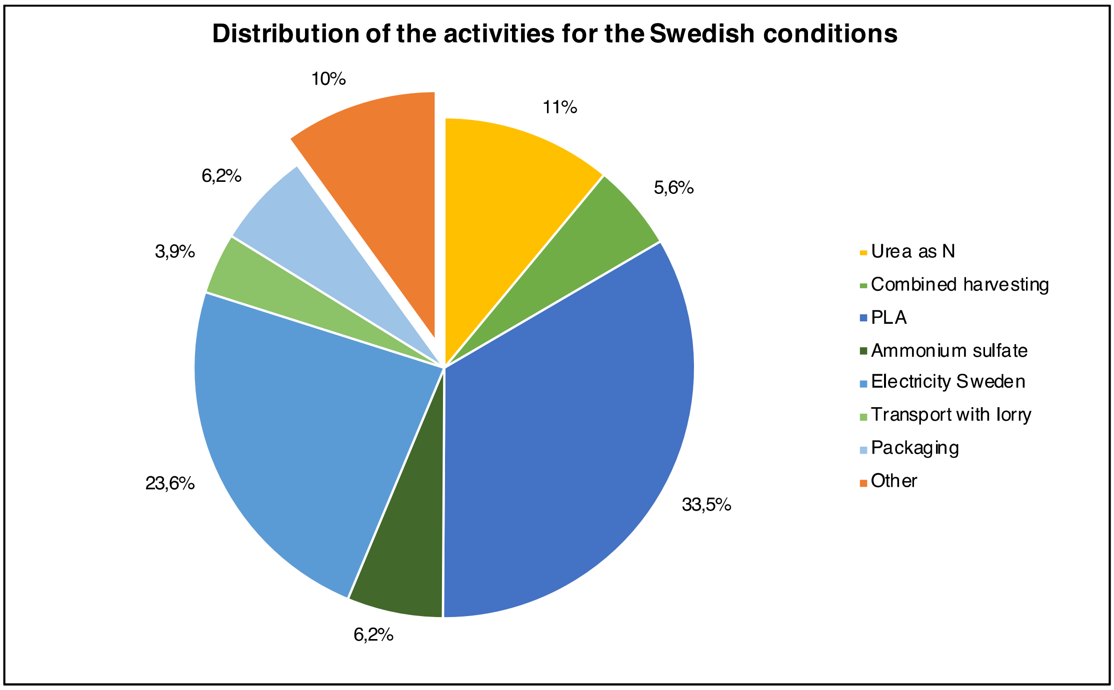


Figure 5.15. The distribution of the activities affecting the result the most on the scenario with the Swedish conditions.

5.4.2 Evaluation of result robustness

In order to verify the credibility of the LCA, the data quality and the methodological choices that had a significant impact on the results were evaluated.

5.4.2.1 Completeness check

In order to ensure that all important flows are included in the LCI, a completeness check was carried out.

Due to limited knowledge within the field of cultivation of hemp, a correct flowchart for the production line of hemp plants and hemp insulation may not correspond to the flowchart in this LCA. However, different manufacturers use different production procedures and there are several different ways to produce hemp insulation. One example where the production method differs between different manufacturers is whether gas is used during the insulation formation or not. In the impact assessment, gas is not used, and instead, electricity has been used. In the parametrical study in subchapter 5.4.2.4, the LCA is modelled with gas instead of electricity for the parts requiring heat.

The decision was made in the scope to study a cradle-to-gate LCA without accounting for the waste. If different scenarios for the waste were developed and studied the total GWP for hemp insulation might have been higher. However, since there are large uncertainties regarding the end-of-life of hemp insulation, the result might have been misleading. Another reason to exclude the waste is that the EPDs that this LCA is compared with, does not include waste.

The economic and the social aspects of using hemp insulation are not included in this LCA. An example of a social aspect that could have been assessed is the effect on job opportunities that come with the production of hemp insulation, but also the effect of unemployment if mineral wool was replaced with hemp insulation. Another aspect is that different insulation materials can have different effects on the human health and, thus, be more suitable in a preschool.

5.4.2.2 Data quality analysis

The feasibility of the result of this LCA was assessed by comparing it with the GWP for two other hemp insulation products. The products used in the comparison were Naporo Klima and Thermo Hanf with data gathered from the Austrian database Baubook. Baubook is an info-communication platform for energy efficient and ecological construction (Baubook, 2018). Baubook (2018) has collected environmental data from two different hemp insulation producers. The data presented on the platform is according to Baubook (2018) a simple product documentation and right up-to-date. The environmental data presented on the web page only presents the results, and the assessment of the products are not presented. However, it is still an indicator of the credibility of the results of this LCA. The results presented in Baubook has the functional unit kg, thus, the results were recalculated to the functional unit of this LCA, 1 m^2 insulation with R=1 m^2K/W, see Appendix II.

The result of this LCA is also compared to the result of an LCA performed by Zampori, Dotelli, and Vernelli (2013).

Table 5.13 presents the GWP of the different hemp insulations.

Table 5.13. Collected data for the two hemp insulation products with a functional unit of 1 m^2, R=1 m^{2}K/W compared with the results in the LCI.

Data from products in Baubook			
Supplier	Thermal conductivity [W/mK]	GWP_{100} [kg CO_2e]	GWP_{100} with CO_2-storage [kg CO_2e]
Naporo Klima	0.041	2.35	0.126
Thermo Natur	0.045	2.57	0.140
LCA study Zampori, Dotelli, & Vernelli	-	0.91	-0.86
Base scenario [GLO]	0.038	3.44	1.29
Base scenario [SE]	0.038	0.98	-1.17

Compared to the results in this LCA, the GWP of the products in Baubook (2018) is between the results for the scenarios with the Swedish and the Global conditions. The reason behind the difference in GWP for the products can only be assumed since the data behind the results in Baubook could not be accessed. One reason for the difference between the Global result and the result presented in Baubook could be that many of the assumptions in this study have been conservative. Baubook might have had access to direct data from the manufacturers and conservative assumptions might not have been needed to the same extent.

One of the reasons that the Swedish result has a lower GWP could be because the electricity has a large impact on the production of hemp insulation and the Swedish electricity has lower GWP than the electricity used in the production of hemp insulation in many other countries. Baubook also accounts for that more CO_2e is stored in the hemp plant than what is accounted for in this LCA.

The differences in the results between the base scenario and the LCA study made by Zampori, Dotelli, and Vernelli (2013) is not very large compared with the scenario with the Swedish conditions.

5.4.2.3 Consistency check of the allocation method

The allocation was based on economic values as presented in subchapter 5.2.5. The base scenario was also allocated based on weights with the assumption that a hemp plant provides 20% long fibres (that can be used for hemp insulation), 75% short fibres and 5% dust. The results for the two allocation methods are presented in Table 5.14.

Table 5.14. Results for the GWP of hemp insulation allocation based on economic values and weight.

Allocation method	**Global [kg CO_2e]**	**Sweden [kg CO_2e]**
Economic values	3.61	1.00
Weight	3.02	0.80

As the Table 5.14 illustrates, the GWP would have been reduced if the allocation was based on weight and not on economic values. The PCR for insulation materials from Environdec (2014) states that allocation should, if it cannot be avoided, be based on physical properties, e.g. weight. However, to allocate the emissions on weight might not illustrate the main reason for the emissions correctly.

5.4.2.4 Sensitivity analysis and parametrical study

In this subchapter, the activities with the most uncertain input values are varied in a parametrical study and the possible effects on the GWP of the variations are analysed. Further, the effect of different electricity scenarios is analysed and finally, the effect of adding gypsum as an extra fire protection is analysed.

The activities with uncertain input values are varied in a parametrical study. The parameters studied was the following:

- *Tillage activities*
  The tillage activities (ploughing, harrowing, sowing, fertilising, and harvesting) are processes defined by area in Ecoinvent 3.0. However, this is with the assumption that the width of the machinery is two meters wide, but machinery with a wider span is available on the market and could instead be used. Thus, the value for the tillage activities is halved with the assumption that the machinery is four meters wide.

- *Fertilisation*
  The amount of fertilisation required for the cultivation can vary a lot depending on i.a. the location of the cultivation, and the yearly weather condition. Thus, the amount of fertilisation used is varied between the recommended values from Jordbruksverket (Rosenqvist, 2017) and zero according to Johansson and Olofsson (2009).

- *Transportation from the cultivation to the insulation factory*
  The transportation distance between the cultivation and the insulation factory is assumed to be 3 km since the cultivation and the factory is assumed to be located within the same area. However, they could be located on different locations and thus, a variation was made where the distance was increased to 100 km.

- *Insulation production factory*
  The inputs for the hemp insulation factory was not established by any manufacturers. Thus, assumptions were made based on already existing insulation factories in Ecoinvent 3.0. Consequently, the input for the hemp insulation factory is very uncertain. As a more conservative assumption, a stone wool factory was used in the simulation as a variation. This is a more conservative assumption since stone wool requires more heavy machinery to melt the stone.

- *PLA-binder content*
  The PLA-content differs between the three hemp insulation products, as seen in Table 5.1. Additionally, PLA is one of the largest contributors to the GWP, thus, it was varied from the largest (15%) to the smallest (5%) content used in the products in Table 5.1. When the PLA-content was varied, the hemp fibre content was adjusted.

- *Electricity consumption during the insulation production*
  The electricity consumption of the insulation production was conducted from a secondary data in form of an LCA of a hemp-based insulation product from 2008 (Murphy & Norton, 2008). No other values were found; however, the electricity consumption of flax insulation was identified and since the production method for hemp and flax insulation are similar (González-García, Hospido, Feijoo, & Moreira, 2010), the value for the electricity consumption of flax insulation was used for the hemp insulation.
- *Gas*
  In some descriptions of the production process of hemp insulation, gas is used during the formation of the insulation boards instead of electricity (Murphy & Norton, 2008). However, this is not used for all identified production methods and thus, gas was added in the parametrical study to see how that would affect the result. When gas was added, some of the electricity was deducted.
- *Packaging*
  The LCA was also analysed without the packaging process to see how much the packaging affected the total GWP.

All parameters stated above were varied separately on the base scenario to assess how much the GWP would differ in percentage with the variation. The initial and the new input values, together with the percentage difference for each variation, are presented in Table 5.15.

Table 5.15. The initial and varied input values and the percentage difference for each variation.

	Input values		**Percentage difference**	
Activity	Initial	Varied to	Global conditions	Swedish conditions
Tillage	0.1538	0.0769	-2%	-5%
Fertilisation	With	Without	-4%	-13%
A2 transport	3 km	100 km	-1%	3%
Type of factory	Hemp	Stone wool	1%	3%
Increase of PLA-content	9%	15%	4%	20%
Decrease of PLA-content	9%	5%	-3%	-13%
Total electricity consumption	4.846 kWh	1.167 kWh	-52%	-16%
Gas consumption*	0 kWh	2.38 kWh (0.15 kWh el.)	-44%	13%
Packaging	Without	With	-2%	-6%

* Less electricity is required when using gas for heat.

For the scenario with the Global conditions, the parameter that made the largest difference in the parametrical study was the electricity. This was not unexpected since the electricity was the significantly dominant activity identified in subchapter 5.4.1. Secondly, gas also affects the result largely since the emissions from the gas production are much lower than the electricity production from the Global conditions. Moreover, when gas is used for heating instead of electricity, the energy losses are reduced since electricity generated heat entail energy losses. However, the scenario with the Swedish conditions get worse when using gas for the heating. This is probably because Swedish electricity consists of more renewable energy sources, thus, adding gas for the process in the Swedish conditions increases the GWP.

The variation of PLA-content affected the GWP of the scenario with the Swedish conditions the most since this is one of the most dominant activities for the Swedish conditions as seen in subchapter 5.4.1.

The worst and best scenario were modelled for both the scenario with Global conditions and the Swedish conditions to establish the range of the GWP for hemp insulation. All the results for the varied parameters in the Table 5.15 were included except the packaging process since packaging is assumed to be a required activity in order to transport the product properly. The results for the worst and best scenarios with both the Global and Swedish conditions are presented in Figure 5.16. Arguments can be made regarding if biogenic CO_2-storage should be included, thus the results are presented both with and without biogenic CO_2-storage.

