# A Life Cycle Assessment of the Environmental Impacts of Cross-Laminated Timber

David Panojevic & Emma Svensson

LUNDS
UNIVERSITET

Lund University, LTH Faculty of Engineering
Division of Construction Management

Telephone number: +46 46 2227421
Website: www.bekon.lth.se

ISRN LUTVDG/TVBP-19/5580-SE

# Sammanfattning

För att bidra till minskad global uppvärmning behöver den negativa miljöpåverkan från nya byggnader och den bebyggda miljön reduceras. Miljöcertifiering av byggnader, såsom Miljöbyggnad och DGNB, infördes som åtgärd för att bidra till mer ekonomiskt, miljömässigt och socialt hållbara byggnader. Den vetenskapliga studien undersöker korslimmat massivträs miljöpåverkan och skillnaderna samt effekterna vid livscykelanalys av byggnadsmaterial i Miljöbyggnad 3.0 och DGNB. Studien ämnar även att studera effekterna av kolinlagring i korslimmat massivträ.

Byggsektorn vill minska miljöpåverkan från byggmaterial och överväger att öka användningen av alternativa byggmaterial, såsom korslimmat massivträ. Korslimmat massivträ anses vara ett mångsidigt, förnyelsebart och miljömässigt hållbart konstruktionsmaterial. Om hänsyn tas till kolinlagring, atmosfäriskt kol som lagras i biomassa, minskar växthusgasutsläppen kraftigt för korslimmat massivträ.

För att begränsa resursförbrukningen är det nödvändigt att anamma en cirkulär strategi avseende byggmaterial och byggavfall. Avfallshantering och avfallsplanering är viktigt för en byggnads sammanlagda miljömässiga prestanda. Det finns tre typer av avfallshantering för byggnadsmaterial, vilket generellt kan definieras som återanvändning, återvinning eller bortskaffande av avfall. Avfallshantering har stor inverkan på byggnadsmaterials totala miljöpåverkan. Möjliga avfallsscenario för korslimmat massivträ är återanvändning, delvis återvinning och förbränning med eller utan energiåtervinning. Det mest miljömässigt fördelaktiga avfallsscenariot för korslimmat massivträ är återanvändning medan det värsta är förbränning utan energiåtervinning.

Korslimmat massivträ ger de mest miljövänliga värdena för fem av de sju bedömda miljöpåverkanfaktorerna i DGNB:s livscykelanalys, i jämförelse med stål och betong. Den globala uppvärmningspotentialen är lägre för korslimmat massivträ, oavsett om kolinlagring ingår, för majoriteten av de möjliga avfallsscenarierna jämfört med stål och betong.

Identifierade skillnader mellan Miljöbyggnad 3.0 och DGNB:s livscykelanalys är komplexiteten, antalet inkluderade livscykelfaser och vilka miljöpåverkansfaktorer som bedöms. Om kolinlagring tas hänsyn till i en livscykelanalys minskar den globala uppvärmningspotentialen för korslimmat massivträ drastiskt.

**Nyckelord:** Livscykelanalys, Korslimmat massivträ, Miljöbyggnad, DGNB, Miljöpåverkan, End of life, Cirkulär ekonomi

# Abstract

Negative environmental impacts generated by new buildings and the built environment needs to be reduced in order to contribute to mitigation of anthropogenic global warming. Sustainable building certifications such as Miljöbyggnad and DGNB was introduced as a measure to transition into more sustainable buildings. The research study explores the environmental impacts of cross-laminated timber and the differences and effects in life cycle assessment of construction material in Miljöbyggnad 3.0 and DGNB. In addition, to study the impact of carbon sequestration for cross-laminated timber.

The construction sector is taking measures to reduce environmental impacts from construction materials and consider increased use of alternative construction materials, such as cross-laminated timber. Cross-laminated timber is considered a versatile, renewable and sustainable structural construction material. The global warming potential is significantly reduced for cross-laminated timber if carbon sequestration, atmospheric carbon being stored in bio-mass, is accounted for.

To minimize resource consumption, a circular approach regarding construction material and construction waste is necessary. Waste management is important for the overall environmental sustainability performance of buildings. There are three types of waste disposal, generally defined as either reuse, recycling or disposal. The environmental impacts for construction materials heavily depend on the chosen waste disposal scenario. Regarding cross-laminated timber, possible waste disposal scenarios is reuse, partial recycling and incineration with or without energy recovery. The most environmentally beneficial waste disposal scenario for cross-laminated timber is reuse while the worst is incineration without energy recovery.

Cross-laminated timber shows the most environmental beneficial values for five out of the seven assessed environmental impacts in the DGNB life cycle assessment tool, compared to steel and concrete. The global warming potential is lower for cross-laminated timber regardless if carbon sequestration is included, for most waste disposal scenarios compared to steel and concrete.

Identified differences in the life cycle assessments between Miljöbyggnad 3.0 and DGNB are the level of complexity, the number of included life cycle phases and assessed environmental impacts. An inclusion of carbon sequestration in a life cycle assessment will drastically decrease the global warming potential for cross-laminated timber.

**Keywords:** Life cycle assessment, Cross-laminated timber, Miljöbyggnad, DGNB, Environmental impact, End of life, Circular economy

# Acknowledgements

This master's thesis was conducted during the fall semester of 2018, as the final part of our Master of Science in Engineering, Civil Engineering. The thesis equals 30 ECTS and was completed in January 2019. The thesis was supervised by LTH Faculty of Engineering, Division of Construction Management at Lund University, Sweden. The thesis was made in collaboration with C.F. Møller in Denmark.

We would like to thank C.F. Møller for their guidance and for providing essential information to the master's thesis. Furthermore, we would like to sincerely thank Rob Marsh, Head of Sustainability at C.F. Møller, for all insightful meetings, support, inspiration and knowledge within the research field.

We would like to thank Urban Persson at the Division of Construction Management for being our examiner. We would also like to thank our supervisor Stefan Olander at the Division of Construction Management for valuable insights, interesting discussions and feedback.

Lund, January 2019

David Panojevic Emma Svensson

# List of abbreviations

ADPE- Abiotic depletion potential elements
ADPF- Abiotic depletion potential fossil fuels
AP- Acidification potential
BBSR- Federal Institute for Research on Building, Urban Affairs and Spatial Development
BREEAM- Building Research Establishment Environmental Assessment Method
CASBEE- Comprehensive Assessment System for Built Environment Efficiency
C&D- Construction and Demolition
CFC- Chlorofluorocarbon
CLT- Cross-laminated timber
CSR- Corporate Social Responsibility
DGNB- Deutsche Gesellschaft für Nachhaltiges Bauen
DK-GBC- Green Building Council Denmark
EEA- European Economic Area
EOL- End of life
EP- Eutrophication potential
EPD- Environmental Product Declaration
ESUCO- European Sustainable Council Construction Database
FSC- Forest Stewardship Council
GHG- Greenhouse gas
G-SEED- Green Standard for Energy and Environmental Design
GTP- Global temperature change potential
GWP- Global Warming Potential
HWP- Harvested Wood Product
ISO- International Organization for Standardization
LBC- Living Building Challenge
LCA- Life cycle assessment
LCC- Life cycle cost
LEED- Leadership in Energy and Environmental Design

MB 3.0- Miljöbyggnad 3.0
ODP- Ozone depletion potential
PCR- Product Category Rules
PEF- Product Environmental Footprint
POCP- Photochemical ozone creation potential
R1 SGBC- Respondent one, Sweden Green Building Council
R2 DK-GBC- Respondent two, Green Building Council Denmark
R3 C.F. Møller- Respondent three, C.F. Møller
sfB- Samarbetskommittén för Byggnadsfrågor
SBi- Danish Building Research Institute
SGBC- Sweden Green Building Council
UNFCC- United Nations Framework Convention on Climate Change
USGBC- U.S. Green Building Council
VOC- Volatile organic compound

# Table of contents

# Chapter 1 Introduction

## 1.1 Background

Taking immediate action against climate change is urgent and essential for present and future generations and their ability to maintain a sustainable existence. The Paris agreement is a climate agreement between all member states supporting the United Nations Framework Convention on Climate Change (UNFCC). The central aim within the agreement is to raise awareness for policymakers and assuring urgent action against climate change. The Paris agreement concluded a 2ºC global temperature increase limit of global warming and preferably not exceeding 1,5ºC, above pre-industrial levels (United Nations 2015).

A 1, 5ºC global temperature increase will affect the planet in numerous ways. The industry, building and transport sector are responsible for a large amount of anthropogenic greenhouse gases. The different sectors therefore carry a significant responsibility in limiting their emissions and preventing the progressing global warming. The Intergovernmental Panel on Climate Change (IPCC) (2018) highlights behavioral changes and technical developments as central instruments for limiting the anthropogenic global warming.

Cellura, Guarina, Longo and Tumminia (2018) depicts the building sector as one of the most influential sectors regarding occupation and wealth. However, the sector is also one of the greatest contributors to greenhouse gas emissions and energy use. In 2017, the building sector accounted for 30% of total global final-energy use. End-users such as industry, agriculture and households are accountable for 55% of global electricity demand and 25% of energy-related carbon dioxide emissions (International Energy Agency 2018). Regarding the previous reasons, the building sectors contribution will be essential for balancing low carbon emissions and economic sustainability whilst not exceeding the increase of 2ºC global average temperature (Cellura et al. 2018).

It is important to focus on both new buildings and the existing built environment. Adaptation and systematic transition towards reducing emissions that entails global warming from the built environment is needed, in urban as well as in rural areas. This can be achieved with more regulations and effective planning (IPCC 2018). The building sector has the potential to contribute to the UN sustainable development goal, *Climate Action: Take urgent action to combat climate change and its impacts* (United Nations 2018a). To achieve the aim of reducing emissions, technical innovations may work as a promotor (Mundaca, Ürge-Vorsatz & Wilson 2018).

Initiatives proposed to reduce the built environment's global warming impact are stricter building regulations and green standards, carbon pricing and labelling programs (Mundaca, Ürge-Vorsatz & Wilson 2018). Monno and Conte (2015) highlight the importance of developing approaches and methods to integrate economic, social and environmental aspects of sustainability in the built environment. There are many different sustainable building certifications available and different certification systems focus and emphasize different aspects of sustainability.

There has been a shift of focus regarding sustainability for buildings, from operational energy towards the production energy required to produce construction materials (Hafner 2014). Life cycle assessments are central in sustainable building certifications such as Miljöbyggnad and the Danish version of DGNB. Life cycle assessments are used considering construction material evaluation for buildings. This may result in higher demands on the manufacturing of construction material regarding transparency. Conducting a life cycle assessment requires information about some or all of the construction material's environmental impacts throughout the different life cycle phases of the product. This information may be presented in an environmental product declaration (Hafner 2014).

The building sector has started to explore alternative construction materials, which can mitigate climate change, mainly by reducing or storing carbon emissions. According to the Forest Products Association of Canada (2009), wood can contribute to both critical tasks, as forest products can sequestrate atmospheric carbon. An application in the building sector, regarding wood, is cross-laminated timber. Cross-laminated timber can serve as a structural construction material comparable with steel and concrete, being applicable as a structural construction material in multi-storey buildings. However, cross-laminated timber's potential within the construction sector needs to be explored further.

## 1.2 Purpose and research aims

The overall objective is to identify the environmental impacts of cross-laminated timber in life cycle assessment tools. In addition, to identify which environmental impacts that are assessed within the sustainable building certification systems Miljöbyggnad and DGNB.  The objective is also to assess the effects of including carbon sequestration in life cycle assessment tools for cross-laminated timber. The research will hopefully contribute with knowledge to the very important and current need of more sustainable construction materials. Moreover, shed light on the effects of life cycle assessment tools and further develop the understanding of finding true sustainable alternative construction materials for the construction sector. The research study aims to contribute with knowledge regarding improvements of traditional construction materials. In addition, the aim with the research study is to increase the collaboration between civil engineers and architects.

## 1.3 Research questions

- What are the differences in life cycle assessment evaluation of construction materials in Miljöbyggnad 3.0 and DGNB?
- What are the effects of evaluating a certain way in life cycle assessments regarding cross-laminated timber?
- What are the environmental impacts of cross-laminated timber, taking account of carbon sequestration?
- How can life cycle assessment tools be designed to better attend the environmental impacts from structural construction materials, in terms of included life cycle phases?

## 1.4 Focus and delimitations

The research study focuses on assessing the environmental impacts from the construction material cross-laminated timber. To be able to get an idea of which impacts that are regarded as the most important ones, the included life cycle phases in environmental building certifications are identified. The main focus is on life cycle phases that are directly related to the structural construction materials, regarding environmental impacts. The research study does not aim to determine if the environmental impact values are high or low for cross-laminated timber. A comparison is conducted between the identified environmental impacts for cross-laminated timber with the environmental impacts for other traditional construction materials.