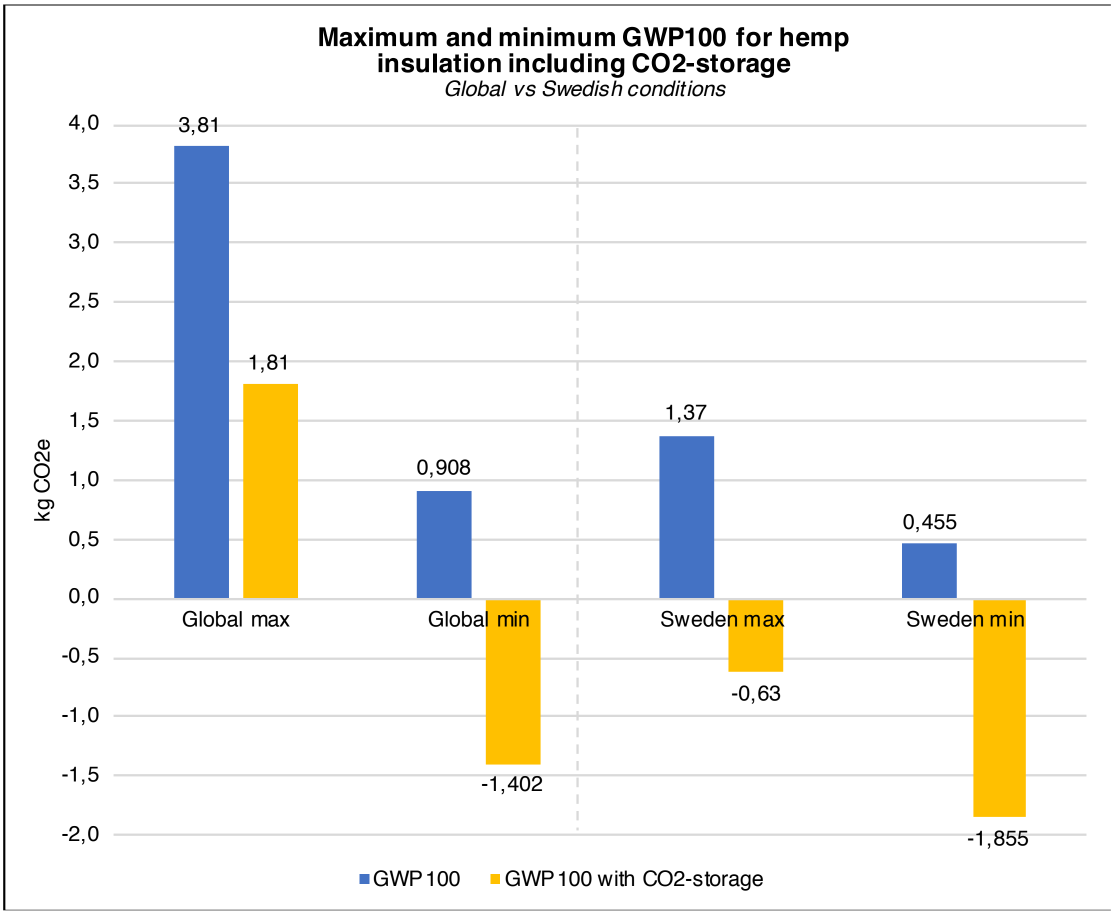


Figure 5.16. The worst and best scenario for the Global and the Swedish conditions with and without biogenic CO_2-storage.

The difference between the results for the Global conditions and the Swedish conditions are mainly due to the difference in electricity mixes between the different countries. Thus, a sensitivity analysis was made on the energy source of the electricity. Liljenström, et al. (2015) describes that depending on what electricity scenario that is developed, the emissions from the electricity varies. Three scenarios, besides the base scenario, were developed for the hemp insulation. These were:

- *Specific electricity from a high proportion of renewable fuels*
  In this scenario, the electricity used in the in the production of hemp insulation is specifically chosen to be from a high proportion of renewable fuels.
- *Average country mix*
  In this scenario, the electricity used in the in the production of hemp insulation is an average Norwegian country mix.
- *Electricity from a low proportion of renewable fuels*
  In this scenario, the electricity used in the in the production of hemp insulation is either specifically chosen to be from a high proportion of renewable fuels nor a Norwegian average country mix.

In Table 5.16, the GWP for three electricity scenarios are presented together with the base scenarios. For the new scenarios, the values of the GWP are from Liljenström, et al. (2015). The GWP for the total electricity use of 4.25 kWh is also presented.

Table 5.16. Calculation of emissions from the different electricity scenarios. Note the unit for GWP as [g CO_2e/kWh].

Emissions from different electricity scenarios					
	High proportion renewable fuels	Average country mix	Low proportion renewable fuels	Global conditions	Swedish conditions
GWP [g CO_2e/kWh]	7.8	160	327	637	55.5
Total GWP [g CO_2e]	34	680	1390	2710	236

As Table 5.16 presents, the choice of electricity largely affects the GWP. Thus, the total GWP of hemp insulation production could be increased if electricity from a high proportion of renewable fuels was used. If 'specific electricity from a high proportion of renewable fuels' were used instead of the currently used electricity, the GWP for the Global and Swedish conditions would be as presented in Figure 5.17.

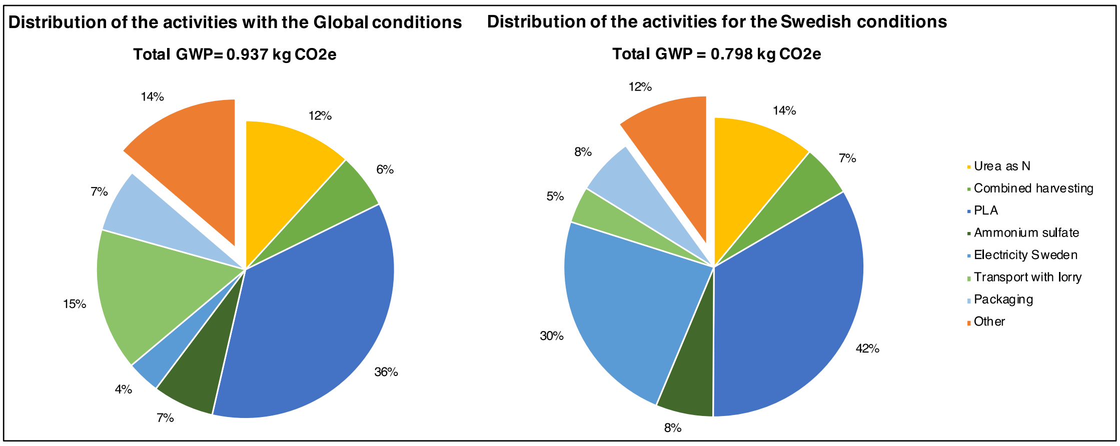


Figure 5.17. GWP for the Global and Swedish conditions with electricity from a high proportion of renewable fuels.

As stated earlier, hemp is not as fire-resistant as some other insulation products. Thus, in order for hemp insulation to have a good fire resistance, a fire-resistant gypsum board could be used. The amount of gypsum required would be 2 m^2 for 1 m^2 of a wall, as recommended by the interviewee 'Fire Consultant'. Gypsum boards are usually already used in walls, so the difference between a normal gypsum board and a fire-resistant board is investigated. Standard values for gypsum boards are stated in Table 5.17. Norwegian products where used, since no Swedish EPDs were found.

Table 5.17. Standard values for a conventional gypsum board and a fire-resistant board.

	Functional unit	**GWP**	**Source**
Gypsum plasterboard	1 m^2	2.46 kg CO_2e	(Norgips, 2018a)
Fire-resistant board	1 m^2	3.40 kg CO_2e	(Norgips, 2018b)

The use of a fire-resistant gypsum board, instead of a standard gypsum board increased the total GWP for the base scenario with 0.94 kg CO_2e, see Figure 5.18.

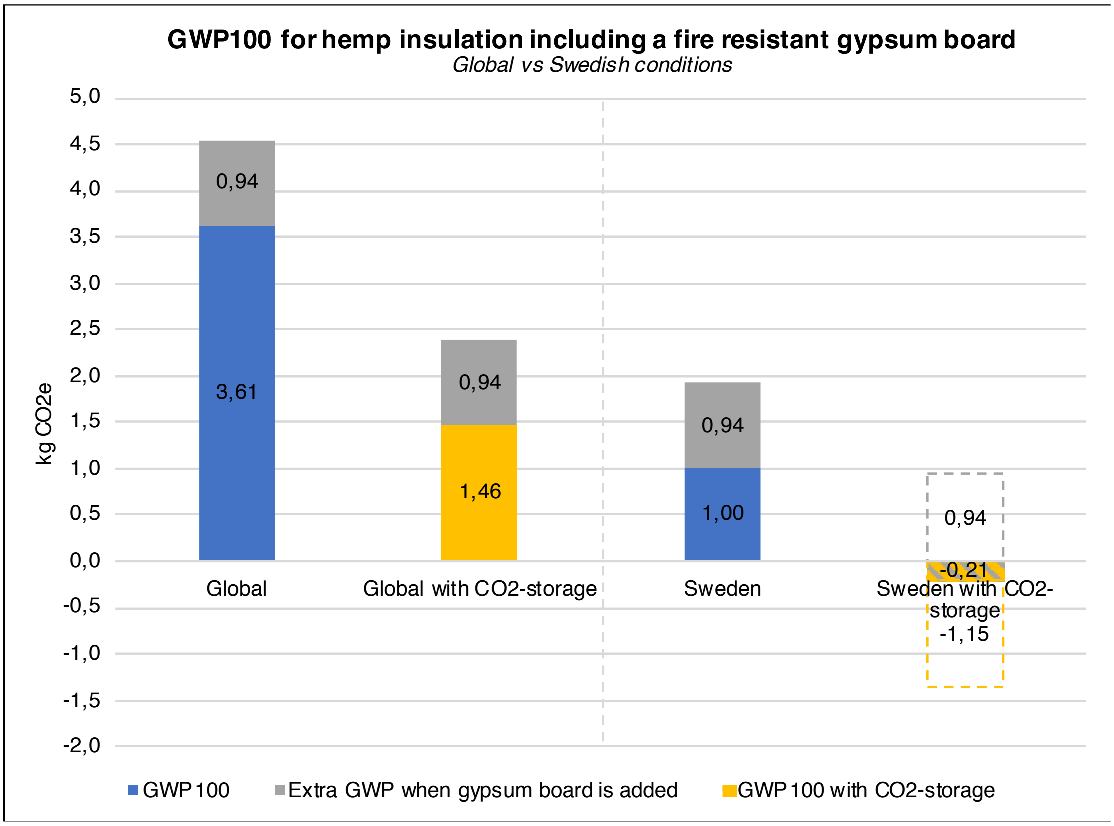


Figure 5.18. The total GWP for the base scenario including a fire-resistant gypsum board.

As seen in Figure 5.18, if a fire-resistant gypsum board was added to the wall, the total GWP for 1 m^2 hemp insulation in a wall gets higher. If a fire-resistant board is added to the base scenario with Swedish conditions including CO_2-storage, the hemp insulation would have a negative GWP of -0.21.

Besides a fire-resistant gypsum board, there are other ways to fireproof a wall and a fire-resistant gypsum board is therefore not necessarily essential according to the interviewee *Fire Consultant*.

6 Material Comparison of Mineral Wool and Hemp Insulation

In this chapter, the results of the LCA in Chapter 5 are compared with the GWP for mineral wool (stone wool and glass wool). To gather information about the GWP of stone wool and glass wool, EPDs developed by suppliers were used together with generic data from IVL and Ecoinvent 3.0.

6.1 Environmental product declaration data for stone wool

In this subchapter, the data gathered of the EPDs from the different stone wool suppliers are presented and the methodological choices and specifications for the EPDs are shortly described. The data is summarised in Table 6.2.

6.1.1 Rockwool's stone wool insulation

Rockwool's EPD (Rockwool, 2013) is developed on a cradle-to-gate basis and has the functional unit 1 m^2 of 37 mm thick stone wool insulation with a density of 29 kg/m^3 and a thermal resistance of R=1 m^2 K/W. The GWP for the stone wool is assessed to be 1.27 kg CO_2e for the stages A1-A3. The EPD is developed for the Norwegian market and this results in that the transport distances are calculated for an average distributor in Norway. An EPD for the Swedish market is not available. The EPD includes the extraction and transportation of the raw materials and the manufacturing processes. Transportation from all factories to a central storage in Norway is accounted for. Data from Gabi and Ecoinvent has been used for the acquisition of raw materials and the transportation. The production data from the sites are from the year 2011. The EPD has been critically reviewed in accordance with ISO 14025.