The environmental impacts are related to the load-bearing construction and foundation. Consequently, non-load-bearing structures, insulation, windows, doors and so on is not included in the research study.  It is strongly advised that the material choice in a building is not solely based on the obtained results regarding material choice in this study. Regarding material choice, other factors than environmental impacts must also be considered, such as fire safety, moisture safety, acoustic properties, load-bearing properties etcetera.

The research study is limited to study construction material indicators in sustainable building certifications. The research study only focuses on Miljöbyggnad 3.0 and the Danish version of DGNB. The environmental product declarations for different construction materials are chosen based upon which manufacturers that are potential manufacturers for Swedish buildings, with available environmental product declarations. As a result, the environmental impacts for the construction materials is based solely on specific data from the chosen environmental product declarations and not an average of different environmental impacts from several environmental product declarations for the construction material. The research study is limited to only assess and compare evaluation criteria related to environmental sustainability in Miljöbyggnad and DGNB.

## 1.5 Thesis outline

Apart from the introductory chapter one and two, where the research questions and method is presented, chapter three through twelve presents the theoretical foundation on which the research study is based on. Chapters thirteen through sixteen presents the empirical research conducted based on the research questions. Finally, chapter seventeen through nineteen discusses and analyses the obtained results and compares it to the theoretical framework. Additionally, recommended future research which can increase knowledge within the research field is presented in chapter twenty.

# Chapter 2 Method

The research process is illustrated in figure 2.1 below, as well as the different subcategories of the research. Each of the below stated research categories will be further assessed in this chapter.

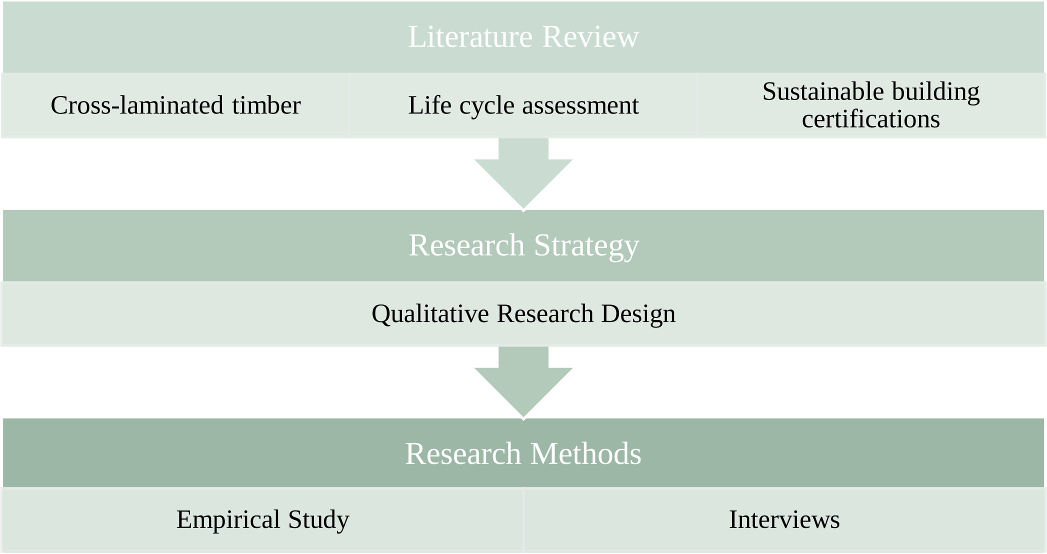


*Figure 2.1: Illustrates the research method for the research study.*

## 2.1 Literature review

The purpose of the literature review is to present the existing theory within the chosen field of research. The literature review presents definitions as well as relevant literature that highlights the proposed research questions (Svenning 2003). The literature review creates a theoretical framework which serves as a foundation for the research study as well as a greater knowledge base for the authors. The literature review serves as a platform in which the results from the research methods can be put in perspective and lead to valuable discussions covering the literature subjects.

The cited literature within the research study is mainly based on scientifically published material available in the database LUBsearch via Lund University. Some topics within the literature review have limited scientifically published material whereas older sources of information have been used. Scientific articles, academic literature, EU directives, environmental products declarations and standards by the International Organization for Standardization outline the theoretical foundation.

## 2.2 Research strategy

A strategy is necessary to be able to conduct research of any kind. The strategy should focus on the research methods required to be able to measure, get results and answer the research questions proposed. The methods are different and chosen based on the aim of the study. To get desired results and minimize future issues, the strategy and method for the research should be planned and decided in advance (Svenning 2003). A research study can be characterized by either deductive or inductive thinking. The inductive approach is often used in qualitative research, where new theories and conclusions in general is developed throughout the research process as a result of the studied phenomenon. The deductive research approach on the other hand, aims to test and challenge theories that are already generally accepted (DePoy & Gitlin 1999). The strategy chosen for this research study is of a qualitative nature, relying on observations and deductions from different types of data. The aim of analyzing results deriving from different sources is to highlight the complexity and find common ground related to a specific subject. In this research study different types of research methods have been used, relying on diverse types of data. An inductive approach is used for the research study.  All data based on life cycle assessment tools, values from environmental product declarations and interviews have been assessed qualitatively, suggesting a higher weighing of the quality of the data rather than its statistical verification.

### Qualitative and quantitative method

Quality can be related to certain properties of high standard while quantity can be related to size or amount. Cause and effect can be identified through a quantitative or a qualitative approach (Watt Boolsen 2007). The qualitative research method is focusing on meaning and interpretation, while the quantitative research method requires connections to be statistically verifiable. Quantities can be present when conducting a qualitative research as well, for instance with results. However, the quantity itself is not what is important, rather the interpretation of the quantity. The qualitative method is concentrated on the interpretation of the research. The interpretations are limited to the identified phenomenon within the research boundaries, with the aim to contribute to the development of knowledge and preferably to the general conception of a phenomenon (Alvehus 2013). One direct derivation of the above stated facts regarding quantitative datasets is the limited amount of environmental product declarations used in the research study. As the research study aims to highlight the meaning and interpretation of a specific phenomenon, a quantitative dataset of environmental product declarations is not necessary. However, it is worth to mention that, any variation of used environmental product declarations in the research study will possibly affect the obtained results. However, the interpretation and qualitative analysis will most likely not differ based on varying environmental product declarations. A quantitative research approach would yield more statistically solid findings, whereas the results would be based on a quantity of environmental product declarations that represent a larger variance of values.

### Qualitative and quantitative data

The data for the research varies, depending on which method is being used. Quantitative data is used if the method is quantitative and respectively are qualitative data used when the research approach is qualitative (Watt Boolsen 2007). Quantitative data are, simplified, often presented as numbers and illustrates for instance collected data about age, education and gender among a population (Svenning 2003). Qualitative data on the other hand is more sensible and can consist of for example an interview, a picture or a book (Watt Boolsen 2007).

In the research study different types of data has been used for different research methods:

*Table 2.1: Origin and data type for each research method.*

| **Research method** | **Data set** | **Type of data** |
|---|---|---|
| **Empirical study** | • Life cycle assessment tools in Miljöbyggnad 3.0 and DGNB<br>• Environmental product declarations | Excel sheets and declared values (quantitative) |
| **Interviews** | Interview notes | Text analysis (qualitative) |

## 2.3 Research method

The main purpose of using different research methods is the idea to illustrate a problem with solutions through different points of view. In the research study, the initial goal was to conduct research based on three research methods. Firstly, an observatory walkthrough of the life cycle assessment tools available in Miljöbyggnad 3.0 and DGNB. The life cycle assessment tool analysis would later serve as platform and knowledge-base when using the life cycle assessment tools for a certain case study.

The case study was supposed to involve specific building criteria regarding material consumption and dimensions for different building types made of cross-laminated timber, concrete and steel. The second research method, case study, was supposed to illustrate the applications from the life cycle assessment tools by using a real case study, evaluating environmental impacts based on varying building types and construction materials. However, the data for this type of research was insufficient and thus excluded from the research study.

The above-mentioned scenario led the research study to weigh the empirical study based on environmental product declarations higher and rely on other data related to material usage. The final part of the empirical study was conducted by using interviews as research method.

### 2.3.1 Empirical study

Empirical evidence consists of the data or information about a phenomenon that is required to conduct an analysis. It is important to thoroughly consider the phenomenon before selecting a certain object to study and to recognize what is in fact being studied. The empirical evidence must be aligned with the research purpose and research questions (Alvehus 2013).

The empirical research methods aim to provide empirical evidence that covers the formulated research questions. By using different types of empirical assessments, the ways to describe and possibly answer the research questions multiplies. Since the research questions are complex and cover intertwined areas that all affect each other. A qualitative approach, evaluating different aspects of the research questions by using different methods, proposedly yield a greater understanding of the subject in question.

The first part of the empirical analysis was conducted by studying the life cycle assessment tools available in DGNB and Miljöbyggnad 3.0, regarding structural construction materials. For Miljöbyggnad 3.0 the life cycle assessment tool covers the structural material indicator fifteen. The method includes a step-by-step walkthrough of the two life cycle assessment tools, highlighting differences and similarities regarding evaluation aspects and complexity.

The second part of the empirical analysis studies the environmental impact of cross-laminated timber, steel and concrete as structural construction materials based on values derived from environmental product declarations. Based on the values for different environmental impacts for each life cycle stage, calculations were made to illustrate what the effects of including certain life cycle stages in Miljöbyggnad 3.0 and DGNB will be. There are some available environmental product declarations from different manufacturers for each of the structural construction materials. For the research study, one demarcation is the limited amount of studied environmental product declarations. The most complex research conducted regarding inclusion of life cycle phases follows the DGNB criteria for life cycle assessment, which include life cycle production stage, end of life stage phase C3 and C4 as well as the benefits and loads beyond the system boundary stage. The assessment is done while excluding use stage. This is to limit the research scope and only assessing the direct implications of the structural construction materials environmental impact.

The third part of the research study is to compare different structural construction materials environmental impact. It is important to evaluate the same functional performance of different structural construction solutions within a building system boundary. However, different materials have different performance in varying construction criteria, which substantially limits the evaluation possibilities. Basically, an evaluation of different structural construction material types, should be based on evidence that prove that all different scenarios result in the same functional performance for each structural construction material. There is no claim that this research study compares the same functional performance of the different structural construction materials. A further description of the material usage ratios used in the research is presented in chapter 11.3 Material usage comparison, which also mention the functional comparability between the different structural construction materials.

There is no current available standardized procedure regarding the complexity or content of environmental product declarations, which concludes the following extraction of environmental product declarations for the different structural construction materials:

*Table 2.2: Presentation of used environmental product declarations validity and end of life scenarios used in the research.*

| | **CLT** | **Steel** | **Concrete** |
|---|---|---|---|
| **A1-A3 Production stage** | Stora Enso EPD | Bauform stahl EPD | EPD-Norge EPD |
| **A4 Transport** | Stora Enso EPD | X | X |
| **C3 Waste processing & C4 Disposal** | Stora Enso EPD | Bauform stahl EPD | Institut Bauen und Umwelt EPD |
| **D Benefits and loads beyond the system boundary stage** | Stora Enso EPD | Bauform stahl EPD | Institut Bauen und Umwelt. EPD |
| **Valid until** | 2022 | 2018 | 2021/2018 |
| **End of Life** | • Reuse 100%<br>• Recycling 100%<br>• Incineration 100% | • Reuse and recycling of structural steel at End of Life | • Reuse of demolished concrete + Carbonisation after building |
| **Source** | Stora Enso (2017) | Bauformstahl (2013). | EPD-Norge (2016a) + Institut Bauen und Umwelt. (2013a-f) |

Regarding cross-laminated timber, an environmental product declaration from Stora Enso is used for all life cycle stages included in the research, with values regarding life cycle stage *A4 Transport*. There are three types of end of life scenarios available for cross-laminated timber in the studied environmental product declaration, namely reuse, recycling and incineration.

For steel, an environmental product declaration for *Structural steel: Sections and plates* are used, which is not an environmental product declaration that fits ideally with the research. However, it provides some basis for the environmental impact from structural steel. There is one end of life scenario available which is combined reuse and recycling. This end of life scenario is a general scenario which covers many different ratios of reuse and recycling as an average value.

The environmental product declaration used to describe the life cycle for concrete, stems from five environmental product declarations with different concrete qualities. Production stage phases derives from one pre-manufactured concrete wall. The life cycle phases C3-C4 in the end of life stage and life cycle stage *D Benefits and loads beyond the system boundary*, derives from concrete in different strength grades which all have the same values for the end of life scenario. The end of life scenario is reuse of demolished concrete as well as some carbonisation of the demolished concrete, which uptakes some carbon dioxide.

Finally, a sensitivity analysis of cross-laminated timber’s life cycle phase *A4 Transport* is studied. Based on a steel environmental product declaration from Sävsjö in Sweden, the distance from factory to construction site is assumed to be 250 kilometres. Based on average distances to concrete manufacturers in Sweden, 50 kilometres is assumed to be the distance from manufacturing of concrete to construction site. The distance from cross-laminated timber’s manufacturing in Austria to Sweden is approximately 1890 kilometres (Stora Enso 2017). Depending on where in Sweden the construction site is located, the transportation distance will vary. However, the transport analysis only aims to highlight the drawbacks of the inclusion of life cycle phase *A4 Transport* for cross-laminated timber.

### 2.3.2 Interviews

It is common to have interviews as a part of the empirical study when using a qualitative research method. There are multiple ways to conduct an interview, for example using video, audio, e-mail or meetings in person. An interview can be short or extensive and is used in different ways in the study, depending on the purpose with the interview. Interviews are subjective and highly dependable on the interviewee's personal opinions (Alvehus 2013). The questions in a qualitative interview is often rather simple while the answers are extensive and often complex. In a qualitative interview study, it is not the interviewees' individual properties that is interesting, but different patterns that can be identified in their answers. A qualitative interview study should be used if the aim is to understand the interviewees' way of thinking and to give the interviewees a possibility to explain their opinions. If the study on the other hand aims to know the quantity of a certain aspect among a population, the quantitative interview study is recommended. The interview method should be chosen aligned with the theoretical framework of the research as well as the research questions (Trost 2005).

For the research study, qualitative interviews have been conducted with the aim to feature differences and similarities based on the varying professions and placements nationally between the respondents. Due to the respondents' professional positions and substantial knowledge, ideas and complex answers deriving from the interviews serve as important input in the discussion regarding the research questions and the research study's overall scope.

#### Interviewee selection

The choice of interviewees is important, for both qualitative and quantitative research studies. For quantitative interviews the choice of interviewees should often be a part of a homogenous population and statistical representative. For qualitative interviews on the other hand, the interviewees may be heterogeneous rather than homogeneous. The choice of people to interview should however not be too diverse and within the studies limitations. The number of interviews required for a qualitative study varies but tend to not exceed ten in most cases. Naturally, it is important to prioritize quality over quantity regarding qualitative interview studies (Trost 2005).

In the research study, interviewees were selected by their positions within green building councils in Sweden and Denmark as well as within a Danish architectural firm. The selection was made to present different, alternatively the same approaches and ideas corresponding to the interview questions. The interviewees aim to reflect different stakeholders in the built environment, covering Sweden Green Building Council, Green Building Council Denmark and the sustainability department at C.F. Møller in Denmark.

*Table 2.3: Presentation of the different interview respondents.*

| **Abbreviation** | **Profession/role and placement** | **Type of interview** | **Interview questions** |
|---|---|---|---|
| R1 SGBC | Director Miljöbyggnad, Sweden Green Building Council, Stockholm | Telephone | Appendix A |
| R2 DK-GBC | Technical director, Green Building Council Denmark, Copenhagen | In person | Appendix A |
| R3 C.F. Møller | Head of sustainability, architect, C.F. Møller, Copenhagen | In person | Appendix B |

### Structured, unstructured and semi-structured interview

An interview can be arranged in three different ways, namely as structured, unstructured or semi-structured interview. The structured interview contains predetermined questions and sometimes even proposed answers. The structured interview has a lot in common with a survey. Since the structured interview is meticulously planned, the interview can be held short with limited opportunity for spontaneity. Hence, several interviews can take place with various respondents in a shorter amount of time compared to the other interview arrangements.

The unstructured interview does not include any predetermined questions and it focuses on keeping a conversation about a certain theme. The semi-structured interviews are based on themes and open questions and does not lead the interviewee a certain direction by for example suggesting the answers. It is essential for the interview to keep an open dialogue and go off the script and ask follow-up questions (Alvehus 2013).

For the research study a semi-structured interview was designed to concentrate the interviews to specific subjects, whilst not limiting the specific answers and maintaining a discussion concerning the interview questions. For the qualitative research approach a semi-structured interview was the most apt approach in preserving the qualitative perspective on pursuing answers to complex questions. Any type of over-structuring would delimit the complexity of answers, thus reducing the overall performance of the interviews.

### Standardization and interview structure

If the interview questions are identical regardless of the number of interviews that is conducted, the level of standardization is high. In a quantitative interview study, the standardization is normally high whereas in a qualitative interview study, the level of standardization tends to be low. When the standardization is low, the interview becomes dynamic and the opportunity to ask follow-up questions or changing the order of the questions is common. If the interview questions already have predefined answers for the interviewee to choose from, the interview is structured. On the other hand, if the questions do not have answer options the interviewee is the one who defines what kind of structure the answer gets and consequently the interview is unstructured. If the interview has answer options, the interview is likely to be of quantitative nature. However, this does not exclude elements of structure for a qualitative interview overall, since they are structured in the aspect that they focus around one predefined theme or subject and not several (Trost 2005).

The standardization of interviews conducted with the representatives from Sweden Green Building Council and Green Building Council Denmark is high, whereas the interview questions are the same. The aim is to highlight variances in the answers between the interviewees and the green building councils in Sweden and Denmark. The interview conducted with the representative from the architectural firm C.F. Møller is somewhat different, taking a slightly different approach to the interview questions.

## Qualitative interview phases

According to Kvale (1996) an interview can be divided into seven interview phases. The phases are somewhat integrated and often follows a determined chronological order. The same systematic approach was conducted for the research study, following the same interview phases as shown in figure 2.2 below:

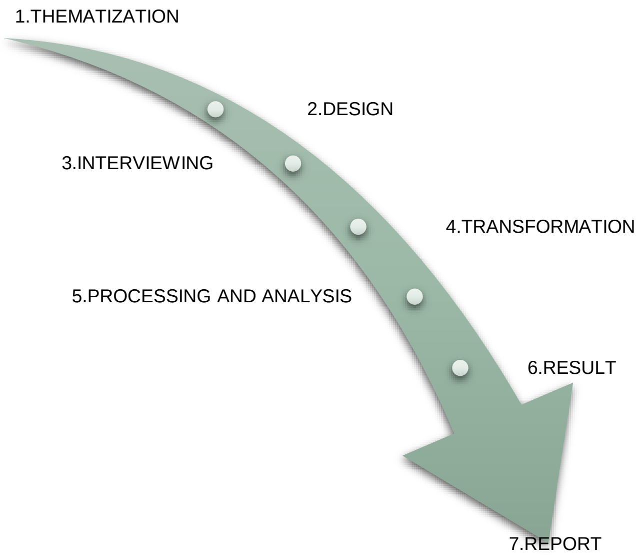


*Figure 2.2: Adapted phases of conducting an interview (Kvale 1996).*

### *1. Thematization*

During the first interview phase the theme and the purpose of the interview is decided. The theoretical foundation behind the interview questions are also established. Since the interview is in its earliest phase, the overall planning of the interview study should not be considered in any wider extent.

### *2. Design*

Considering the second interview phase, it should focus on planning the study thoroughly. The interview method is decided as well as which questions should be used.

*3. Interviewing*

When the interview takes place, the interview design should preferably be followed according to plan. It is important for the interview leader to be attentive towards the interviewee, be curious to the answers and if the opportunity is given, ask follow-up questions.

*4. Transformation*

During the fourth phase of the interview study, the interview has already taken place and the material from the interview should be collected and prepared to be processed in an accessible way. The material should be transformed to a processable form.

*5. Processing and analysis*

In this interview phase the material from the interview should be analysed and assessed based on the theoretical framework.

*6. Result*

With the processed material from the previous interview phase, conclusions and results can be made from the data. The material should also be checked in regards of validity and reliability. It is important to be critical when studying the used interview questions, answers and the conclusions made.

*7. Report*

During the final phase, a report, article etcetera can be written based on the information from the interview. The interview can be presented as a part of a larger study or represent the study itself.

## 2.4 Validity

Validity is about creating a link between theoretical and empirical research and it is essential to measure what was initially intended. The theoretical part must support the empirical part of the research. How well and to what extent a study corresponds with reality varies. A holistic perspective is to prefer when conducting research to make sure all the included components interact well together and creates a coherent study. If for instance interviews are used in the study a lot of thought must be put into designing the questions and thinking about how the interviewees might interpret them. Interviews are sensitive in that way. The validity of the research concerns how well the research can measure or study what the research intends to study. The concept of validity can be divided into two different types of validity, internal and external validity.

External validity is sometimes referred to as construct validity (Svenning 2003). However, Broniatowski and Tucker (2017) claim that construct validity is a separate concept and consequently a third type of validity. The validity demand remains the same regardless of if the study is of qualitative or quantitative nature. For a qualitative study, it is easier to obtain validity and particularly internal validity. The external validity on the other hand is equally difficult regardless of a quantitative or qualitative research is being conducted (Svenning 2003).

### Internal validity

The internal validity depends on if a variation in a dependent value is caused due to variation of an independent value. The study does not have internal validity if other factors than independent values are the reason for the variations of the dependent value (Broniatowski & Tucker 2017). The internal validity can be defined as the connection between theoretical and empirical studies in the specific project. The project design and disposition are central for the internal validity. Having interviews with relevant people for the study is a key element to achieve internal validity (Svenning 2003).

### External validity

External validity concerns to what extent the results of the study contribute to the development of knowledge and how well the entire study can be translated into another context. To be able to generalize the results of the study, it is essential that the empirical research is substantial and accurate. In case the empirical research is inaccurate, all the other attempts of generalizing the results will also be inaccurate and thus the external validity of the research become insubstantial (Svenning 2003). Furthermore, external validity can be defined as a remaining causal relationship even though a change of context is made (Broniatowski & Tucker 2017). If interviews are conducted as a part of qualitative research the results from the interviews must be correct to generalize and use them in other contexts as well as gaining external validity (Svenning 2003).

**Construct validity**

This type of validity focuses on to what extent the theory described in the study corresponds to the chosen study in the empirical research. There must be support in the theoretical construct for all measurements and studies in the empirical research to gain construct validity (Broniatowski & Tucker 2017).

## 2.5 Reliability

There are several factors that can influence how reliable the results of a study become. These factors are often unintentional and can be caused by numerous unpredicted circumstances. Depending on if the study is qualitative or quantitative the demand of reliability is diverse. Since the results from a quantitative study is more apt to be generalized, the demand of reliability is higher. (Svenning 2003). The concept of reliability is about how repetitive a certain study is, related to if a reiteration of a study will get the same results as for the prior study (Broniatowski & Tucker 2017). To reiterate a study, the methodology must be strictly followed to evaluate the study's reliability. If a metric is constant even if it is measured several times, the reliability for the study is high. The test-retest reliability assesses whether the same study, for instance an interview will give the same results if the interviewee is given the same questions at two separate occasions with some time apart (Broniatowski & Tucker 2017).

The concept of reliability can be categorized into four types, namely objectivity, congruence, precision and constancy reliability. The objectivity of a study measures how similar different readers interpret the report and especially the answers from the qualitative interview in the same way. The objectivity is high if many readers understands the answers from the interview in the same way. Congruence is related to what extent the interview questions that aim to measure the same aspects are similar. Another perspective of congruence can in a qualitative interview study be the number of questions posed about a certain theme to get the full picture. Regarding precision within the concept of reliability, it refers to how the interviewer perceive and register the interviewees' answers. As an interviewer it is important to make sure that the interviewees' answers are interpreted correctly. The aspect of constancy when it comes to reliability of a qualitative interview study is about whether a certain answer from an interviewee will remain the same or change if the question is asked another time (Trost 2005).

## 2.6 Validity and reliability for the research study

To holistically put the research study in perspective regarding its fundamental construction, the validity of the research is presumed to be at a medium level. Given that the research study aims to find answers to the research questions. To break it down further the internal validity is deemed high, due to the relevance of the interviewees as well as the systematic approach of the empirical assessments. However, the external validity of the numeric results is low. By using other data, the obtained results can vary greatly which poses difficulties to translate the results into another context. More subjective discussions and findings have some external validity due to, different numerical results and would most likely still correlate to the obtained discussions and findings in the research study. Most of the theoretical framework is scientifically supported, which provides construct validity. Worth to mention is the weighted resource use, used in the research study which can limit the internal and construct validity.