6.1.2 Knauf's stone wool insulation

Knauf's EPD (Foster, 2016) is developed on a cradle-to-gate-with-options basis and has the functional unit 1 m^3 of insulation with a density of 33-45 kg/m^3. The GWP for the material is calculated for cradle-to-construction-site and is 53.8 kg CO_2e for the stages A1-A3. The insulation has a thermal conductivity of 0.035-0.037 W/mK. The GWP was recalculated to the functional unit 1 m^2, R=1 m^{2}K/W in Appendix II. This resulted in that the GWP, calculated for the functional unit 1 m^2 insulation with a thermal resistance of R=1 m^2 K/W, would be 1.94 kg CO2e for the stages A1-A3. The EPD has been critically reviewed in accordance with EN ISO 15804:2012.

6.1.3 Paroc stone wool insulation

The EPD for Paroc's stone wool insulation (Hammarberg, 2014) is developed on a cradle-to-gate basis and has the functional unit of 1 m^2 of insulation with a density of 35 kg/m^3 and a thermal resistance of R=1 m^2 K/W. The GWP for the stages A1-A3 is 1.48 kg CO_2e. The EPD is developed for the Norwegian market and this results in that the transport distances are calculated for an average distributor in Norway. An EPD for the Swedish market is not available. The EPD includes the extraction and transportation of the raw materials and the manufacturing processes. Transportation from the factory to a central storage in Norway has been included. Data from Gabi has been used for the acquisition of raw materials and the transportation. The production data was collected from the production sites in Scandinavia. The EPD has been critically reviewed in accordance with ISO14025.

6.1.4 Summary of EPD data of stone wool

In Table 6.1 the GWP data gathered from the EPDs for stone wool is summarised for the functional unit 1 m^2 of insulation with a thermal resistance of R=1 m^2 K/W.

Table 6.1. Summary of EPD data for stone wool for the stages A1-A3.

EPD				
Supplier	Type of mineral wool	Functional unit	GWP100 [kg CO_2e]	Reference
Rockwool	Stone wool	1 m^2 stone wool insulation, R=1	1.27	(Rockwool, 2013)
Knauf	Stone wool	1 m^2 stone wool insulation, R=1	1.94	(Foster, 2016)
Paroc	Stone wool	1 m^2 stone wool insulation, R=1	1.48	(Hammarberg, 2014)

6.2 Environmental product declaration data for glass wool

In this subchapter, the data gathered for the EPDs from the different glass wool suppliers are presented and the methodological choices and specifications for the EPDs are shortly described. The data is summarised in Table 6.2. As described by Berge (2009), glass wool can be produced by using recycled glass. When assessing the GWP of materials, the allocation of the recycled products, which serve as a raw material, can differ in EPDs. This can result in that the EPDs for glass wool has accounted for the emissions from the recycled glass in different ways. In which way the recycled glass is accounted for is not presented in the EPDs below.

6.2.1 Knauf Glass Wool Insulation

Knauf's EPD (Foster, 2015) is developed on a cradle-to-gate-with-options basis and has the functional unit of 1 m^3 of insulation with a density of 15 kg/m^3. The GWP for the material is calculated for cradle-to-construction-site and is 18.7 kg CO_2e for the stages A1-A3. The insulation has a thermal conductivity of 0.036-0.039 W/mK. The EPD has been critically reviewed in accordance with EN ISO 15804:2012. If the GWP is recalculated for a functional unit of 1 m^2 insulation with a thermal resistance of R=1 m^2 K/W, the GWP would be 0.70 CO_2e for the stages A1-A3. The calculations are presented in Appendix II.

6.2.2 Isover glass wool

Isover's EPD (Lindholm, 2017) is developed on a cradle-to-gate-with-options basis and has the functional unit of 1 m of insulation with a thermal resistance of R=1 m^2 K/W. The GWP for the material is calculated for cradle-to-construction-site and is 0.62 kg CO_2e for the stages A1-A3. The EPD is developed for Sweden. Lindholm (2017) argues that allocation can be made on mass since the exact same manufacturing process is used for every product, thus, the allocation of the calculations is based on mass. The data used for the raw materials, the energy consumption and the transportation distances, have been taken from the manufacturing plant of Saint-Gobain Sweden. The EPD has been critically reviewed in accordance with ISO 15978.

6.2.3 Summary of EPD data for glass wool

In Table 6.2 the GWP data gathered from EPDs for glass wool is summarised for the functional unit 1 m^2 of insulation with a thermal resistance of R=1 m^2 K/W.

Table 6.2. Summary of EPD data for glass wool for the stages A1-A3.

EPD				
Supplier	Type of mineral wool	Functional unit	GWP100 [kg CO_2e]	Reference
Knauf	Glass wool	1 m^2 glass wool insulation, R=1	0.70	(Foster, 2015)
Isover	Glass wool	1 m^2 glass wool insulation, R=1	0.62	(Lindholm, 2017)

6.3 Generic data for stone wool and glass wool

The difference between generic data and specific data is that generic data is an average of the products in the market and specific data is data for a specific product. In this subchapter, generic data for stone wool and glass wool are presented from two different sources.

6.3.1 Ecoinvent 3.0

For the products in Ecoinvent 3.0, the density of the glass wool is 40 kg/m^3 and the thermal conductivity is 0.040 W/mK. The density of the stone wool in Ecoinvent is 32 kg/m^3 and the thermal conductivity is 0.036 W/mK. The GWP for 1 m^2 insulation with R=1 m^2 K/W, is 1.64 kg CO_2e for the stages A1-A3. The GWP for 1m^2 glass wool insulation with R=1 m^2 K/W is 4.29 kg CO_2e for the stages A1-A3. The data for both stone wool and glass wool are made as global processes.

6.3.2 IVL Svenska Miljöinstitutet

Byggsektorns Miljöberäkningsverktyg is an LCA-tool developed by IVL for the Swedish construction industry, with generic data for the commonly used building products in Sweden (IVL, 2018). IVL (2018) describes that the tool can be used to assess a building’s climate impact by non-experts. The data behind the generic data in Byggsektorns Miljöberäkningsverktyg is not accessible through the program. However, it is stated that the gathered data is an average of the products on the Swedish market. The GWP is presented in the software to be 1.19 kg CO_2e per kg stone wool and 1.25 kg CO_2e per kg of glass insulation. Since the data is non-transparent and the specific properties for the products are not available, the assumption is made from the statement that the products are an average product on the market.

The GWP data is recalculated for the functional unit of 1 m^2 insulation with a thermal resistance of R=1 m^2 K/W. The recalculated GWPs were 1.37 kg CO_2e for stone wool and 2 kg CO_2e for glass wool.

6.4 Comparison of hemp insulation and mineral wool

The data gathered of the GWP for stone wool varies between 1.27 kg CO_2e and 1.94 kg CO_2e for the stages A1-A3 and for glass wool between 0.62 kg CO_2e and 4.29 kg CO_2e. Since glass wool and stone wool are produced in Sweden and the data for the emissions in Ecoinvent 3.0 probably has an energy source consisting of less renewable energy sources than the ones available in Sweden, the data from Ecoinvent 3.0 is not used in the comparison.

To be able to recalculate the GWP for the products in IVL, some assumptions regarding the insulations materials' properties were made. Thus, the GWPs obtained from IVL are not credible and are therefore not used in the comparison either. However, the generic data from Ecoinvent 3.0 and IVL can be seen as an indication. In Figure 6.1 all data gathered from the EPDs are compared to the assessed GWP for hemp insulation. The Global base scenario, the Swedish base scenario and the best Swedish scenario are used in the comparison.

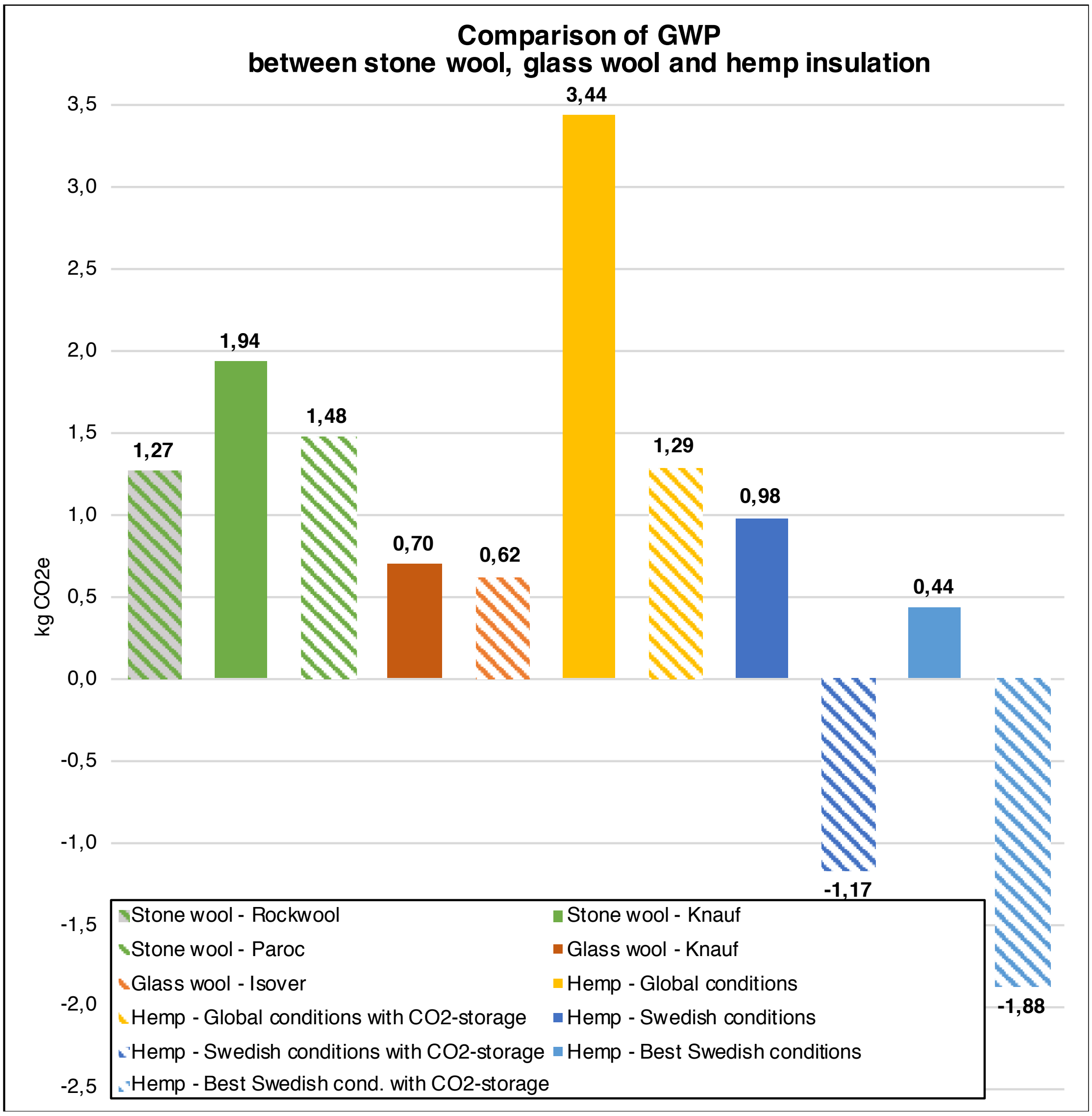


Figure 6.1. Comparison of the GWP of stone wool, glass wool and hemp insulation.

All the data gathered for mineral wool was presented instead of a calculated average. This decision was made to present a transparent comparison since an average would present a higher value for mineral wool and hemp insulation would seem better. If a fossil-free preschool is aimed, the decision makers would probably select an available material with the lowest GWP. The reason for comparing the scenario with both the Swedish and the Global conditions was because the scenario with the Global conditions is constructed from an average of three different hemp insulation products available on the market that is being transported to Gothenburg.

As the comparison illustrates, the hemp insulation only has a better environmental performance than glass wool if it is produced in Sweden and biogenic CO_2-storage is accounted for. Even if an extra fire-resistant gypsum board was added to increase the hemp insulation's fire resistance, the scenario with the Swedish conditions with CO_2-storage has a negative GWP. Thus, a conclusion can be drawn that hemp insulation would have a better GWP if it was produced in Sweden, with the aim to be a fossil-free material.