Regarding reliability, the method description in combination with all used data presented, any type of reiteration of the research study should be reliable and consistent. Only by using other data, such as new environmental product declarations, the obtained results would be influenced, thus contributing to the research study’s low external validity.

# Chapter 3 Global warming

## 3.1 Climate change and its impact

It is no longer a matter of if the average temperature increases globally, but how much it increases and what can be done do to prevent the increase. It is a matter of time when the anthropogenic climate change will result in devastating consequences for the environment (Lane 2018). According to United Nations (2018b), climate change is one of the major challenges of our time and will possibly affect coming generations' existence. The consequences of global warming are for example desertification and deforestation, starvation, severe weather, ocean acidification, species extinction and food and fresh water decline (Lane 2018).

One of the major reasons behind climate change is the extensive use of greenhouse gases (GHGs) which accelerates the natural greenhouse effect that keeps some of the sun's radiative energy from reflecting back into space. This is a result of the GHG's ability to reabsorb infrared radiation that is reflected from Earth, thus trapping the heat in the lower atmosphere (United States Environmental Protection Agency (EPA) 2018). The greenhouse effect is crucial for all life on Earth. However, the accelerated anthropogenic production and emission of GHGs by industrialization is directly correlated to the Earth's rising average global temperature, thus a driver for climate change (The Intergovernmental Panel on Climate Change (IPCC) 2013; United Nations 2018b).

There are many different GHGs, gases that absorb infrared radiation that both occur naturally and are produced by mankind and the most occurring ones are (EPA 2018):

- *Water vapour ($H_20$)* - Occurs naturally and is also the most common GHG.
- *Carbon dioxide ($CO_2$)* - All life on Earth participate in the carbon cycle, which simply can be explained as plants extraction of carbon dioxide from the air and its later decomposition as carbon and oxygen. The carbon is being stored in the plant’s biomass and through photosynthesis the oxygen is released into the atmosphere. The biomass decays and releases carbon dioxide back into the nature and atmosphere. Carbon dioxide is also released by the combustion of fossil fuels which impose a great threat for the climate.
- *Methane ($CH_4$)* - Natural methane is mainly produced and released by anaerobic processes of decay of vegetation in wetlands. It is also released by leakages from production of fossil fuels. Anthropogenic releases are estimated to be 60% of the total emissions of methane.
- *Nitrous oxide ($N_2O$)* - The main natural source is speculated to be bacterial breakdown of nitrogen compounds in soils. The major man-made sources of nitrous oxide are derived from nitrogen fertilizers and combustion of fuels in fossil-fuelled power plants.

From the above short summary about GHGs, it is identified that the combustion of fossil fuels is a significant driver for climate change. As the United Nations (2018b) claims, climate change is one of our times greatest challenges to overcome, for present and coming generations. This stresses the importance and urgency to find solutions of reducing and storing GHGs.

The GHG carbon dioxide is associated with energy consumption, consequently implying that the higher energy demand, the higher carbon dioxide emissions. Energy demand is closely related to prosperity. According to energy consumption projections, by 2050 the energy demand is predicted to double. Generally, the governments want to combine economic development with decarbonization, although an economic depression is more profitable for the environment (Lane 2018).

With the current understanding of anthropogenic climate change GHG emissions, especially carbon dioxide emissions have a high correlation with the greenhouse effect which is impacting the global average temperature. According to Green and Karsh (2012) there are two ways that the world could address climate change, by reducing carbon and other GHG emissions and finding ways to store GHGs.

## 3.2 Radiative forcing

The energy balance of the Earth's atmosphere is influenced when climate is affected by different factors, radiative forcing measured in watts per square meter is a way to measure this influence. Radiative forcing stems from balancing incoming solar radiation and reflected outgoing infrared radiation within the Earth's atmosphere. The quota between incoming and outgoing radiation energy controls the Earth's surface temperature. Furthermore, the term forcing is subjected to the alteration of the radiative balance straying from its normal state. Positive radiative forcing means that the energy balance of the Earth's atmosphere is increasing. Similarly, negative radiative forcing implies a decrease of the energy which cools the Earth's surface temperature (Forster et al. 2007).

One of the major challenges for climate scientists is to identify all the different factors that contributes to radiative forcing and additionally assessing the total radiative forcing by these factors. The burning of fossils fuel increases the atmospheres concentration of GHGs which is correlated to the decreased reflection of infrared energy from Earth's atmosphere into space, thus contributing to excessive radiative forcing (Forster et al. 2007).

An important aspect to limit the anthropogenic climate change, is the ability to quantify, measure and compare trade-off values between emissions numerically. Global warming potential is one available instrument to quantify metrically discrepancies between emissions to enable mitigation actions and emission constraints for multi-gas emitters such as industries and nations (Forster et al. 2007).

## 3.3 Global warming potential

The most common indicator to compare emissions climate impact in a life cycle assessment is generally considered to be global warming potential (GWP). The GWP method categorizes different emissions to the same quantified climate effect as carbon dioxide equivalents ($CO_2$-e), more precisely GWP measures different GHGs contribution to the greenhouse effect compared to the same emission of carbon dioxide (Bhochhibhoya et al. 2017).

GHGs affect climate change if they are active in the atmosphere. GHGs will not last in the atmosphere forever and different GHGs are more or less reactive, which decides their lifespan in the atmosphere. A GHG's lifespan is defined as the time for the GHG to reach 1/e (1/2.71) of its original concentration in the atmosphere (Kungliga Tekniska Högskolan 2014).

The atmospheric lifespan for different GHGs diverge strongly. Common lifespans to investigate the GWP for different GHGs are during 10, 20, 100 and 500 years. According to IPCC (2013), 15-40 % of carbon dioxide could still be present after 1000 years.

To the discussion concerning choosing lifespan from the above-mentioned context, there is no scientific factors that strengthens any lifespan over another. Worth to mention is that in the Kyoto protocol, $GWP_{100}$ with a lifespan of 100 years is considered standard (Kungliga Tekniska Högskolan 2014).
Another way to quantify the effects from GHG emissions, is to use another indicator called global temperature change potential (GTP). GTP derives from the GHGs contribution the greenhouse effect, through the result of its effect on global temperature (Kungliga Tekniska Högskolan 2014; DGNB System 2018).

# Chapter 4 Circular economy

To be able to continue living on this planet, the attitude and habits related to consumption needs to change. Instead of using a linear model when it comes to a material's or product's lifespan from *cradle-to-grave*, a circular model should be used. The full life cycle assessment of a product includes phases from raw material extraction (cradle) to the use phase and finally the disposal phase (grave), hence the term *cradle-to-grave*. The *cradle-to-grave* approach can be described as a linear process for the full life cycle of a product (ScienceDirect 2019).

There can be other scopes regarding the included life cycles for products, *cradle-to-gate* being one and implying the lifespan from raw material extraction to the factory gate, before transportation to the customer. To convert the terms from traditional life cycle assessments to the circular approach, *cradle-to-cradle* is often used. *Cradle-to-cradle* implies that the end of life stage for a product is to be reused. The product can be reused with or without processing and can serve as raw material for production off new products. The reused product can also be reused in its existing form. By implementing a circular process, *cradle-to*-cradle, the aim is to minimize harmful environmental effects and reduce raw material extraction and prevent excessive production of waste (ScienceDirect 2019).

A key element for working towards implementing circular economy is cooperation and involvement from companies and manufacturers (Nussholz & Milios 2017). The construction sector is accountable for approximately a third of the total 2.5 billion tonnes of waste generated by the industrial sector within the European Union (European Environment Agency 2018). Circular economy is the idea of optimizing material use and maximizing the value from resources. Since the construction sector often is perceived as conservative, circular economy must be integrated in the value chain through innovation and creative new approaches. According to Ness and Xing (2017), the current research about circular economy is more extensive when it comes to new buildings compared to the built environment. During a property boom the general perception is that even though the built environment increases rapidly, it is increasing with sustainable buildings that have low carbon emissions, electricity from renewable sources and so on. However, this may not be an accurate perception (Ness & Xing 2017).

To be able to accomplish an important reduction of emissions globally, sustainable production and consumption is a key component towards reducing anthropogenic climate change (United Nations 2015). A sustainable production of the built environment is therefore essential and an important component towards reducing climate change. The focus among many stakeholders in the construction sector seems to be reducing energy use during the operation of the building, as an incentive to reduce carbon dioxide emissions. Many stakeholders in the construction sector neglects the fact that strategically selected resources such as construction material for the building has the potential to decrease carbon dioxide emissions significantly (Ness & Xing 2017). It is highly recommended to increase the usage time for construction materials to prolong carbon storing and reduce carbon dioxide emissions instead of regular replacement of building components (Stahel 2008).

By implementing circular economy, primary benefits such as reduced greenhouse gas emissions and energy savings will occur. Circular economy might also have the effect of increased competitiveness between companies and create job opportunities. Circular economy is about conducting sustainable production and consumption processes and at the same time endorse sustainable economic growth. The ecological circular processes found in nature can work as an inspiration for the concept of circular economy. With companies working together, one company’s used material can work as raw material, nourishment, for another. This way, the amount of waste produced will be reduced in favour of reuse and recycling (Chen & Ma 2015).

The concept of circular economy is not to reach economic growth solely on resource consumption, but to gain economic growth in a sustainable way. Industrial ecology was an inspiration and a predecessor that was a driver for developing circular economy into an independent concept. Circular economy emphasizes the importance of utilizing resources as much as possible to prevent waste and unsustainable consumption. The concept of circular economy accentuates four main areas namely, resource efficiency, optimization of used assets and closed-loop approaches. In relation to the construction sector, both resource efficiency and optimization of used assets can be achieved through an increased usage of the built environment instead of new developments. New buildings are resource consuming which will result in more consumption, even though it is in the form of *green buildings*. Creating a closed-loop for construction materials is possible by choosing robust materials with long lifespans (Ness & Xing 2017). Both the real estate and the construction sector are recognized as promising businesses for adapting the principles of circular economy (Ellen MacArthur Foundation 2015).

# Chapter 5 Life cycle assessment

The globalization and companies manufacturing their products in countries that are more economically beneficial sometimes result in neglecting environmental effects due to production. As sustainability is gaining more attention globally, there is a risk for increased resource costs. The sustainable movement and stricter regulations demand transparency. To meet the market's demands, companies are focused on making their brands more sustainable. As a result, annual sustainability reports are conducted, life cycle assessment (LCA) of products are made as well as consultants hired to improve and modify product chains towards less environmentally harmful solutions (Freidberg 2015).

LCA evaluates the impact on the environment throughout a products life cycle. The LCA's major advantage is that it quantifies different environmental effects and enables comparison between different processes and products for a specific case. However, LCA has some limitations considering time-related factors (Levasseur, Lesage, Margni, Deschenes & Samson 2010).

As a reaction to limit climate change within the construction industry, the occurrence of low-energy buildings has increased in recent years. This has led to a shift in LCAs of buildings, increasing the importance of construction material choice to further improve the buildings' life cycle emissions and energy use. To address this development, LCA models must also be developed to be able to integrate construction material choices in a just and correct manner (Blengini & Carlo 2010).

Blengini and Carlo (2010) clarifies that an LCA is a tool that quantifies the total environmental effects from raw material extraction to its eventual disposal. For a building there is usually the following phases involved in its lifespan, *cradle-to-grave*, when evaluating climate impact:

1. Raw material extraction and processing
2. Product shipment to site
3. Construction
4. Use and maintenance
5. Demolition and disposal

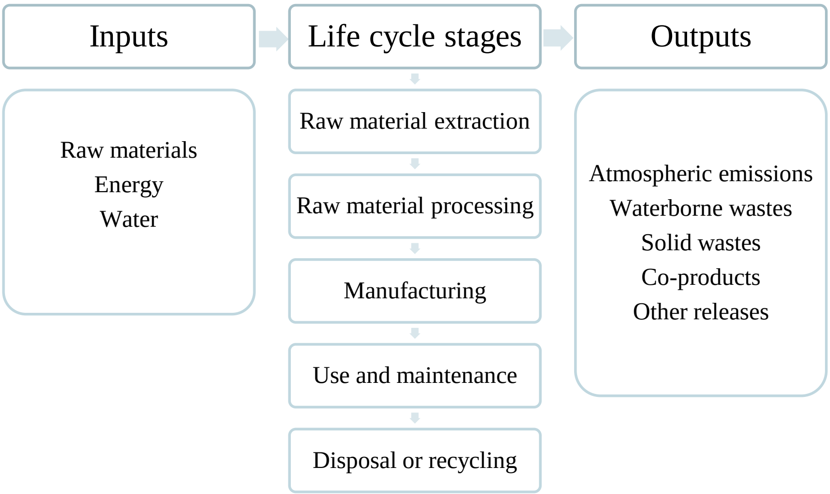


*Figure 5.1: System boundaries regarding life cycle cradle-to-grave for construction materials (Crawford 2011).*

LCA can be used as a tool to identify the largest supply chain impacts, sometimes referred to as *hotspots*, and thereafter try to reduce them. It is both beneficial for the company as well as for the environment to for instance identify energy consuming activities and optimizing them. By performing an LCA it can serve the company's greater interest on product level, since reducing the *hotspots* will result in more sustainable production and hopefully a more sustainable company. The LCA can contribute to sustainable production without compromising the producer's interest of continuous economic growth, by adjusting to the market demands. LCA is also a useful tool for making decisions within the own company, as a source of information and a way to support business decisions. How the results in the LCA are used and interpreted as well as in which context they are used is important for their relevance regarding business decisions. However, companies expect relatively fast produced, up-to-date information that is accessible and easy to interpret which an LCA not necessarily can provide (Freidberg 2015).