The result of the interviews indicates that hemp insulation board fulfils many of the criteria presented by the interviewee, such as easy to install not requiring extra tools or special building elevators. Hemp insulation is organic which was something that the structural engineer argued against because of the risk of mould. However, there is no risk of mould in hemp insulation according to Berge (2009).

7 Discussion

In this chapter, the results of the thesis' research questions are discussed. The first subchapter discusses the first research question *"How can material choices be made when constructing a fossil-free preschool?"*. In the second subchapter the second research question "*Which are the challenges and the advantages of replacing mineral wool with hemp insulation for achieving a fossil-free preschool in Gothenburg?"* is discussed. In the third part of the discussion, the consequences of the chosen methodology and delimitations are discussed.

7.1 Discussion of how material choices can be made when constructing a fossil-free preschool

The discussion of the first research question is divided into three parts. The first part discusses the expression 'fossil-free'. The second discusses how materials are chosen today and the last how material choices can be made for a fossil-free preschool.

7.1.1 Discussion of the expression 'fossil-free'

To be able to choose a fossil-free material, an important aspect for the actors in the construction industry is to know what a fossil-free material is. No clear common definition of fossil-free was identified in the literature. Lokalnämnden's (2018) definition of a fossil-free preschool is that a fossil-free preschool should be fossil-free at all stages including raw materials, fuels in all vehicles (transportation and work equipment) and energy (heat and electricity) at the manufacturing stage and at the construction site. Lokalnämnden's definition includes more of a lifecycle perspective than the definition given by some of the interviewees. The interviewees had different ideas about what fossil-free means and what a fossil-free material is. Some of the interviewees such as the Researcher and the Client included the materials' lifecycle in the definition. Other interviewees, such as Architect 2 and the Controller, focused on the raw material of the material and Architect 1 focused on that a fossil-free material should be renewable.

One of the reasons for the difference in the definition could be that some of the interviewees had been in contact with Lokalnämnden before and heard their definition of fossil-free and some of the interviewees had not. Another explanation could be that some of the interviewees had worked with LCA previously and was accustomed to the principle of accounting processes upstream in the supply chain to the material. A misinterpretation of the definition of fossil-free might result in that a material that is fossil-free in some aspect, might be chosen prior to a material that is fossil-free in other aspects.

Baker (2006) describes that strong sustainability is when environmental protection is needed to ensure economic growth. The Politician described in the interview that the goal of fossil-free is set to create an incentive for change in the industry and to put a focus on the environmental aspect, as in Baker's (2006) description of strong sustainability. However, when asked about why the goal *fossil-free* was chosen, no answer was given by the Politician. Mulder, Ferrer, and Van Lente (2011) describe that by simplifying the term of sustainability, the aim can be easier to communicate. Further, one of the reasons not to state a clear definition of the term could be not to constrain the development toward a specific goal and enable everyone to be a part of the development.

None of the interviewees believed that a fossil-free building could be constructed today without accounting for some sort of CO_2-compensation. As described in subchapter 3.1.2, whether compensations can be accounted for, is not always an option due to political and institutional uncertainties. Thus, it is hard to predict if a building can be completely fossil-free or climate neutral and the question needs to be answered by the politicians. It can also be motivated that if compensations were to be accounted for, a limit for the maximum allowance of CO_2e that can be compensated should be stated.

In this thesis, GWP was used to asses if a material is fossil-free or not. A problem when investigating the GWP of a material is that only the GWP is investigated. However, other environmental issues are hazardous to the environment. Thus, other impact categories should also be analysed in order to make sure that the material is a good alternative.

GWP is considered to be a suitable indicator to assess to what extent a building or a material is fossil-free since the goal with fossil-free is to reduce the greenhouse gas emission to the atmosphere. The term *fossil-free* also indicates what type of raw materials that a material can consist of as mentioned by Architect 2 and the Controller. A measurement which considers the raw material could also be suitable for assessing to what extent a material is fossil-free. Another measurement regarding the environmental impact could have resulted in a different result for the hemp insulation. However, when using fossil-free as a goal that is measured by GWP, the difference between fossil-free and other sustainability terms such as climate neutral and carbon neutral becomes hard to detect and the Researcher commented that it is hard to distinguish between the terms.

7.1.2 Discussion of who chooses the material

In the literature review, three parts of the construction process are identified as the time when materials are chosen: the design phase, the procurement and the construction phase. Several references (Ogunkah & Yang, 2012; Sveriges Byggindustrier, 2017; Boverket, 2018), argue that the material choices are made in the design phase, and describes different methods on how the "right" materials can be chosen. Other researchers such as Sporrong, and Bröchner (2009), Naturvårdsverket (2010), and Varnäs, Balfors, and Faith-Ell (2009), argue that the procurement phase can affect which choices are made by using criteria and requirements and, thus, affect the sustainability of a project. This thesis focuses on public procurement in Sweden which needs to follow LOU, resulting in that the client cannot specify that a specific supplier's material should be used. This leads to that the final decision regarding which supplier to choose in some way ends up in the construction phase when the material actually is being used in the building. However, the contractor needs to prove that the selected material is equal performing as the one described from the design phase and specified in the procurement.

The Client described that today the possibility exists for a client to specify how much a material or a product can emit during its lifecycle, in the procurement. By specifying the allowed amount of emissions in the procurement, a client can guarantee that the product used by the contractor will be at least as good as specified in the procurement. In the interview study, all interviewees, except the Client, thought that the material choices should be made as early in the design phase as possible to be able to thoroughly assess the consequences of replacing a standard material. The Client, on the other hand, wanted to delay the material choices to enable the market to adjust to being fossil-free.

The goal is that the fossil-free preschool will be completed within three years and it can be argued that no drastic change will happen regarding the availability of materials on the market within three years. However, during the discussion with the Client, the distinction between materials and specific products from a supplier was sometimes a bit diffuse. The Client could have meant that they want to select a specific supplier as late as possible in the process and not the material.

In the interview study, all the interviewees described that the client affect the material choice and many of the interviewees also thought that the client is responsible for the material choice. This statement correlates with the fact that the client is, according to Boverket (2018b), responsible for the products used in the building. However, after the discussions with the interviewees, it has become evident that the process of choosing materials is not made in one step. It happens successively with restrictions on the possible materials to be used, set by both the client, the consultants and the architect. It has also been presented that it is important to consider both the materials and the specific suppliers since the properties of one material can differ between suppliers.

From Table 4.1 in Chapter 4, it can be concluded that the interviewees have different opinions regarding who is choosing the materials and who is responsible for the choices. One of the reasons for the difference in opinion could be that the interviewees interpreted the questions differently and assigned different meanings to the words ‘choose’ and ‘responsible’.

7.1.3 Discussion of how material choices for a fossil-free preschool could be affected

The interviewees work with sustainability in different manners and described that they can affect the environmental performance of a building in different ways. The interviewees also had conflicting perceptions about the actors’ possibility to affect the choices. This is clear in the description from the Structural Engineer and the Site Manager, where both parties mentioned each other as the one who affects the sustainability of the material choices the most. Kardefors and Dwulf (2012) describe that in partnering, the client, the contractor and the consultants are systematically strengthening and developing their collaboration to reach the project’s aim. An increment of the collaboration between actors in a project could increase the understanding of each other’s role. It could also decrease the risk of misinterpreting the actors’ possibility to affect the sustainability of a project.

Architect 1 suggested having one person responsible for the environmental aspect of the whole building processes. This could, for example, be done in collaboration with an environmental certification tool as described by Thuvander, Femenias, Norling Mjörnell, and Meiling (2012). However, there are no certification tools correlated to fossil-free today. By implementing a routine of always having a person responsible for the sustainability of the building could also solve the problem of who is responsible for the sustainability. The Fire Consultant and the Researcher believed that it is important to include all actors in the material choices, for all actors’ knowledge to be considered and used to realize the goal of choosing more fossil-free materials. That everybody aims for the same goal might be a good idea if a fossil-free construction is aimed, but as Architect 1 describe it might be good to always assign a person, such as an environmental controller, to lead the development.

The Client and the Politician described in the interview that the goal to build a fossil-free preschool was set to initiate a change in the industry. Multiple of the interviewees described that materials are chosen out of habit, and if no incentive is given to change the material choices, the same materials will be chosen. Public procurement could be used as a mechanism to regulate the market towards an aimed result (Naturvårdsverket, 2012). Boverket (2018) proposes to develop criteria for green public procurement to make it easier for clients to procure environmental solutions, and by doing this, regulate the market.

A solution suggested by the HVAC & Energy Engineer was to develop new standard criteria for a fossil-free construction in AMA. Sporrong and Bröchner (2009), Naturvårdsverket (2010), Varnäs, Balfors and Faith-Ell (2009) describe that, by setting environmental requirements in the procurement, a client can affect the environmental performance of a building. Multiple of the interviewees also highlighted the importance of that the client specifies *fossil-free* as a requirement if a change towards fossil-free is aimed for. The Politician described that it is important for a public client to demand change for the industry to develop. However, the Researcher described that all actors in the industry are responsible and all actors' commitment is needed to succeed to reach a fossil-free construction industry.

All the interviewees work for organisations that have environmental policies and internal environmental goals within environmental management systems. However, the interviewees still think it is better to work with the environmental goal for a building project instead of the environmental management system implemented in the internal organisation since they do not want to have conflicting goals. An example of this could be that one consultancy firm wants to build fossil-free and the client that pays for the project has a different sustainability goal.

The problem that different organisations define sustainability in different ways is a problem that correlates with a simplified communication of sustainability (Mulder, Ferrer, & Van Lente, 2011). The result that the use of environmental management systems is not a way of achieving a fossil-free material choice, is identified in this study. This could be explained by the statement from Gluch (2005), that environmental management systems for organisations were designed for permanent organisations and not project-based organisations.

In this thesis, an LCA is performed to assess the possibility of using hemp insulation as a replacement material for mineral wool. By developing an LCA, it becomes clearer to what extent a material is fossil-free and the materials GWP can be compared. Gluch et al, (2014) explain that to perform an LCA is a way of transferring information and accountability between the actors involved in the construction process in an effective way. Developing an LCA to be able to compare materials is time-consuming and requires knowledge both about the materials' production and the materials' supply chain. This results in that it is not feasible for a client, architect, contractor or consultant to perform LCAs on every possible material that is considered as a possible replacement material for a standard material, even if it is a way of making a thoroughly assessed material choice. However, if the material manufacturer all had developed their own assessments, it would be less time consuming and more feasible to do a comparison between different materials. It can also be argued that it would be more efficient for the industry if the manufacturer assessed their products, instead of all the actors that considered to use the product. To have EPDs of products could be a competitive advantage for the manufacturers on a fossil-free market.

The Fire Consultant described that the availability of information about a material's environmental performance was an issue with choosing fossil-free materials. A solution to this problem, described by the Client, is to require an EPD for all products sold in Sweden. This would make the environmental impact of different choices more accessible. Boverket (2018) proposes to implement life cycle assessments and require climate declarations of buildings, to increase the demand of specific information about the GWP and remove the gap between the client and the manufactures awareness about the materials climate impact. As a result of this study, it can be said that EPDs can be used to show the GWP for a material. However, it is not transparent in an EPD how the GWP is assessed. Usually, it is specified that the EPD follow a specific PCR, but an issue with PCRs is that they specify how the GWP should be assessed in a simplified way and it is not always feasible. Besides the PCR, it is sometimes specified that the assessment behind the EPD is built upon generic data, which might not be feasible either. Another problem related to PCRs is that there are multiple PCRs and it is not guaranteed that all EPDs follow the same PCR. Thus, an EPD is just an indicator and estimation on the GWP of a product and is not always usable when comparing materials. As stated before, it is debatable whether GWP can be used to measure to what extent a material is fossil-free.

7.2 Discussion of the challenges and the environmental advantages that exist when replacing mineral wool with hemp insulation

In this subchapter, the discussion of the second research question is presented. The discussion starts with discussing the possibility of replacing mineral wool with hemp insulation and continues to discuss the challenges and advantages of replacing mineral wool with hemp insulation.

7.2.1 Discussion of the possibility of replacing mineral wool with hemp insulation

Described in the interview study, the materials chosen in the construction industry are chosen out of habit and if no incentive is given towards a change, the same material will be used. Further, it was explained that since a building has a long lifespan and it is important that a material is functional and suitable for several years, it can be hard to assess possible problems in the future when replacing a standard material. Mineral wool is a standard material that is one of the most commonly used insulation materials in walls (Hera, et al., 2016). Mineral wool is not a fossil-free material and if the client requires a fossil-free preschool this could be the incentive described in the interviews as needed for changing a standard material.