The reason for doing an LCA may be for the sake of the environment but return on investment is in many cases a significant driver. This may pose a threat to the credibility of LCAs (Freidberg 2015). Weber and Matthews (2008) claim that the *hotspots* are rarely the ones that are expected to be. Furthermore, an LCA can shed light on the compromises, or *tradeoffs,* of processes made during a products lifespan. By, for instance, choosing recyclable packaging it will have the consequence of less waste but possibly more energy is required to produce the packaging material. This results in *tradeoffs* between different processes and ultimately between different life cycle phases, according to Plevin (2009). By identifying these imbalances in an early stage, before implementing a new product, the negative environmental effects may be easier to reduce.

Freidberg (2015) claim that to be able to conduct an LCA it is important to know what is important to measure and solely measure that with the best information available. To identify the required information can be challenging especially when the supply chain is complex. By only measuring what is important in relation to the product results and not having standardized methods for LCA can contribute to uncertainties in LCA calculations. There is no complete calculation method in any standard by the International Organization for Standardization (ISO) for LCA. There is no ISO standard calculation method since it must cover many product segments, which may cause confusion. Since, some areas are not clearly explained in the ISO standard allows interpretation to some extent which results in inconsistent LCA’s for different products (Freidberg 2015).

## 5.1 ISO 14044

Regulations and guidance for doing an LCA are stated in the international standard from 2006 called *ISO 14044, Environmental management- Life cycle assessment- Requirements and guidelines.* An LCA can be useful for instance when making business decisions, to increase environmental awareness, marketing and optimize products environmental impact in different product stages. Products are analyzed from *cradle-to-grave*, which means through all phases between obtaining raw material to recycling and disposal. The concept *products* include both services and goods (International Organization for Standardization 2006).

To be able to conduct an LCA of a product, four main stages should be followed according to ISO 14044. During the first stage of the process, the goal and scope must be defined. The second stage covers inventory of the studied product or system, where all input and output data are assembled and registered. In the third stage the life cycle impact assessment is performed to clarify and assess the information gathered during the second stage. In the fourth stage the acquired information from stage two and three, the life cycle inventory analysis and life cycle impact assessment are interpreted. Moreover, in the fourth and final stage the results from the LCA are further analysed and summarized to work as comprehensive data for decisions, recommendations and so on. How to summarize the results obtained from the LCA into one total score is not universally decided (International Organization for Standardization 2006).

A functional unit for the LCA should be chosen for quantifying and comparative reasons. The boundaries for the product's LCA must be determined since they establish a system. The enclosed system decides the life cycle stages that are included in the system. A sensitivity analysis should be conducted with the aim to check if the boundaries are satisfying or if life cycle stages potentially should be excluded, if they do not contribute with any additional information. To compare two systems, for two different products, all included aspects must be identical in the two LCAs, such as boundaries and functional unit (International Organization for Standardization 2006).

## 5.2 Environmental Product Declaration

An LCA for a building contains a lot of information and the results are often extensive and can be interpreted in different ways. The input data in an LCA is often derived from an environmental product declaration (EPD), or equivalent a Type III environmental product declaration, for each construction material in the building respectively. An EPD is a declaration that contain information about a products environmental impact, produced by the manufacturers. The EPD is a summary of the results obtained from an LCA conducted for the material (Shepherd 2016).

For construction materials the EPDs contain crucial information about the material in question and is useful for evaluating the different effects the material has on the environment. Each phase of the materials’ lifespan is considered when conducting the LCA which makes it an intricate and time-consuming process. Energy, material, water, emissions and waste related to the material is being collected and assessed for the EPD. A third party reviews the EPD before it is published. The EPD can be developed using the ISO 14025 Standard or ISO 21930 which is better adapted for construction materials. No evaluation about the information stated in the EPD is given and consequently left to the observer to assess. The extracted information can be used in LCA tools that require data about a product’s environmental impacts during its lifespan. Therefore, the increased use of EPDs for construction materials works as an enabler to increase the amount of environmentally certified buildings (Shepherd 2016).

## 5.3 The EN 15804 standard

The standard used when making an environmental product declaration (EPD) for a construction product is EN 15804. Sustainability of construction works-Environmental product declarations Core rules for the product category of construction products. An EPD can be created in different ways. An EPD based on cradle to gate incorporates life cycle phases A1-A3, which are the least phases required to produce an EPD. To create an EPD cradle to gate with options, life cycle phases A1-A3, one or more phases from B1-B7 and C1-C4 and possibly phase D should be included. For an EPD with information from cradle to grave, all life cycle phases are mandatory to include although life cycle stage D is optional. The different life cycle phases are divided into five areas, or life cycle stages for construction products; Production, Construction, Use, End-of-life and Benefits and loads beyond the system boundary (Building Research Establishment 2013).

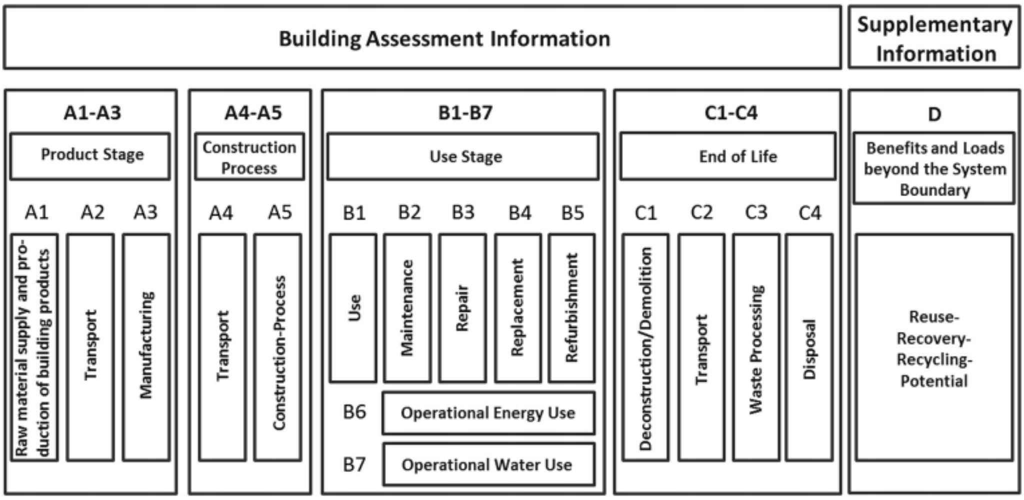


*Figure 5.2: System boundaries according to EN 15804 LCA (Achenbach, Wenker & Rüter 2018)*

### Production stage, phase A1-A3

Mining and refining of raw material in phase A1. Phase A2 covers the transport of raw material to the manufacturer. Phase A3 includes manufacturing and packaging of the construction product. The environmental impacts from the production stage can be summarized or presented individually. The acquisition of required products and material to make the construction product shall be considered in the production stage. By-products as a result of the production shall also be included in the production stage. Energy use, for producing the product and factory energy must be included as well as energy for waste processing (Building Research Establishment 2013).

### Construction stage, phase A4-A5

Phase A4 covers the environmental effects of the transport of the construction material from factory gate to construction site. Phase A5 consist of the environmental impact as a result of setting up the construction material in the building and the waste processing needed for the waste created from that process. Any subsidiary components, such as water or energy needed for the setup of the construction product must be included in phase A5. In addition, energy needed to ensure necessary thermal conditions while and if the construction material is being stored on the construction site can be included (Building Research Establishment 2013).

### Use stage, phase B1-B7

Phase B1-B5 are associated with the building structure, while phase B6-B7 is about the operation of the building. The service life must be taken into consideration if the use stage is included in the LCA, since refurbishment and replacement might be necessary throughout the selected duration for the LCA.

Phase B1 is related to use or application of the installed product, which means for instance the emission of substances due to surface treatment, such as painting on the construction product

Phase B2 includes maintenance, which involves the required actions taken to maintain the installed construction product for example cleaning and will be assessed based on realistic scenarios, given thought to the purpose of the building and its area of use.

The same approach is used for phase B3, B4 and B5 which is repair, replacement and refurbishment, where the phases are related to the specific building and its use. The studied aspects in phase B3-B5 are energy and water use, waste, production, transportation and end-of-life scenarios.

Phase B6 covers the operational energy use and phase B7 is about the operational water use. These two phases contain the water and energy usage while the construction product is operating in the building. In addition, any transport or waste associated with the energy and water consuming processes should be taken account of (Building Research Establishment 2013).

### End of life stage, phase C1-C4

A construction product can naturally enter the end of life stage when a building is being demolished, which can be a consequence due to various reasons. The end of life stage can also be entered when the construction component is being dismantled or replaced.

Phase C1 is deconstruction or demolition, phase C2 is transport, phase C3 is waste processing and phase C4 is disposal. For the demolished material to be considered anything else than waste, it must reach the end-of-waste step. For material components to be considered end-of-waste there must for example be a demand for the waste or a defined existing area of use. On the other hand, the use of the waste material shall not result in additional undesirable environmental effects (Building Research Establishment 2013).

**Benefits and loads beyond the system boundary stage, phase D**

Phase D is incorporated in life cycle phases A4-A5, B1-B7 and C1-C4 regarding the net benefits and loads in the form of energy extracted from end-of-waste materials, recycling or reuse. Phase A1-A3 are not included since the outcome from these phases are categorized as by-products or waste. It is only allowed to count in benefits and loads based on the technology present today and not potential future technology. It is important to have knowledge of all the flows in the system since counting something twice is evaded (Building Research Establishment 2013).

## 5.4 Transport

The three most common modes of transport regarding the construction sector is water transport, rail transport and road transport. Depending on the project application and where in the supply chain certain materials are considered, different modes of transport provide different possibilities and challenges.

Water transport is the slowest mode of transport regarding common available transport methods. Water transport enables transports between harbors/ports and not directly from the supplier's and customer's facilities. Water transport's greatest assets is its ability to ship great shipment loads and its low costs to maintain the infrastructure (Jonsson & Mattsson 2016).

Rail transports are most aptly used when transporting great volumes over long distances. Almost any type of goods can be transported via railway, however long transport times will tie up capital, hence the inappropriateness of transporting high value goods (Jonsson & Mattsson 2016).

Road transports is the most common type of transport, considering long and short distance transports. Road transports enables direct transport from supplier facilities to the customers (Jonsson & Mattsson 2016).

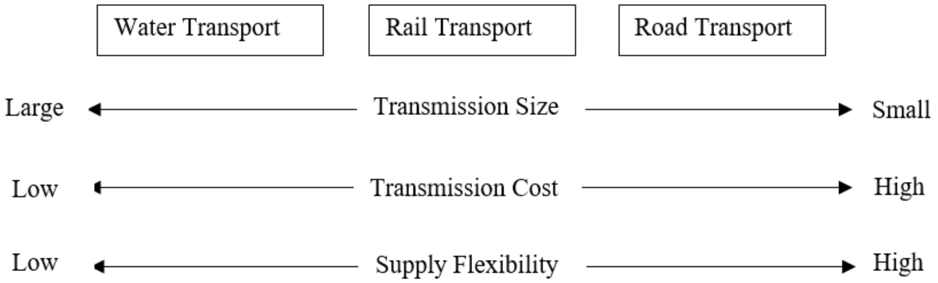


*Figure 5.4: Systematic representation of different modes of transport (Jonsson & Mattsson 2016).*

A more specific application is depicted in table 5.1, regarding infrastructure, distances and type of goods correlated to the different modes of transport.