Mineral wool has multiple functions as an insulation material and it is not assessed as possible to find a replacement material with lower GWP and same properties as mineral wool. Hemp insulation is described in Chapter 3.4.8 to be functionally equivalent in many of mineral wool's functions and superior regarding its moisture performance. Mineral wool is superior regarding the fire resistance compared to hemp insulation, but as described by the Fire Consultant in the interview study the fire resistance of the building can be guaranteed in other ways. Thus, each project needs to be assessed regarding if the total environmental impact of a building is lower with a material with lower fire resistance.

One of the risks with hemp insulation is that the cultivation is dependent on the weather and it can be hard to forecast the yield from the cultivation. This results in that the use of renewable resources can be a larger uncertainty compared to stone wool and glass wool. However, hemp plants can regrow and there is no risk of the raw material to deplete. In the EPDs for glass wool, the emissions from the recycled glass that is used as a raw material might be excluded. This is done because recycled materials can be argued as sustainable since it is better to the available resources in the system. However, if a replacement material for glass is found and the use of glass products is decreased, there might not be any recycled materials available. Thus, if the recycled glass was accounted for in the GWP for glass wool, the value might be higher.

Stone wool and glass wool that are produced in Sweden is, in Chapter 6, presented to have a relatively low GWP compared to the GWP of the hemp insulation with Global conditions. The scenario with Swedish conditions and biogenic CO_2-storage had a lower GWP than both glass wool and stone wool. Today there are no Swedish manufactures of hemp insulation boards, and this results in that the scenario with the Swedish conditions is not applicable in reality. However, as the result in Chapter 6 presents; if hemp insulation was produced in Sweden it could result in a lower GWP. If hemp insulation manufacturers established on the Swedish market, other environmental impacts might occur in the production of the hemp insulation factory and the use of land for growing hemp. A part of the environmental effect from a hemp insulation factory is allocated to the hemp insulation in the LCA in Chapter 4. However, if the factory was built solely to use in one project, the allocation of the GWP need to be reconsidered.

An uncertainty with the life cycle assessment of hemp insulation is that generic global data was used for all parts except for the transportation distances, the electricity, and the heat and gas. This results most likely in a higher GWP than what is reasonable both for the Global and the Swedish conditions. Another uncertainty is that the scenario with the Global conditions is an assembly of the inputs from the UK, Germany and Italy for the transportation distances, the electricity, and the heat and gas. Thus, it is not a reliable scenario, but an average of three scenarios. If a fossil-free preschool was to be built in Sweden, the best of those three scenarios would have been used. Also, since the electricity is the activity affecting the GWP the most in the Global conditions, it could be a possibility that a hemp insulation factory would use electricity from a higher proportion of renewable fuels since the material developed to be a more environmentally friendly material. If this would be the case, the result of the scenario with the Global conditions would be about as low as the Swedish base scenario. Further, if the product was mainly transported by train, the GWP would decrease even more and the Global product would then be superior to mineral wool.

Appendix V illustrates that, even if the processes that only contributes to the total emissions with more than 1 % is presented, hemp insulation with the Swedish conditions has at least 19 processes that emit greenhouse gasses and are not fossil-free. To be able to achieve a fossil-free hemp insulation without accounting for compensations and biogenic CO_2-storage, all of these processes need to be changed. One example of a possible change for a more fossil-free hemp insulation would be to use specific electricity from a high proportion of renewable fuels when producing the insulation, as presented in the sensitivity analysis of the LCA.

7.2.2 Discussion of the challenges with replacing mineral wool with hemp insulation

One of the challenges with finding a replacement material for mineral wool is that no identified materials are fossil-free and has zero global warming potential without accounting for biogenic CO_2-storage. The reason behind this is that all studied materials require transportation and energy, which are not fossil-free.

7.2.2.1 Accessibility and transparency of environmental data

One of the problems identified when replacing a standard material is the availability and transparency of information regarding the performance of the replacement material, both environmental properties and other functional properties. This results in that the possibility of assessing the replacement material's possible performance is difficult. Much of the available information regarding alternative material's performance comes from the material supplier, which it is not a completely independent source. The Client argued that to set a requirement on material suppliers of the Swedish market to provide an EPD, could solve this problem. However, to develop an EPD is expansive and not every supplier can afford it. Another problem is the availability of information regarding possible replacement materials that exist on the market. A benefit with that the researchers do not have long experience in the field, is that the researchers do not have prejudges regarding the possibilities of materials. However, the downside is that the researchers do not know as much as a person with long working experience.

7.2.2.2 Meet the requirements on materials

An identified problem is the challenge to fulfil all the requirements set on materials in the construction industry today as many of the requirements are developed around the properties that the available materials on the market have. New materials might have better and different properties than the standard materials, but since the requirements are developed around different properties, these requirements might not be met. However, buildings often have a long lifespan and the functions of the building need to be maintained. Therefore, when trying a new material, it might be a large risk for the client. Another problem identified was the definition of fossil-free and that the actors in the building industry did not include the same aspects of a material's lifecycle in the definition of fossil-free.

7.2.2.3 Economic aspects

One issue that is outside the scope, is the economic issue with replacing a conventional material. First of all, a product is always more expensive in the beginning before the demand is large enough. Since hemp insulation boards are not produced in Sweden yet, the possibility of using it in Sweden today could be expensive.

7.2.2.4 Lack of knowledge about organic materials

Another challenge when implementing organic and natural materials on the market in the building industry is the lack of knowledge about materials' performance. Usually, the perception of organic materials is that they have bad moisture properties and that mould easily can occur, as the Structural Engineer mentioned. However, hemp insulation has a great moisture performance and has good resistance to microbial growth such as mould. Thus, the knowledge of organic materials needs to be propagated.

7.2.3 Discussion of the advantages of replacing mineral wool with hemp insulation

The advantages aimed for in this study was to find a fossil-free replacement material for mineral wool with basically the same functional properties. If biogenic CO_2-storage is accounted for the hemp insulation with the Swedish conditions, the hemp insulation used in the exterior wall of the preschool could serve as a way to reduce the GWP for the whole fossil-free preschool.

One of the advantages with trying to replace a standard material is that standard materials are assessed and if a standard material is still assessed as the superior material, the material choice is not made just out of habit. Described by the Client in the interview study, by requiring fossil-free alternatives before standard materials, is a way to show interest in the future of the industry and give an incentive to the manufacturers to change.

The main reason for assessing the possibility of replacing mineral wool with hemp insulation from the beginning is to reduce the CO_2e-emissions when building a preschool and reach the goal of a fossil-free preschool. Today the assessment from Lokalförvaltningen states that insulation stands for 5% of the total emissions for a preschool and if an insulation with a negative GWP was used instead, it would affect the total emissions of the building.

7.3 Discussion on the delimitations and the methodological choices

In this subchapter, some of the effects of the methodological choices are discussed. The subchapter focusses on the methodological choices that are assessed as affecting the results largely.

7.3.1 Mixed methods research

An advantage of using a mixed methods research approach was described by Cresweel & Plano Clark (2011) to be that a duality in a study's aim can be covered. By using a mixed methods research approach, both qualitative data of how materials are chosen for as fossil-free preschool, as well as the quantitative data of how fossil-free materials can be measured and compared could be covered in the study. However, the mixed methods research approach also creates some duality in the study and large efforts were required to keep the parts integrated throughout the study. A duality in the study was also a challenge with a mixed methods research approach described by Cresweel & Plano Clark (2011).

7.3.2 Number of interview objects

For the interview study, the choice to interview many different actors in the construction industry and people with different background and experience was made. This resulted in that many different actors' opinions could be gathered and analysed. However, the result presents the interviewees' reflection of the reality, and ten interviews are not representative of all actors in the sector. The choice was also made to focus on public preschool projects since this is the first type of building project that applies to the goal to be fossil-free. This delimitation affected the result largely since the responsibilities of a public and private client differs. However, the result is still an indication of the situation in the construction industry.

7.3.3 Assumptions during the LCA

The data regarding the hemp insulation's GWP was achieved by an LCA. As mentioned in Chapter 5, specific data regarding the production was not available. This resulted in that multiple assumptions were made, and second-hand sources were used to enable an assessment of hemp insulation. However, this further discussed in the sensitivity analysis, see subchapter 5.4.2.4. The data regarding the GWP for stone wool and glass wool was gathered from material suppliers' EPDs. The difference of sources of data in the material comparison might have resulted in that the comparison does not present the case of the reality. However, since no EPDs of hemp insulation was available, the comparison is an indication of the situation.

7.3.4 Waste scenario

One methodological choice that was made was to exclude the waste scenario in the life cycle assessment of hemp insulation. This choice was made because other insulation materials usually do not include the waste scenarios in their EPDs and because it is difficult to predict what will happen with the waste in 40 years. The latter was also an argument that the Client mentioned during the interview. The Client had made the delimitation for now, since Lokalförvaltningen predicted that they would have a fossil-free waste disposal in Gothenburg in 40 years. If this would be the case, it would be legit to exclude the waste from the LCA, however, it is a utopia.

If waste would be included in the LCA for hemp insulation, the GWP would increase. How much the GWP would increase would depend on the waste scenario. The main components in hemp insulation are compostable and if the hemp mass would be composted, the stored carbon dioxide would continue to be stored in the ground. The plastic components in the insulation could be recycled, which would be a good alternative. If the hemp insulation would be treated as combustible waste, the stored carbon in both the hemp fibres and the plastic could be released into the atmosphere and thus contribute to the greenhouse gases. If this would be the case, it would not be accurate to account for the stored carbon dioxide in the hemp fibres in its LCA, since the carbon dioxide would be released again. However, during the time hemp insulation would be installed in the house it would serve as a CO_2-storer.

7.3.5 Loose hemp insulation

Another methodological choice was to only investigate insulation boards that would function in an exterior wall. In order to get a hemp insulation board to retain its form and stability, plastic (PLA) is a necessary component. However, if it was not a requirement that the insulation should be able to be used as a board, loose hemp insulation could be used instead. If loose hemp insulation were used instead, no plastics would be required. Without any plastics in the insulation, the GWP would be at least 33.5% lower since that is how much the plastics affected the results for the hemp insulation board. The energy required during the production would also probably be a lot lower since the material would not need the machinery and the energy required to form the insulation into bards. Another aspect of it is that loose hemp insulation would be 100% compostable, and thus the waste scenario would be a lot more environmentally beneficial. However, loose hemp insulation is not as comparable to the mineral wool board since it requires another type of wall construction.

7.3.6 Other possible replacement materials

The choice to only investigate hemp insulation boards in the LCA and comparison was made due to time limitations and due to the result of the literature study, that resulted in that hemp insulation would be a good alternative to mineral wool. However, there could be other insulation materials more suitable as a substitute for mineral wool and it would be interesting to investigate the difference between hemp insulation and other insulation materials.

8 Conclusions

A conclusion that can be drawn for both of the research questions is that the methodological choices affect the results largely. Both regarding the definition of *fossil-free* and regarding the life cycle assessment.

A conclusion that can be drawn to answer the first research question: "*How can material choices be made when constructing a fossil-free preschool?",* is that the definition of fossil-free needs to be clearly defined, motivated and applied. A decision needs to be made regarding how *fossil-free* will be measured and if compensations can be accounted for. Further, a decision also needs to be made on how and what kinds of compensations that can be accounted for. Today, the material choice happens successively and is made by more than one person. Further, it can be concluded that all actors involved in the material choice need to work together and aim for a fossil-free result to reach the goal of a fossil-free preschool. To break the habit of choosing the same materials, incentives and different mechanisms are needed. Possible incentives can be that the client sets the requirements for achieving a fossil-free preschool in the procurement. Another way of affecting the material choice could be to implement a routine to always have an environmental coordinator in a fossil-free construction project, with the responsibility of follow-up and evaluate the material choices. A mechanism that can be used to evaluate if a building is fossil-free is LCA. To use an LCA can also increase the demand for specific information about climate emissions from construction materials and remove the gap between the client and the manufacturers' awareness about the climate impact of materials.

To answer the second research question: "*Which are the challenges and the advantages of replacing mineral wool with hemp insulation to achieve a fossil-free preschool in Gothenburg?"* the conclusion can be drawn that if hemp insulation was produced in Sweden, it would be a more suitable material than mineral wool for a fossil-free preschool. However, there is no hemp insulation production in Sweden today and if mineral wool is compared to a hemp insulation produced in Germany, Italy or the UK, mineral wool is superior. An identified challenge is to gather reliable data regarding the production process of hemp insulation in order to get a reliable result of the GWP. Another conflict when assessing the GWP is whether the biogenic CO_2-storage in the hemp fibres can be accounted for. If it is accounted for, it would be an advantage for hemp insulation and replacing mineral wool with hemp insulation could contribute to achieving a fossil-free preschool.

8.1 Future works

The fossil-free preschool is not yet constructed. Thus, future works could asses how materials were chosen for the pilot case of building a fossil-free preschool and if the result presented in this study was a correct description. For future works, it could also be assessed how one actor could affect the material choices more deeply, by focusing on fewer actors. Multiple mechanisms that could affect the material choice were studied in this thesis and for future works, one of the mechanism's effects on the material choices could be studied more closely.

The life cycle assessment of hemp insulation was performed without a collaboration with a hemp insulation supplier. For future works, a collaboration with a hemp insulation supplier could be established and the difference in the result of this study could be assessed.

In this study, the lifecycle of hemp insulation boards was studied. In future works, the effect of using loose hemp insulation could be studied to assess the difference between the materials' performance. Other insulation material such as sheep wool could also be assessed and compared to mineral wool.

The difference in price of hemp insulation and mineral wool is only mentioned in this thesis, thus, a future work could be to study the effect of the price of hemp insulation. Insulation is used in many other building elements, besides an exterior wall and the possibility of using hemp insulation as technical insulation, insulation in an interior wall could also be studied in future works.

In this thesis, three different compensation methods for CO_2e-emissions available today are shortly described. In future works, the effect of using different compensation methods for compensating CO_2e-emissions to achieve a fossil free preschool could be studied.

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Appendix I: Questions used in the interview study

In this appendix, the questions used in the interview study are presented. The interviews were semi-structured interviews and the follow-up questions is not presented in this appendix. The interviews were also adapted to fit the specific interviewee. This results in that when the words ‘company’ and ‘actor’ are used in this appendix, the specific company and actor was inserted. Some of the actors got individual questions beside the foundation questions and these are presented after the foundation questions. Below the foundation questions are presented.

Introducing question regarding the interviewee

- Which is your professional background?

Background information of the sustainability work

- How does your company work with sustainability issues?
- What is the role of your actor in the building industry's development towards sustainability?
- How much do you feel that you can affect the sustainability of a construction project?

Fossil-free materials

- How would you define a fossil-free material?
    - Do you know of any fossil-free materials?
- Do you know of any alternative insulation materials which are assessed as having low impact on the environment?
- If mineral wool would be replaced by an alternative material, what functions and properties would that material need to have?
- Do you or your company work in any specific way with trying to identify new solutions for materials?

Material choices in the construction industry

- How would you describe the material choices in a construction project?
    - Who makes the material choice?
    - Who is responsible for the material choice?
    - When in the construction process is the choice made?
- How do you think the material choice could be affected to achieve a fossil-free preschool?
    - Does anything need to be changed?
- If a fossil-free material choice is aimed for, who do you think is responsible for realizing that aim?
- What challenges do you see in achieving a fossil-free construction?

Concluding questions

- Do you have anything more you would like to add to the interview that you think we have missed to cover?
- Do you have any recommendations of other persons you think we should interview for this study?

Questions asked to the Client

- How was the goal to build a fossil-free preschool decided upon?

- Which contract strategy have you decided to use in the project to build a fossil-free preschool?

Questions asked to the Fire Consultant

- If an identified replacement material is identified for mineral wool with inferior fire resistance, could the fire resistance be improved in any ways to fulfil the requirements placed on an insulation material?
- Do you think that the fire requirement on materials of today will be changed to enable other alternative materials to be used?

Questions asked to the Politician

- How was the goal to build a fossil-free preschool decided upon?
- Why was the goal set to be fossil-free and not another environmental goal?

Appendix II: Calculation of GWP for the functional unit

The functional unit in the EPD did in some cases differ from the functional unit used in the LCA study in this thesis. This resulted in that the functional unit needed to be recalculated. All calculations below are performed according to Hagentoft (2001) and an assumption was made that the relationship between the GWP and the volume/mass of an insulation material is linear. References is found in the end of this appendix.

i. Calculation of the mass used for the functional unit for hemp insulation

$d = R * \lambda$ (Equation 1)
$m = \rho * A * d$ (Equation 3)

Below, the values used and the calculations are presented:
R – thermal resistance = 1 m^2K/W
λ – thermal conductivity = 0.038 W/mK
d – thickness [m]

{Equation 1} → $d = 1 * 0.038 = 0.038m$

A – area = $1m^2$
ρ – density = 30 kg/m^3
m – mass [kg]

{Equation 2} → $m = 1 * 0.038 * 30 = \mathbf{1.14\ kg}$

ii. Recalculation of the functional unit for Baubook's hemp insulation

To recalculate the functional unit from kg to 1 m^2 insulation with R=1 m^2K/W. The following equations were used:

$d = R * \lambda$ (Equation 1)
$\frac{d * A * \rho}{m} = P \rightarrow P * GWP_1 = GWP_2$ (Equation 3)

Below, the values for the GWP for Napro Klima are calculated:

R – thermal resistance = 1 m^2K/W
λ – thermal conductivity = 0.041 W/mK
d – thickness [m]

{Equation 1} → $d = 1 * 0.041 = 0.041m$

A – area = $1m^2$
m – volume = 1kg
ρ – density = 40 kg/m^3
P – percentage used of 1kg for the functional unit $1m^2$, R = 1 m^2K/W
$GWP_{1,1}$ – emissions for the functional unit 1 kg without CO_2-storage = 1.43 kg CO_2e
$GWP_{1,2}$ – emissions for the functional unit 1 kg for whit CO_2-storage = 0.0774 kg CO_2e
$GWP_{2,1}$ – emissions for the functional unit $1m^2$, R = 1 m^2K/W without CO_2-storage [kg CO_2e]

$GWP_{2,2}$ – emissions for the functional unit 1m^2, R = 1 m^{2}K/W with CO_2-storage [kg CO_2e]

$$\{\text{Equation 3}\} \rightarrow GWP_{2,1} = \frac{0.041*1*40}{1} * 1.43 = \mathbf{2.35\ kg\ CO_2e}$$
$$\{\text{Equation 3}\} \rightarrow GWP_{2,2} = \frac{0.041*1*40}{1} * 0.0774 = \mathbf{0.126\ kg\ CO_2e}$$

Below, the values for GWP for Thermo Natur are calculated:

R – thermal resistance = 1 m^{2}K/W
λ – thermal conductivity = 0.045 W/mK
d – thickness [m]

$$\{\text{Equation 1}\} \rightarrow d = 1 * 0.045 = 0.045m$$

A – area = 1m^2
m – volume =1kg
ρ – density = 40 kg/m^3
P – percentage used of 1kg for the functional unit 1m^2, R = 1 m^{2}K/W
$GWP_{1,1}$ – emissions for the functional unit 1 kg without CO_2-storage = 1.43 kg CO_2e
$GWP_{1,2}$ – emissions for the functional unit 1 kg for whit CO_2-storage = 0.0774 kg CO_2e
$GWP_{2,1}$ – emissions for the functional unit 1m^2, R = 1 m^{2}K/W without CO_2-storage [kg CO_2e]
$GWP_{2,2}$ – emissions for the functional unit 1m^2, R = 1 m^{2}K/W with CO_2-storage [kg CO_2e]

$$\{\text{Equation 3}\} \rightarrow GWP_{2,1} = \frac{0.045*1*40}{1} * 1.43 = \mathbf{2.57\ kg\ CO_2e}$$
$$\{\text{Equation 3}\} \rightarrow GWP_{2,2} = \frac{0.045*1*40}{1} * 0.0774 = \mathbf{0.140\ kg\ CO_2e}$$

iii. Recalculation of the functional unit Zampori, Dotelli, & Vernelli

This LCA is performed on hemp insulation from Italy and the result of that LCA was that 1 m^2 of insulation with U-value = 0.2 W/ m^{2}K emitted -4.28 kg CO2e. A wall with U-value 0.2 W/ m^{2}K needs to be five times thicker than a wall with R-value = 1 m^{2}K/W. If the result is divided by 5 to correspond with the functional 1 m^2 of insulation with R = 1 m^{2}K/W, the emissions would be **-0.856 kg CO2e**.

iv. Recalculation of the functional unit for Knauf's stone wool insulation

To recalculate the functional unit from m^3 to 1 m^2 insulation with R=1 m^{2}K/W, the following equations was used:

$$d = R * \lambda \qquad \text{(Equation 1)}$$
$$\frac{d*A}{V} = P \rightarrow P * GWP_1 = GWP_2 \qquad \text{(Equation 4)}$$

Below, the values used and the calculations are presented:
R – thermal resistance = 1 m^{2}K/W
λ – thermal conductivity = 0.036 W/mK
d – thickness [m]

$$\{\text{Equation 1}\} \rightarrow d = 1 * 0.036 = 0.036m$$

A – area = 1m^2
V – volume = 1m^3

P – percentage used of $1m^3$ for the functional unit $1m^2$, R = 1 m^2K/W
$GWP_{1(A1\text{-}A3)}$ – emissions for the functional unit 1 m^3 for stages A1-A3 = 53.8 kg CO_2e
$GWP_{1(A4)}$ – emissions for the functional unit 1 m^3 for stage A4 = 0.605 kg CO_2e
$GWP_{2(A1\text{-}A3)}$ – emissions for the functional unit $1m^2$, R = 1 m^2K/W for stage A1-A3 [kg CO_2e]
$GWP_{2(A4)}$– emissions for the functional unit $1m^2$, R = 1 m^2K/W for stage A4 [kg CO_2e]

{Equation 4} → $GWP_{2(A1-A3)} = \frac{0.036*1}{1} * 53.8 = \mathbf{1.94\ kg\ CO_2e}$
{Equation 4} → $GWP_{2(A4)} = \frac{0.036*1}{1} * 0.605 = \mathbf{0.02\ kg\ CO_2e}$

v. Recalculation of the functional unit for Knauf's glass wool insulation

To recalculate the functional unit from m^3 to 1 m^2 insulation with R = 1 m^2K/W, the following equations was used:

$d = R * \lambda$ (Equation 1)
$\frac{d*A}{V} = P \rightarrow P * GWP_1 = GWP_2$ (Equation 3)

Below, the values used, and the calculations are presented:
R – thermal resistance = 1 m^2K/W
λ – thermal conductivity = 0.0375 W/mK
d – thickness [m]

{Equation 1} → $d = 1 * 0.0375 = 0.0375m$

A – area = $1m^2$
V – volume =$1m^3$
P – percentage used of $1m^3$ for the functional unit $1m^2$, R = 1 m^2K/W
$GWP_{1(A1\text{-}A3)}$ – emissions for the functional unit 1 m^3 for stages A1-A3 = 18.7 kg CO_2e
$GWP_{1(A4)}$ – emissions for the functional unit 1 m^3 for stage A4 = 0.26 kg CO_2e
$GWP_{2(A1\text{-}A3)}$ – emissions for the functional unit $1m^2$, R = 1 m^2K/W for stage A1-A3 [kg CO_2e]
$GWP_{2(A4)}$ – emissions for the functional unit $1m^2$, R = 1 m^2K/W for stage A4 [kg CO_2e]

{Equation 4} → $GWP_{2(A1-A3)} = \frac{0.036*1}{1} * 53.8 = \mathbf{0.70\ kg\ CO_2e}$
{Equation 4} → $GWP_{2(A1-A3)} = \frac{0.036*1}{1} * 0.26 = \mathbf{0.01\ kg\ CO_2e}$

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Appendix III: Data gathered from a hemp farmer

A Swedish hemp farmer was contacted by telephone to verify the input data identified in articles and reports and the hemp cultivation and the hemp insulation production was discussed. This appendix presents the data source and the collected data, see Table 1.