*Table .5.1: Specification of abilities and prerequisites regarding modes of transport (Region Skåne 2017).*

| **Mode of transport** | **Infrastructure** | **Distances** | **Type of goods** |
|---|---|---|---|
| Shipping | No specific infrastructure needed beyond terminals and docks. Great flexibility | Interregional and international transports | Low value goods in great volumes. Preferably not time sensitive |
| Rail | Limited rail-capacity, expensive to expand by new construction | Intermediate distances, mostly applicable >300km | Low to intermediate value goods with some time sensitivity |
| Road | Great flexibility, good road infrastructure available | Local to long-distance remote transports | Lower volumes of intermediate to high value goods with some time sensitivity |

## 5.5 Life cycle assessment in the construction sector

Production stage phases A1-A3 have the most standardized calculations throughout the entire LCA, which leads to the same methods being used and thus a more accurate evaluation of environmental impacts between LCA calculations from different stakeholders. This demarcation of only including certain life cycle phases may result in imbalances of different products overall environmental impact. By excluding certain phases in the LCA it will result in a deficient depiction and possibly an unfair representation when comparing different construction materials, considering how sustainable they are altogether from *cradle-to-*grave. Even though cradle to grave calculations in theory give the correct total life cycle environmental impact, some LCA stages depends on assumptions which may decrease the overall validity of the LCA calculations (Kutnar & Hill 2017).

Since LCA is complex and depends on many variables and possibly some assumptions, transparency and knowledge are required to be able to compare different LCA calculations and results. One way to diminish the effects of assumptions in LCA calculations is to use third party verified EPDs. Naturally, there must be a framework that regulates the method for producing an EPD. Since there is a lot of different product categories, a systematic approach was introduced via product category rules (PCR). The PCR presents which functional unit and declared unit that should be used for the specific product. The ISO standard 14025 only requires production stage phases A1-A3 to be included in the LCA. However, more phases can be included (Kutnar & Hill 2017).

When comparing different construction materials there is a need to not only compare the production stage phases but the use stage and end of life stage as well. By doing so, potential differences regarding service life, maintenance, performance in service and operating energy can be identified (Hafner 2014; Finkbeiner 2014). The overall objective to introduce EPDs is to standardize methods for evaluating products in LCAs. Product environmental footprint (PEF) is yet another tool for assessing products and aims to increase comparability between products (Kutnar & Hill 2017). The PEF system was introduced with the aim to achieve what EPDs aimed to achieve when they were introduced, hence it does not serve any additional purpose according to Finkbeiner (2014).

# Chapter 6 Sustainable building certifications

As a reaction to the increased sustainability awareness, sustainable building certifications were created. Sustainable building certifications enables buildings to be given a voluntary label and get certified through a certification system. By introducing sustainable building certifications, information asymmetry regarding sustainability in a building between different stakeholders is reduced. The sustainability focus in different certification systems can vary between construction materials, energy or emissions. There are several sustainable building certifications available in Sweden that are adopted for the Swedish market, such as Miljöbyggnad, BREEAM-SE and the Swedish version of LEED (Sweden Green Building Council 2019a). In Denmark, the most used certification systems are the Danish version of DGNB, LEED and BREEAM (Green Building Council Denmark 2018).

Sustainable building certification systems are often provided by national *Green Building Councils.* There are currently 90 *Green Building Councils* established worldwide. *Green Building Councils* are national, transparent and non-profit organizations. The councils strive for creating a sustainable built environment by cooperating with its members and involve all professions in the built environment (Sweden Green Building Council 2019b). The green building councils are committed to contribute and deliver what is decided in the Paris Agreement (World Green Building Council 2019). The Danish version of DGNB is provided by Green Building Council Denmark (Green Building Council Denmark 2019a). Similarly, Miljöbyggnad, BREEAM-SE and the Swedish version of LEED is provided by *Sweden Green Building Council* (Sweden Green Building Council 2019a).

## 6.1 The purpose of sustainable building certifications

There are different kinds of environmental assessment tools that has been developed over the years for different environmental building certifications, based on prior research within the field. The tools have resulted in a wider understanding and an increased interest in sustainability for the stakeholders in the construction sector. Construction clients and property developers also contribute to more sustainable buildings through their demands and by collecting data of environmental impacts and trying to reduce them (Ding 2008).

Furthermore, a sustainable mind-set among the construction clients naturally leads the construction sector towards higher environmental standards, as opposed to enforcing mandatory regulations. The sustainable approach when it comes to construction enables innovative solutions within all areas to adopt and increase sustainability (Park, Yoon & Kim 2017). By including life cycle assessment in sustainable building certifications, chemicals and pollutants related to material choice can be identified and the amount of waste generated in the construction process can be limited (Turk, Quintana & Zhang 2018).

## 6.2 The motives for certifying buildings

The objective for certifying a building may differ and company values and corporate social responsibility (CSR) seems to be a strong motivator for some companies that acquire sustainable certified buildings. Early adjustments towards sustainable solutions in the building sector can act as a prevention for future stricter regulations or high energy prices (Reichardt, Fuerst, Rottke & Zietz 2012).

The fact that sustainable building certifications are optional may result in a transformation of the construction sector without enforcing stricter building regulations. The required performance in some criteria within the sustainable building systems have in many cases affected the building regulations towards using the performance as a building standard. It is common to have national sustainable building certification systems which is in line with the country's climate and building properties. It may seem reasonable that the sustainable building certifications are based on domestic prerequisites although it might not be profitable. The comparability between different building's certification grades or systems internationally is generally low. It is therefore proposed that the certification systems are more standardized internationally. The American system LEED and British system BREEAM are two sustainable building certification systems that are recognized and may be used in an international setting since there are international versions available. In Sweden for instance, BREEAM-SE and LEED are used. Generally, it is not common to use another country's sustainable building certification and adjust it to fit domestic conditions. BREEAM and LEED are mostly used in countries that already have a national sustainable building system. However, Denmark have adjusted the German system DGNB to Danish conditions and use it as a national sustainable building certification (Cole & Jose Valdebenito 2013).

A potential driver for the obsession of reducing operational energy in buildings could be the progress with constantly elevated energy prices since the 1990s (Pivo & Fischer 2010). In addition, the increased interest and awareness for sustainability and climate related issues combined with stricter regulations have been a significant enabler for the development of sustainable building certifications. However, the sustainable building certifications does not always incorporate all three dimensions of sustainability, some are limited to green or environmental building certifications. Miljöbyggnad is an example of an environmental building certification (Reichardt et al. 2012).

## 6.3 Timber as a sustainable construction material choice

Material choice in buildings have gained a lot more attention recently. The focus in buildings regarding sustainability has traditionally been to reduce the operational energy use. However, material choice in a building can impact the emissions generated from the building significantly. Usually, the most energy demanding life cycle stage has been regarded as the use stage and specifically phase B6. Since there are many methods available to reduce the operational energy of a building, other life cycle phases increase in level of importance. For timber buildings the material ratio regarding total building volume and total building mass varies. The timber tends to represent a higher share when it comes to volume than mass in a building. This can be explained as even buildings regarded as timber buildings have a high percentage of non-wooden material. When comparing wooden buildings with massive concrete buildings, results indicate that wooden buildings have a higher ratio of renewable material than massive concrete buildings when comparing, mass construction material per floor area. There are challenges associated with building high rise timber buildings, for instance strict fire regulations. The regulations can influx a higher amount of non-renewable materials such as gypsum boards (Hafner 2014)

## 6.4 Construction material consideration

There are several environmental issues related to the production of construction materials, such as energy consumption, impact on biodiversity, pollution and natural resource depletion. The results from the building assessment tools highly depend on the weighting of each evaluation area and the chosen criteria included in the material evaluation area. The assigned weight for the material evaluation area tend to be lower for materials than for indoor environment quality and energy in CASBEE, LEED and BREEAM. In addition, the life cycle assessment tools share the same intentions which is reducing the environmental impacts for the building from *cradle-to-grave*. The environmental aspect of sustainable development is generally in focus, while social and economic sustainability are neglected in the material evaluation criterion (Park, Yoon & Kim 2017). LEED is taking account of the use of certified raw material in the aspect regarding sourcing of raw materials. For instance, wood products are required to be certified by U.S. Green Building Council (USGBC) or the Forest Stewardship Council (FSC). Construction material do not only affect the assigned building assessment tool but also other areas such as indoor air quality and energy, within the building certification. The tendency among building certifications such as CASBEE, LEED and BREEAM is that a transition towards only assessing the main materials in a building is beginning to be implemented.

Environmental impact data for all construction products do not exist, or is not published, which makes a complete material evaluation difficult. Product level data needs to be more transparent and easier to access, since it will benefit the large number of manufacturers claiming they produce sustainable materials without being able to prove it. In addition, it will be beneficial for construction clients with making sustainable material choices and enable material assessment in various building certifications. Transparency is crucial for a sustainable society globally (Park, Yoon & Kim 2017). A potential barrier towards being open and transparent from the manufacturer’s perspective might be the risk of revealing components in the construction material and possibly even trade secrets, hence loosing market shares (International Living Future Institute 2016).

Park, Yoon and Kim (2017) have identified a common ground among the sustainable building certifications LEED, BREEAM, CASBEE, G-SEED and LBC regarding the consideration of environmental indicators for sustainable materials. The three core environmental indicators are energy, ecology and resource. The energy indicator is about how material choice can improve energy performance. The ecology indicator refers to choosing materials with a limited impact on the environment. The resource indicator aims to use life cycle assessment as a tool to minimize the material demand. Park, Yoon and Kim (2017) state that present material assessment tools within sustainable building certifications emphasizes the environmental aspect of the triple bottom line. On the other hand, it might be difficult to quantify social and economic sustainability. Furthermore, it is crucial for sustainable building certifications to be confirmed by a third party to vouch for its credibility and independence (Park, Yoon & Kim 2017).

## 6.5 Framework for sustainability

In Sweden there are currently no legal framework that regulates the production stage or the use stage regarding greenhouse gases from buildings (Boverket 2018). According to the Swedish Environmental Protection Agency (2018a) the national Swedish aim is to have zero environmental impact emissions 2045. The aim can partly be realized with increased education and knowledge regarding life cycle assessment for different stakeholders in the construction sector, which is paramount to achieve the climate goal. The initial learning process among stakeholders is crucial to overcome the barriers of information imbalance. There are different available standards today on how to calculate environmental impacts over a building’s lifespan. However, the standards tend to be complicated and difficult to applicate. There is limited usage of complete life cycle calculations since there is not enough required information available for the different life cycle calculations. The focus for Boverket, the National Board of Housing, Building and Planning, when designing calculation methods for life cycle assessments and product or environmental declarations is to reduce the complexity to invoke more stakeholder participation (Boverket 2018).

# Chapter 7 Miljöbyggnad

## 7.1 The certification

Sweden Green Building Council (SGBC) is the founder and developing organization of Miljöbyggnad, which is an environmental building certification system. Miljöbyggnad version 3.0 is currently used. One of the purposes of Miljöbyggnad 3.0 is to contribute to sustainable development and support the national Swedish environmental goals for year 2020 stated by the Swedish government. The certification is meant to be easy to apply for, cost-effective and verified while the building is in use. Both new and existing buildings can be certified with Miljöbyggnad 3.0. New buildings are defined as buildings which have been operating for less than five years (Sweden Green Building Council 2017a).

The system is developed for the Swedish climate and for Swedish conditions. Consequently, it is used in Sweden and over 1000 buildings are certified. Miljöbyggnad 3.0 focuses on three areas, material, indoor environment and energy use through fifteen measuring indicators for new buildings (Sweden Green Building Council 2018a).

## 7.2 The certification process

To be able to certify a building, a certain process with five main phases requires to be followed. In the first phase the building is registered at SGBC and is set to apply for the Miljöbyggnad certification within three years. In the second phase the application is submitted to SGBC. During the third phase, the application for the registered building is being reviewed by a third party with the purpose of finding and comparing if the measuring indicators are sufficiently satisfied. The third party will resend the application to the applicant for Miljöbyggnad for further review and modify it if necessary. In the fourth phase of the process, the building will be certified, implying that the application has been approved. The fifth phase concerns the verification of the certification. New buildings must be examined and verified that the data given in the application matches the building. The fifth phase of the process must be completed within two years after the building has been put into service. The verification is a recurring event every five years after the first verification (Sweden Green Building Council 2018b).

## 7.3 The certification grading

There are three grades for Miljöbyggnad 3.0, namely bronze, silver and gold, with gold being the best grade. For new buildings grade bronze is equivalent to the Swedish building regulations and praxis, the regulations produced by Boverket, the National Board of Housing, Building and Planning. It requires dedication and effort to be able to certify a building with gold (Sweden Green Building Council 2018c).