Table 1. Data source and data collected from the Swedish hemp farmer

Data source:	
Data collection method	Conversation via telephone
Collection date	2018-03-28
Data source	Roger Olofsson, a hemp farmer at Hampaprodukter
Geographical location	Grästorp, Sweden
Collected data:	
Process	Hemp Cultivation
Sub-processes	Hemp plant
Impute collected	Amount of dry substance of hemp plant yield one hectare
Data	Yield: 30 tonnes /ha
Process	Hemp Cultivation
Sub-processes	Hemp plant
Impute collected	Time needed between sowing and harvesting
Data	Time needed: 100-120 days
Process	Hemp Cultivation
Sub-processes	Fertilisation
Impute collected	Amount of fertilisation (NPK) required per hectare of hemp cultivation
Data:	N: 120kg/ha
	P: 60kg/ha
	K: 9kg/ha
	Hemp plant can grow without any fertilisation
Process	Hemp Cultivation
Sub-processes	Pesticide
Impute collected	Amount of pesticide required for hemp cultivation
Data	No pesticides needed for hemp cultivation
Process	Hemp Cultivation
Sub-processes	CO_2-storage
Impute collected	Amount of CO_2-storage in 1kg hemp fibre
Data	CO_2-storage: 1.5kg CO_2e/kg
Process	Hemp Insulation production
Impute collected	Products produced from the hemp plant
Data	Long fibres → Hemp insulation
	Short fibres → Rabbit pellets
	Dust→ Nothing
Process	Hemp insulation
Sub-processes	Hemp fibre production
Impute collected	How hemp fibres are separated
Data	Fist the plant is hacked then shaken to separate the fibres. The fibres can be shaken in a combine harvester.

Appendix IV: Full inventory list of the LCA

In this appendix, the data for the processes modelled for the LCA are presented in Table 1-Table 10 below. The database Ecoinvent 3.0 was used for the inventory.

Table 1. Input data for the cultivation of hemp fibres.

Process information			
Category type	Material		
Process identifier	ChaClass000037950000002		
Process name	Cultivation of hemp fibres		
Geography	Global		
Date	2018-03-20		
Literature references	(Rosenqvist, 2017); (Zampori, Dotelli, & Vernelli, 2013)		
Collection method	Reports, articles, dialogue with a hemp farmer		
Allocation rules	100 % of the emissions comes from the hemp fibres		
System description	This process represents the cultivation of hemp fibres. It includes the tillage processes ploughing, harrowing, sowing, fertilising and harvesting. Further, the processes baling, and bale loading is included and the fertilisers N, P and K. The inputs are based on that 1tonne hemp plant needs 0.1538 ha to grow.		
Products			
Outputs to technosphere, products	**Amount**	**Unit**	**Allocation**
Hemp fibre {GLO}| hemp production	1000	kg	100%
Inputs			
From technosphere, materials/fuels	**Amount**	**Unit**	**Comment**
Tillage, ploughing {GLO}| market for | Alloc Def, U	0.1538	ha	Ploughing of the land.
Tillage, harrowing, by spring tine harrow {GLO}| market for | Alloc Def, U	0.1538	ha	Assumption: the land is harrowed with a spring tine harrow.
Sowing {GLO}| market for | Alloc Def, U	0.1538	ha	Sowing of the seeds.
Fertilising, by broadcaster {GLO}| market for | Alloc Def, U	0.1538	ha	Fertilisation of N-P-K.
Urea, as N {GLO}| market for | Alloc Def, U	15	kg	Commonly used N-fertiliser in Sweden (Börling et Al, 2017). The amount of fertiliser N required varies between 68-128 kg/ha in Sweden (Rosenqvist, 2017).
Phosphate fertiliser, as P2O5 {GLO}| market for | Alloc Def, U	2	kg	The amount of fertiliser P required varies between 9-17 kg/ha in Sweden (Rosenqvist, 2017).
Potassium fertiliser, as K2O {GLO}| market for | Alloc Def, U	4	kg	The amount of fertiliser K required varies between 18-34 kg/ha in Sweden (Rosenqvist, 2017).
Combine harvesting {RoW}| processing | Alloc Def, U	0.1538	ha	Assumption: combined harvesting of the hemp plants.

Baling {GLO}| market for | Alloc Def, U	1.43	p	Assumption: one bale weights 700 kg as stated in the baling process in Ecoinvent.
Bale loading {GLO}| market for | Alloc Def, U	1.43	p	Assumption: one bale weights 700 kg as stated in the baling process in Ecoinvent.
Outputs			
Emissions to air	**Amount**	**Unit**	**Comment**
Carbon dioxide, fossil	-1000	kg	Constitutes how much CO_2 the hemp absorbs during its cultivation. A hemp plant store 1 kg CO_2e per kg produced hemp.

Table 2. Input data for the market-for hemp fibre.

Process information			
Category type	Material		
Process identifier	ChaClass000037950000004		
Process name	Market-for hemp fibre		
Geography	Global		
Date	2018-03-21		
Literature references	(Black Mountain, 2018); (Thermo Natur, 2018)		
Collection method	Manufacturers		
Allocation rules	100 % of the emissions comes from the market for hemp fibres		
System description	This process represents market-for hemp fibre. Included in the process is the production of hemp fibre and the transport from the cultivation to the insulation production factory.		
Products			
Outputs to technosphere, products	**Amount**	**Unit**	**Allocation**
Hemp fibre {GLO}| market for	1	kg	100%
Inputs			
From technosphere, materials/fuels	**Amount**	**Unit**	**Comment**
Hemp fibre {GLO}| hemp production	1	kg	
Transport, freight, lorry, unspecified {GLO}| market for | Alloc Def, U	3	kgkm	Transportation from the cultivation to factory. Assumption based on product specific data from Black Mountain insulation, UK, and Thermo Natur, GE.

Table 3. Input data for the hemp insulation factory.

Process information	
Category type	Material
Process identifier	ChaClass000037950000016
Process name	Hemp insulation factory
Geography	Global
Date	2018-04-10
Literature references	Ecoinvent 3.0
Collection method	-
Allocation rules	100 % of the emissions comes from the hemp insulation factory

System description	This process represents a hemp insulation factory. The things included in the process are the machinery for drying, scutching and formation of the insulation boards, a conveyor belt and a building hall. This factory is assumed to produce 452488700 units (the same as for the stone wool factory in Ecoinvent).		
Products			
Outputs to technosphere, products	**Amount**	**Unit**	**Allocation**
Hemp insulation factory {GLO}	1	p	100%
Inputs			
From technosphere, materials/fuels	**Amount**	**Unit**	**Comment**
Industrial machine, heavy, unspecified {GLO}| market for | Alloc Def, U	2.546E6	kg	Two third of the machinery required for stone wool
Conveyor belt {GLO}| market for | Alloc Def, U	1E4	m	Same as for stone wool
Building, hall {GLO}| market for | Alloc Def, U	8.4E3	m2	Same as for stone wool

Table 4. Input data for the Global condistions for hemp fibre separation process.

Process information			
Category type	Material		
Process identifier	ChaClass000037950000018		
Process name	Hemp fibre separation		
Geography	Global		
Date	2018-04-16		
Literature references	(Murphy & Norton, 2008)		
Collection method	Articles		
Allocation rules	Allocation based on economic values		
System description	This process represents the Global condition for fibre separation process. It includes the energy and the factory required to separate 4.4 kg hemp fibres.		
Products			
Outputs to technosphere, products	**Amount**	**Unit**	**Allocation**
Hemp fibre long {GLO}	1	kg	48.70%
Hemp fibre short {GLO}	3.3	kg	51.30%
Hemp dust {GLO}	0.22	kg	0%
Inputs			
From technosphere, materials/fuels	**Amount**	**Unit**	**Comment**
Hemp fibre {GLO}| market for	4.4	kg	Amount required to obtain 1 kg long hemp fibres.
Hemp insulation factory {GLO}	2.21E-10	p	
From technosphere electricity/heat	**Amount**	**Unit**	**Comment**
Electricity, low voltage {GB}| market for | Alloc Def, U	0.792	kWh	A third of the required electricity to separate 4.4 kg fibres.
Electricity, low voltage {DE}| market for | Alloc Def, U	0.792	kWh	A third of the required electricity to separate 4.4 kg fibres.

Electricity, low voltage {IT}| market for | Alloc Def, U	0.792	kWh	A third of the required electricity to separate 4.4 kg fibres.

Table 5. Input data for the Swedish conditions for hemp fibre separation process.

Process information			
Category type	Material		
Process identifier	ChaClass000037950000017		
Process name	Hemp fibre separation		
Geography	Sweden		
Date	2018-04-16		
Literature references	(Murphy & Norton, 2008)		
Collection method	Articles		
Allocation rules	Allocation based on economic values		
System description	This process represents the Swedish conditions for fibre separation process. It includes the energy and the factory required to separate 4.4 kg hemp fibres.		
Products			
Outputs to technosphere, products	**Amount**	**Unit**	**Allocation**
Hemp fibre long {SE}	1	kg	48.70%
Hemp fibre short {SE}	3.3	kg	51.30%
Hemp dust {SE}	0.22	kg	0%
Inputs			
From technosphere, materials/fuels	**Amount**	**Unit**	**Comment**
Hemp fibre {GLO}| market for	4.4	kg	Amount required to obtain 1 kg long hemp fibres.
Hemp insulation factory {GLO}	2.21E-10	p	
From technosphere, electricity/heat	**Amount**	**Unit**	**Comment**
Electricity, low voltage {SE}| market for | Alloc Def, U	2.376	kWh	The required electricity to separate 4.4 kg fibres.

Table 6. Input data for the Global conditions for hemp insulation production.

Process information			
Category type	Material		
Process identifier	ChaClass000037950000003		
Process name	Hemp insulation production		
Geography	Global		
Date	2018-04-10		
Literature references	(Murphy & Norton, 2008)		
Collection method	Articles		
Allocation rules	100 % of the emissions comes from the hemp insulation production		
System description	This process represents the Global conditions for hemp insulation production. The process includes all processes needed to produce hemp insulation from long hemp fibres (drying, blending, formation). The use of gas instead of electricity for the drying process is optional.		
Products			
Outputs to technosphere, products	**Amount**	**Unit**	**Allocation**
Hemp fibre insulation {GLO}	1	kg	100%

Inputs			
From technosphere, materials/fuels	**Amount**	**Unit**	**Comment**
Hemp fibre long {GLO}	0.88	kg	88% of the hemp insulation board consists of hemp fibre.
Polylactide, granulate {GLO}| market for | Alloc Def, U	0.09	kg	Used as binder and for stability. 9 % of the hemp insulation panel consists of PLA fibres.
Ammonium sulphate, as N {GLO}| market for | Alloc Def, U	0.03	kg	Fire retardant additive. 3% of the hemp insulation panel consists of ammonium sulphate.
Hemp insulation factory {GLO}	2.21E-10	p	Same as for stone wool
Inputs from technosphere (Electricity/heat)	**Amount**	**Unit**	**Comment**
Electricity, low voltage {GB}| market for | Alloc Def, U	0.953	kWh	A third of the required electricity according to (Murphy & Norton, 2008).
Electricity, low voltage {DE}| market for | Alloc Def, U	0.953	kWh	A third of the required electricity according to (Murphy & Norton, 2008).
Electricity, low voltage {IT}| market for | Alloc Def, U	0.953	kWh	A third of the required electricity according to (Murphy & Norton, 2008).
Heat, district or industrial, natural gas {GB}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Alloc Def, U	0	kWh	The use of gas is optional.
Heat, district or industrial, natural gas {DE}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Alloc Def, U	0	kWh	The use of gas is optional.
Heat, district or industrial, natural gas {IT}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Alloc Def, U	0	kWh	The use of gas is optional.

Table 7. Input data for the Swedish conditions hemp insulation production.

Process information	
Category type	Material
Process identifier	ChaClass000037950000012
Process name	Hemp insulation production
Geography	Sweden
Date	2018-04-10
Literature references	(Murphy & Norton, 2008)
Collection method	Articles
Allocation rules	100 % of the emissions comes from the hemp insulation production
System description	This process represents the Swedish conditions hemp insulation production. The process includes all processes needed to produce hemp insulation from long hemp fibres (drying, blending, formation). The use of gas instead of electricity for the drying process is optional.

Products			
Outputs to technosphere, products	**Amount**	**Unit**	**Allocation**
Hemp fibre insulation {SE}	1	kg	100%
Inputs			
From technosphere, materials/fuels	**Amount**	**Unit**	**Comment**
Hemp fibre long {SE}	0.88	kg	88% of the hemp insulation board consists of hemp fibre.
Polylactide, granulate {GLO}| market for | Alloc Def, U	0.09	kg	Used as binder and for stability. 9 % of the hemp insulation panel consists of PLA fibres.
Ammonium sulphate, as N {GLO}| market for | Alloc Def, U	0.03	kg	Fire retardant additive. 3% of the hemp insulation panel consists of ammonium sulphate.
Hemp insulation factory {GLO}	2.21E-10	p	Same as for stone wool
Inputs from technosphere (Electricity/heat)	**Amount**	**Unit**	**Comment**
Electricity, low voltage {SE}| market for | Alloc Def, U	2.47	kWh	The required electricity according to (Murphy & Norton, 2008) 2,47 or 0,15
Heat, district or industrial, natural gas {SE}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Alloc Def, U	0	kWh	The use of gas is optional (Murphy & Norton, 2008).