An important regulation is that every indicator must be considered. If the building aim for the certification gold, a bronze indicator is not permitted. A prerequisite for a building to get a Miljöbyggnad 3.0 certification of any kind is that every indicator is given the grade bronze. The individual indicator’s grade is successively added in three or four steps, depending on which kind of indicator that is used. There are both indicators on room level and building level. For the area’s energy use and indoor environment, the most critical and disadvantageous rooms are chosen when it comes to calculating an indicator grade on a room level, which thereafter becomes the entire floor’s grade. Certain individual indicators also have an aspect rating consisting of two indicators, where the lower grade decides the aspect grade. The grade for the indicators of each area is decided by the aspect rating for each indicator or indicator group. The main rule for deciding both aspect and area grade is that the lowest grade given decides which grade the combined indicators will get on a higher level. However, if at least half of the aspect grades are higher, the area grade will be elevated to the following higher grade. When it comes to the grade for the whole building, it will be given the lowest grade out of the three area grades (Sweden Green Building Council 2017a).

## 7.4 Construction material indicators in Miljöbyggnad 3.0

There are three measuring indicators in Miljöbyggnad 3.0 that are related to construction material, namely indicator thirteen, fourteen and fifteen. The thirteenth indicator is *keeping a journal with building materials*. The purpose of keeping a journal with building materials is to maintain a solid documentation of the buildings components as well as product declarations for the materials (Sweden Green Building Council 2017b).

The fourteenth indicator is *phasing out toxic substances* and is supported by the previous indicator when it comes to information about the materials in the building. The motivation for this indicator is to reduce the amount of toxic substances that is used in the construction sector. Minimizing hazardous substances for the environment in the building materials is rewarded (Sweden Green Building Council 2017b).

The fifteenth indicator is *the structure of the buildings environmental impact*. An overall motive from SGBC for this indicator is to increase the knowledge about environmental impacts as a result from the usage of certain materials in buildings. The choice of materials is important. To illustrate this information in an accessible and comparable manner the unit kilogram equivalent carbon dioxide (kg $CO_2$-e) per $A_{temp}$ is used (Sweden Green Building Council 2017b). The area $A_{temp}$ is defined by Boverket, the National Board of Housing, Building and Planning as a buildings internal area for each floor including cellar and attic that keep a consistent temperature of at least ten degrees Celsius (Boverket 2014). The indicator requires that the environmental impact from the load bearing construction as well as the buildings foundation is presented. The construction material included in the LCA tool is horizontal and vertical load bearing components as well as load bearing components in the outer wall and material in the foundation. Different phases of a construction materials life cycle should be presented depending on which indicator grade that is strived for. The certification grade bronze requires data from phase *A1 Raw material supply and production of building products, A2 Transport* and *A3 Manufacturing* in standard EN 15804. The three phases are environmental impact as a result from extraction and transportation of raw material, manufacturing and packaging. These phases do not consider the transport from the manufacturing site to the construction site. When attempting to achieve grade bronze, generic data in kilogram carbon dioxide per kilogram construction material and $A_{temp}$ for each construction material is given in the Miljöbyggnad 3.0 life cycle assessment tool. To reach the indicator grade gold or silver, information from EPDs for the building materials must be used. For silver, at least 50% of the total amount of information for each material environmental impact must be originated from an EPD and a source for the EPD must be given. For gold, at least 70% of the environmental impact information must come from an EPD. Besides having a higher percentage of EPDs, for gold the environmental impact for life cycle phases A1, A2 and A3 must decrease with ten percent. This can be achievable by for example reducing the amount of material or change material (Sweden Green Building Council 2017b).

In addition to the phases A1, A2 and A3, phase *A4 Transport* is taken into consideration for indicator grade silver and gold. Phase A4 addresses the transport required from the materials manufacturing site to the construction site. For indicator grade silver, generic data for the environmental impact for each mode of transport is given in the life cycle assessment tool. For indicator grade gold on the other hand, data for environmental impact from transport must be extracted for each individual project and mode of transport (Sweden Green Building Council 2017b).

# Chapter 8 DGNB

## 8.1 The certification

Sustainability within the Danish construction sector is strongly promoted by the Green Building Council Denmark (DK-GBC). A holistic sustainable approach is preferred compared to a green environmental perspective regarding building certifications. Sustainable building certification of buildings is provided by the organization which offer a Danish adaptation of the German system DGNB. The Danish version of DGNB has been available since 2012. The Danish adaptation of DGNB was made achievable through consultation with national expertise within the different sustainable areas that DGNB assess. The adaptation both included changes required to equal the Danish building regulations and translation from the German system (Green Building Council Denmark 2019a). Each criterion within DGNB aims to support the three aspects of sustainability; social, economic and environmental sustainability. In addition, DGNB also include process- and technical quality. The Danish DGNB system is dynamic and updated in accordance with when the Danish building regulations are reviewed and minor changes are implemented continuously (Green Building Council Denmark 2019b). There are available DGNB criteria for residential buildings, commercial buildings, urban areas, hospitals, schools and education premises. Office buildings in operation can also be certified as well as most other buildings since the DGNB criteria can be adapted to certify all kinds of buildings (Green Building Council Denmark 2019c). In Denmark are currently fifty buildings certified with DGNB.

## 8.2 The certification process

The DGNB certification process consists of two phases, one pre-certification of the project documentation and design and one certification of the finished building. The reason for a two-phase process is to verify the intended results from the first phase in the second phase (Green Building Council Denmark 2019d). A DGNB auditor must be involved and assist with the certification process. A DGNB auditor is someone who is certified and educated on the subject of DGNB and certifying new buildings (Green Building Council Denmark 2017). The initial pre-certification phase is optional but strongly recommended. The documentation of the finished building is reviewed in the second phase by a representative from the Danish Building Research Institute (SBi) and DK-GBC. The building is subsequently given a certification grade. The second phase must be completed within three years after the building is finished (Green Building Council Denmark 2019d).

## 8.3 The certification grading

The certification grading of a certain building is decided based on the results of 40 different evaluation criteria. The criteria are all related to the five quality areas social, economic, technical, environmental and process quality. The quality areas are characterized by a certain percentage weight, as seen in figure 8.1

.

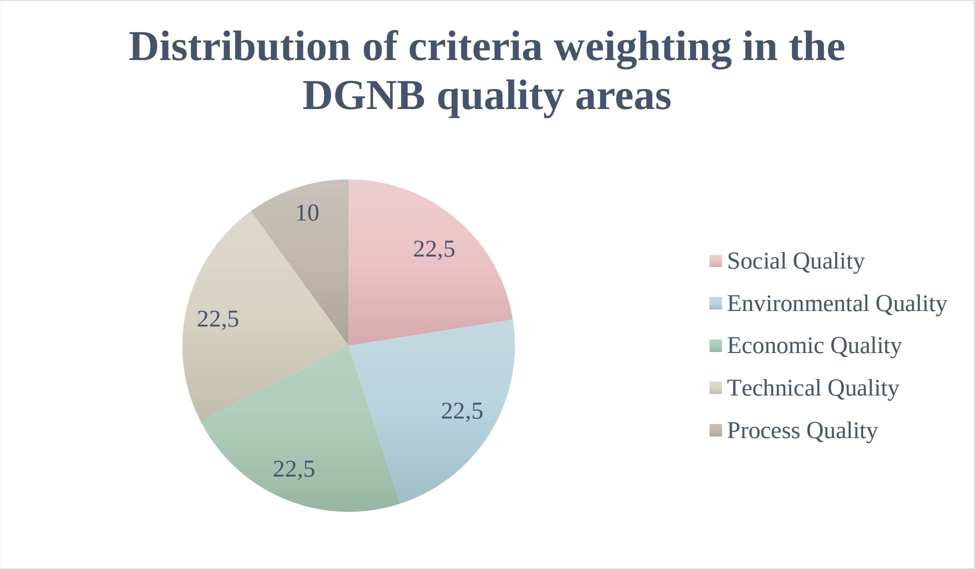


*Figure 8.1: Percentage distribution of each DGNB quality area weight (Green Building Council Denmark 2017a).*

The collected result of the criteria within each quality area is determined based on to which percentage extent each criterion is fulfilled in relation to the highest score possible. Thereafter, a collected percentage result is calculated to decide which DGNB certification grade the building is given, see table 8.1. There are three grades in DGNB, silver, gold and platinum. The grade is calculated in an evaluation matrix. The result from the matrix reflects the overall score of the building. There are minimum values that must be reached within some criteria and also for the each of the quality areas individually, to achieve a fair grading system. The different quality areas can be advantageous or disadvantageous when combined and it is therefore important to contemplate how the different solutions and decisions within each quality area interacts when they are combined. A holistic perspective considering the different quality areas is desirable when striving for a certain grade to achieve a profitable balance between the quality areas (Green Building Council Denmark 2019e).

*Table 8.1: Illustrates the minimum and collected percentage for the quality areas for each grade respectively (Green Building Council Denmark. 2019e).*

| **Grade** | **Minimum percentage in each quality area [%]** | **Collected percentage in all quality areas [%]** |
|---|---|---|
| Silver | 35 | 50 |
| Gold | 50 | 65 |
| Platinum | 65 | 80 |

## 8.4 Architectural consideration in DGNB

Architectural aspects of the building are taken account of in criterion *SOC 3.1 Architectural quality*, within the social quality area. The aim with the criterion is to encourage the maintenance of the building as well as increase the architectural quality in the built environment. It is possible to choose between five types of evaluation perspectives within the criterion. The architectural quality criterion is regarded as important from a sustainable point of view since it gives the building preserving potential. The architectural values related to the building is desirable to keep and it is therefore realistic to refurbish and maintain the building in the future instead of demolishing it (Green Building Council Denmark 2017a).

A DGNB certified building can in addition to the grade it is given be awarded with DGNB Diamond for its architectural qualities. The building is assessed from a holistic perspective regarding the buildings details, character and integration with the surroundings. It is more specific the architectural aspects of beauty, sustainability and functionality. These criteria are assessed in relation to how the material choice and the building project itself can contribute to the built environment in a sustainable perspective (Green Building Council Denmark 2017b).

## 8.5 Construction material indicators in DGNB

Since the DGNB system has a holistic approach, aspects related to construction material choice are integrated in several criteria within the different quality areas. However, there are four indicators that exclusively evaluates the construction material choice, all located within the environmental and the technical quality area (Green Building Council Denmark 2017a).

The first criterion within the environmental quality area is *ENV1.1 Life cycle assessment (LCA) – environmental impacts.* The overall aim with this criterion is to assess and limit the environmental impacts throughout the building's lifespan, from *cradle-to-grave*. The purpose of the criterion is to raise awareness concerning emissions and resource use and hopefully reduce the negative environmental effects related to the building during its lifespan. The environmental impacts assessed in the LCA is ozone depletion potential, global warming potential, acidification potential, photochemical ozone creation potential and eutrophication potential (Green Building Council Denmark 2017a).

The second criterion within the environmental quality area is *ENV 1.2 Environmental risks related to construction material.* The aim with this criterion is to limit or phase out the construction material with toxic substances for organisms and the environment. The evaluation is focused on 45 critical construction materials or coating and finishing processes that can have damaging effects on the environment (Green Building Council Denmark 2017a).

The third criterion within the environmental quality area is *ENV 1.3 Environmental impact due to material extraction.* The overall aim with this criterion is to increase the use of social and environmentally sustainable material related to resource extraction. The criterion is focused on sustainable mineral and stone as well as wood extraction. The mineral and stone products require CE certification if they are from the European Economic Area (EEA). Concerning wood products reused wood, FSC-certified wood or PEFC-certified wood is awarded (Green Building Council Denmark 2017a).

The technical quality area criterion TEC 1.8 *Documentation with environmental product declarations* aims to increase the amount of available EN 15804 EPDs from manufacturers through market demand. The amount of EPDs provided is required to be at least 25% of the construction material's weight or volume (Green Building Council Denmark 2017a).

# Chapter 9 Wood as a sustainable construction material

Wood can contribute to the critical tasks related to climate change, both reduce carbon and other greenhouse gas emissions and store greenhouse gases (Green & Karsh 2012). Additionally, wood contributes with sustainable factors with respect to water usage, carbon emissions and energy use. It is further implied that carbon dioxide pooling or *carbon sequestration* in long-living wood products can contribute to mitigation effects of climate change in numerous ways. The sequestrated carbon in wood-based construction materials in buildings can after its service life be used as a substitute for fossil fuel in adequate furnaces (Werner, Taverna, Hofer & Richter 2005).