Table 8. Input data for the Global conditions packaging process of hemp insulation.

Process information			
Category type	Material		
Process identifier	ChaClass000037950000006		
Process name	Packaging process of hemp insulation		
Geography	Global		
Date	2018-03-22		
Literature references	Ecoinvent 3.0		
Collection method	-		
Allocation rules	100 % of the emissions comes from the packaging process of hemp insulation		
System description	This process represents the Global conditions packaging process of hemp insulation boards. The packaging process includes the same processes as the packaging of stone wool in Ecoinvent.		
Products			
Outputs to technosphere, products	**Amount**	**Unit**	**Allocation**
Hemp fibre insulation, packed {GLO}	1	kg	100%
Inputs			
From technosphere, materials/fuels	**Amount**	**Unit**	**Comment**
Hemp fibre insulation {GLO}	1	kg	
Acrylic dispersion, without water, in 65% solution state {GLO}| market for | Alloc Def, U	5.851E-3	kg	Part of the packaging process.

Corrugated board box {GLO}| market for corrugated board box | Alloc Def, U	9.86E-4	kg	Part of the packaging process.
Packaging film, low density polyethylene {GLO}| market for | Alloc Def, U	6.508E-3	kg	Part of the packaging process.
EUR-flat pallet {GLO}| market for | Alloc Def, U	0.0012379	p	Part of the packaging process.
Industrial machine, heavy, unspecified {GLO}| market for | Alloc Def, U	2.214E-6	kg	Part of the packaging process.
From technosphere, electricity/heat	**Amount**	**Unit**	**Comment**
Electricity, low voltage {GB}| market for | Alloc Def, U	1.03E-3	kWh	Electricity required for the packaging process.
Electricity, low voltage {DE}| market for | Alloc Def, U	1.03E-3	kWh	Electricity required for the packaging process.
Electricity, low voltage {IT}| market for | Alloc Def, U	1.03E-3	kWh	Electricity required for the packaging process.
Heat, district or industrial, natural gas {GB}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Alloc Def, U	5.08E-2	MJ	Heat required for the packaging process.
Heat, district or industrial, natural gas {DE}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Alloc Def, U	5.08E-2	MJ	Heat required for the packaging process.
Heat, district or industrial, natural gas {IT}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Alloc Def, U	5.08E-2	MJ	Heat required for the packaging process.

Table 9. Input data for the Swedish conditions packaging process of hemp insulation.

Process information			
Category type	Material		
Process identifier	ChaClass000037950000014		
Process name	Packaging process of hemp insulation		
Geography	Sweden		
Date	2018-04-10		
Literature references	Ecoinvent 3.0		
Collection method	-		
Allocation rules	100 % of the emissions comes from the packaging process of hemp insulation		
System description	This process represents the Swedish conditions packaging process of hemp insulation boards. The packaging process includes the same processes as the packaging of stone wool in Ecoinvent.		
Products			
Outputs to technosphere, products	**Amount**	**Unit**	**Allocation**
Hemp fibre insulation, packed {SE}	1	kg	100%
Inputs			
From technosphere, materials/fuels	**Amount**	**Unit**	**Comment**

Hemp fibre insulation {SE}	1	kg	
Acrylic dispersion, without water, in 65% solution state {GLO}| market for | Alloc Def, U	5.851E-3	kg	Part of the packaging process.
Corrugated board box {GLO}| market for corrugated board box | Alloc Def, U	9.86E-4	kg	Part of the packaging process.
Packaging film, low density polyethylene {GLO}| market for | Alloc Def, U	6.508E-3	kg	Part of the packaging process.
EUR-flat pallet {GLO}| market for | Alloc Def, U	1.238E-3	p	Part of the packaging process.
Industrial machine, heavy, unspecified {GLO}| market for | Alloc Def, U	2.214E-6	kg	Part of the packaging process.
From technosphere, electricity/heat	**Amount**	**Unit**	**Comment**
Electricity, low voltage {SE}| market for | Alloc Def, U	3.09E-3	kWh	Electricity required for the packaging process.
Heat, district or industrial, natural gas {SE}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Alloc Def, U	0.1524	MJ	Heat required for the packaging process.

Table 10. Input data for the Global condtitions for market-for hemp insulation.

Process information			
Category type	Material		
Process identifier	ChaClass000037950000008		
Process name	Market-for hemp insulation		
Geography	Global		
Date	2018-03-22		
Literature references	(Naturvårsverket, 2017b)		
Collection method	Reports		
Allocation rules	100 % of the emissions comes from the market for hemp insulation		
System description	This process represents the Global conditions for market-for hemp insulation. The process includes transportation of the packed hemp insulation to Gothenburg, Sweden. The distance is an average of the distances to Italy, Germany and the UK.		
Products			
Outputs to technosphere, products	**Amount**	**Unit**	**Allocation**
Hemp fibre insulation, packed {GLO}	1	kg	100%
Inputs			
From technosphere, materials/fuels	**Amount**	**Unit**	**Comment**
Hemp fibre insulation, packed {GLO}	1	kg	
Transport, freight, lorry, unspecified {GLO}| market for | Alloc Def, U	780	kgkm	The global product will be transported in average 1600 km. Allocation of transportation mode is based on Naturvårdsverket's data for transportation modes imported to Sweden. 49% road.

Transport, freight train {GLO}| market group for | Alloc Def, U	297	kgkm	The global product will be transported in average 1600 km. Allocation of transportation mode is based on Naturvårdsverket's data for transportation modes imported to Sweden. 19% rail.
Transport, freight, inland waterways, barge {GLO}| market for | Alloc Def, U	522	kgkm	The global product will be transported in average 1600 km. Allocation of transportation mode is based on Naturvårdsverket's data for transportation modes imported to Sweden. 33% water.

Table 11. Input data for the Swedish conditions for market-for hemp insulation.

Process information			
Category type	Material		
Process identifier	ChaClass000037950000015		
Process name	Market-for hemp insulation		
Geography	Sweden		
Date	2018-04-10		
Literature references	(Transportstyrelsen, 2016)		
Collection method	Reports		
Allocation rules	100 % of the emissions comes from the market for hemp insulation		
System description	This process represents the Swedish conditions for market-for hemp insulation. The process includes transportation of the packed hemp insulation to Gothenburg from Skövde.		
Products			
Outputs to technosphere, products	**Amount**	**Unit**	**Allocation**
Hemp fibre insulation, packed {SE}	1	kg	100%
Inputs			
From technosphere, materials/fuels	**Amount**	**Unit**	**Comment**
Hemp fibre insulation, packed {SE}	1	kg	
Transport, freight, lorry, unspecified {GLO}| market for | Alloc Def, U	107	kgkm	The Swedish product will be transported in average 160 km. Allocation of transportation mode is based on Transportstyrelsen's data for transportation modes imported to Sweden. 67% water.
Transport, freight train {GLO}| market group for | Alloc Def, U	53	kgkm	The Swedish product will be transported in average 160 km. Allocation of transportation mode is based on Transportstyrelsen's data for transportation modes imported to Sweden. 33% water.

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Appendix V: Processes responsible for more than 1% of the total emissions

In this appendix, the processes responsible for more than 1% of the total GWP of hemp insulation for the base scenario both for the Swedish and the Global conditions, are presented. Table 1 below presents the activities of the Global conditions and Table 2 of the Swedish conditions.

Table 1. Processes responsible for more than 1% of the total GWP of hemp insulation for the Global conditions. The column furthest to the left present which activities, of the activities presented in subchapter 4.4.1, the process is a part of.

Global conditions			
Activity	Processes	Unit	Total
	Total GWP of all processes	kg CO_2e	3.61
Ammonium sulphate/ Urea as N/ PLA	Ammonia, liquid {RoW}| ammonia production, steam reforming, liquid | Alloc Def, U	kg CO_2e	0.05
Electricity	Electricity, high voltage {DE}| electricity production, hard coal | Alloc Def, U	kg CO_2e	0.21
	Electricity, high voltage {DE}| electricity production, lignite | Alloc Def, U	kg CO_2e	0.43
	Electricity, high voltage {DE}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Alloc Def, U	kg CO_2e	0.06
	Electricity, high voltage {GB}| electricity production, hard coal | Alloc Def, U	kg CO_2e	0.56
	Electricity, high voltage {GB}| electricity production, natural gas, combined cycle power plant | Alloc Def, U	kg CO_2e	0.05
	Electricity, high voltage {GB}| electricity production, natural gas, conventional power plant | Alloc Def, U	kg CO_2e	0.10
	Electricity, high voltage {IT}| electricity production, hard coal | Alloc Def, U	kg CO_2e	0.20
	Electricity, high voltage {IT}| electricity production, natural gas, combined cycle power plant | Alloc Def, U	kg CO_2e	0.07
	Electricity, high voltage {IT}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Alloc Def, U	kg CO_2e	0.08
	Electricity, high voltage {IT}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Alloc Def, U	kg CO_2e	0.07
	Electricity, high voltage {IT}| heat and power co-generation, oil | Alloc Def, U	kg CO_2e	0.05
PLA/Packaging	Hard coal {CN}| mine operation | Alloc Def, U	kg CO_2e	0.05
	Hard coal {RoW}| mine operation | Alloc Def, U	kg CO_2e	0.18
	Hard coal {WEU}| mine operation | Alloc Def, U	kg CO_2e	0.05
	Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Alloc Def, U	kg CO_2e	0.05
Other	Other processes	kg CO_2e	1.35

Table 2. Processes responsible for more than 1% of the total GWP of hemp insulation for the Swedish conditions. The column furthest to the left present which activities, of the activities presented in subchapter 4.4.1, the process is a part of.

Swedish conditions			
Activity	Processes	Unit	Total
	Total GWP of all processes	kg CO_2e	1.00
Combine harvesting	Combine harvesting {RoW}| processing | Alloc Def, U	kg CO_2e	0.03
	Pig iron {GLO}| production | Alloc Def, U	kg CO_2e	0.01
PLA	Polyethylene, low density, granulate {RoW}| production | Alloc Def, U	kg CO_2e	0.01
PLA/Packaging	Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Alloc Def, U	kg CO_2e	0.04
	Heat, district or industrial, natural gas {RU}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Alloc Def, U	kg CO_2e	0.03
	Heat, district or industrial, natural gas {RoW}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Alloc Def, U	kg CO_2e	0.01
	Hard coal {RoW}| mine operation | Alloc Def, U	kg CO_2e	0.01
	Hard coal {CN}| mine operation | Alloc Def, U	kg CO_2e	0.04
Electricity Sweden	Electricity, medium voltage {SE}| market for | Alloc Def, U	kg CO_2e	0.01
	Electricity, high voltage {SE}| heat and power co-generation, oil | Alloc Def, U	kg CO_2e	0.01
	Electricity, high voltage {SE}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Alloc Def, U	kg CO_2e	0.01
	Electricity, high voltage {SE}| heat and power co-generation, hard coal | Alloc Def, U	kg CO_2e	0.01
	Electricity, high voltage {SE}| electricity production, peat | Alloc Def, U	kg CO_2e	0.01
	Electricity, high voltage {SE}| electricity production, hydro, reservoir, non-alpine region | Alloc Def, U	kg CO_2e	0.02
	Electricity, for reuse in municipal waste incineration only {SE}| treatment of municipal solid waste, incineration | Alloc Def, U	kg CO_2e	0.03
Ammonium sulphate/ Urea as N/ PLA	Ammonia, liquid {RoW}| ammonia production, steam reforming, liquid | Alloc Def, U	kg CO_2e	0.05
	Ammonia, liquid {RoW}| ammonia production, partial oxidation, liquid | Alloc Def, U	kg CO_2e	0.01
Other	Electricity, high voltage {IN}| electricity production, hard coal | Alloc Def, U	kg CO_2e	0.02
	Other processes	kg CO_2e	0.59
	Tillage, ploughing {RoW}| processing | Alloc Def, U	kg CO_2e	0.03