Wood is a versatile raw material and is used in a multitude of areas within the construction sector. Wood products can mitigate climate change effects due to carbon sequestration, where atmospheric carbon gets stored during the growth of forests. Since wood stores energy during the lifespan of a wood-based construction product or a building's lifespan, the stored energy in disposed wood can be retrieved. The retrieved energy from wood can work as replacement for fossil fuel incineration, considering energy extraction (Kutnar & Hill 2017). To avoid deforestation, sustainable forestry is crucial for a sustainable use of construction wood (Hafner 2014; Kutnar & Hill 2017).

Finally, with the above-mentioned mitigation effects by implementing more biomass in building and its effects on climate change, it is not enough to compensate greenhouse gas emissions in other sectors excluding the construction industry. Carbon emissions can be reduced by using wood instead of concrete and steel. However, its impact on the global issue of climate change will most likely be insignificant. Additional mitigation actions in other sectors such as sustainable forestry, logistics etcetera is fundamental to confront climate change effectively (Werner et al. 2005; Fleming, Smith & Ramage 2014).

## 9.1 Environmental impacts of construction materials in life cycle assessments

The climate impact of buildings with a greater ratio of bio-based materials are lower and thus environmentally more sustainable. The climate impact of these buildings is assessed through LCA and traditional LCA methods tend to diminish some environmental aspects, such as carbon sequestration and other environmental phenomena, mainly because of uncertainties of implementing natural effects in LCA models. The main issues at hand are the effects of carbon sequestration and the time of occurrence in the different models (Peñaloza, Erlandsson & Falk 2016).

Bio-based buildings environmental climate impact depends greatly on the bio-materials end of life scenario as well as the time horizons of the environmental benefits of carbon dioxide sequestration. Addressing the above-mentioned effects and issues is crucial to more accurately evaluate bio-based construction materials and secure its correct implementation in LCA models.

As Levasseur et al. (2010) points out, a single big release of pollutants generally has a lesser effect and impact as the same amount of pollutant released over a longer timeframe. Thus, the need to divert from traditional LCA methods is a necessary step in order to improve the LCA to better quantify environmental effects of different materials and processes. A dynamic LCA offers a solution to time-related limitations in a traditional LCA. Thus, evaluating the emissions over time rather than a single occasion. The dynamic evaluation is being evaluated through the mathematical definition of global warming potential, as illustrated below:

*Equation 9.1: Method for calculating GWP (Levasseur et al. 2010).*

$$GWP_i^{TH} = \frac{\int_0^{TH} a_i[C_i(t)\mathrm{d}t]}{\int_0^{TH} a_r[C_r(t)\mathrm{d}t]}$$

*TH* is the chosen time horizon, *a* is the instant radiative forcing by the atmospheric mass increase. *C(t)* is the time dependent atmospheric load. The released gas is indexed by *i*, and *r* is the indexed reference gas, in this case being carbon dioxide.

Levasseur et al. (2010) suggest that in traditional LCA, all emissions for a product or service is added into a single aggregate emission. This total single pulse emission is later categorized into environmental problems such as, anthropogenic climate change, toxic emissions and water usage.

The dynamic LCA enables the biogenic carbon exchange to be included in the LCA, requiring an inventory of emissions and sequestration of greenhouse gases as well as the time of the occurrence.

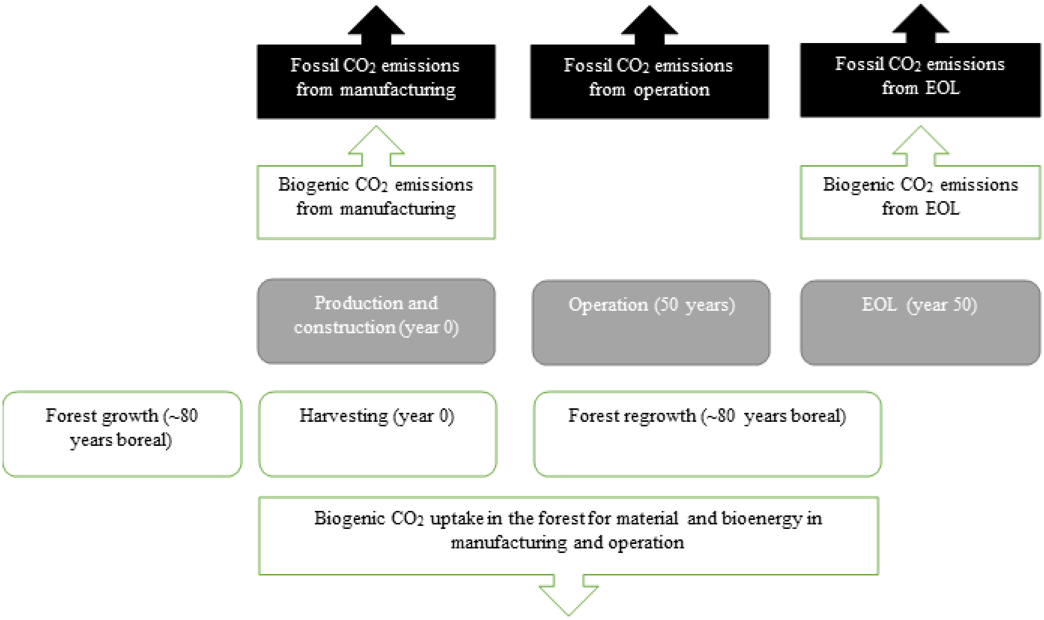


*Figure 9.1: Systematic overview of carbon sequestration depending on growth or regrowth (Peñaloza, Erlandsson, & Falk 2016) adapted from Crawford (2011).*

Carbon sequestration can be accounted for as *growth* before harvesting, following the natural carbon cycle whereas the biomass first must grow and later be sequestrated in bio-based materials. However, another possibility exists, where the biogenic carbon sequestration is accounted for after harvesting, as *regrowth*. Regrowth depicts the debt of biomass that is created at harvest until the forest is regrown (Peñaloza, Erlandsson & Falk 2016).

## 9.2 Carbon sequestration in a sustainable context

Carbon sequestration means storing of carbon in bio-based materials that retains carbon from the atmosphere. This process reduces the concentration of carbon dioxide in the atmosphere, which in turn reduces some radiative forcing. This effect is established if the carbon is sequestrated in the material. However, if the material is combusted or decayed after its service life, the carbon is released into the atmosphere once again. Carbon sequestration has a potential to mitigate climate change during the time interval of the sequestration in the bio-based material (Brandão et al. 2013). There is an ongoing discussion of whether to include sequestration in the LCA or not. If sequestration is being taking account of it may be included in life cycle phase *B1 Use* or *D Benefits and loads beyond the system boundary* (Hafner 2014).

Lehtila and Pingoud (2002) studied forests and wood products in Finland and discovered an estimation of the emissions for production of a wood product compared to the carbon stored in the wood product. The result indicated that only seven percent of the stored carbon were the equivalent production emission in GHGs for the same wood product. Naturally, the more extensive processing the material is exposed to, the higher the production emissions ratio compared to the stored carbon will be.

Sathre and Gustavsson (2009) highlight that environmental benefits can be achieved by using timber products. However, there are economic barriers concerning wood products that diminish economic aspects. The authors also point out possible economic incitements that depend on the actualization of climate change costs that can be derived from products. This could lead to harmful materials for the environment to account for a higher part of the costs related to climate change.

Carbon sequestration is evaluated in production stage phases A1-A3 for bio-mass construction products. The product category rules PCR for EN standard 15804 suggest a method containing an example of how to calculate carbon sequestration (Building Research Establishment 2013).

There are numerous scientific reports suggesting that the environmental benefits of using wood products as construction materials is due to the ability of carbon sequestration. The increasing amount of bio-mass used in buildings, also called harvested wood products (HWPs), can be interpreted as an additional carbon pool.

HWPs is parted from the already massive carbon pool found in all vegetation on Earth. During COP 15 in Copenhagen, the member states agreed upon the matter of regarding bio-mass in buildings as an additional carbon pool (United Nations 2009). However, the environmental benefits of including yet another carbon pool will not impact the climate over time. This is due to the balance of the HWP pool, all the embodied carbon leaving the HWP pool due to product manufacturing is later added due to regrowth of the harvested forests. It was presumed that over time the net balance of inflow and outflow would be zero. Furthermore, resulting in the negation of mitigation effects of implementing bio-mass in the built environment.

The IPCC (2013) mentions materials with low embodied energy, further implying the importance of energy consumption rather than carbon emissions. However, the possibility of wood products as carbon sinks is not mentioned. During the first commitment period of the UNFCCC between 2008 and 2012, it was recognized that wood products are important and environmentally beneficial, due to their carbon storage possibilities. Later, changes in the HWP pool could be included for the second commitment period for the UNFCCC between 2013 and 2020, implying possible mitigation possibilities based on the balance of the HWP pool. Climate scientists are not unanimous whether carbon sequestration should be accounted for, or not.

Cherubini, Bright and Strømman (2012) emphasize the importance of wood products with long lifespans, towards depicting some environmental benefit for carbon sequestration. There is no platform on which these types of calculations can be made, in numerous instances there has been disagreement and indecisiveness in forming a standard which either include or exclude carbon sequestration calculations. An example is the standard EN 16485 *Round and sawn timber. Environmental Products Declarations. Product category rules for wood and wood-based products for use in construction*.

Finally, Brandão et al. (2013) mean that there are benefits regarding environmental aspects by using timber products that store carbon during long lifespans. However, there are currently no stringent way to calculate and account for it, in the LCA framework.

# Chapter 10 Cross-laminated timber

Cross-laminated timber (CLT) is an engineered timber product, which is mainly used as a structural building material. However, the material can also be used as a façade-material as well as secondary constructions such as walls and floors. In recent years its usage accelerated due to its versatility and sustainable properties as a building material (Brandner 2013).

Due to the importance and urgency of reducing climate change, important stakeholders in industries, including the building sector, are looking for mitigation measures against climate change. The construction industry has recently been focusing on the forests as a source of raw materials and as an option to decrease the climate change impact, mainly by implementing and further introducing bio-based materials. One of these bio-based materials being wood, and more specifically CLT (Peñaloza, Erlandsson & Falk 2016).

Figure 10.1 below illustrates that the total European CLT production 2017 reached 670 thousand cubic metres. Most of the production of CLT is based in Europe. The data shows a positive trend for the production rate of CLT both in Europe and the predominant manufacturing countries; Austria, Germany, Switzerland, Italy and the Czech Republic. Figure 10.1 also depicts trendlines as future projections, based on the expected rise of CLT production through the many CLT projects in the pipeline from 2016-2020. The two different projections are correlated with the expected expansion of manufacturing, especially in Scandinavia (Jauk 2017a).

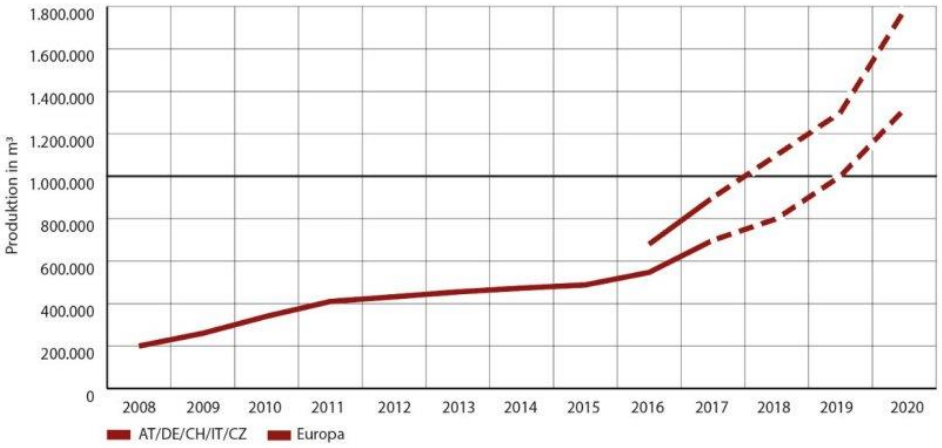


*Figure 10.1: Future projections of CLT production in Europe. (Jauk 2017a).*

## 10.1 The history of cross-laminated timber

The construction material CLT was developed in Germany and Austria during the 1990s as a measure to limit and manage the waste-wood produced by mills. CLT got traction and interest both from Austrian academia and industry and as a joint venture was further developed to the CLT used in Europe and worldwide today (Stauder 2013).

Figure 10.2 illustrates the increased rate of CLT production from the 1990s to 2013 with future predictions for the years 2013-2015, which in fact correlates with the actual figures of production for the predicted years, see figure 10.1 (Brandner 2013).

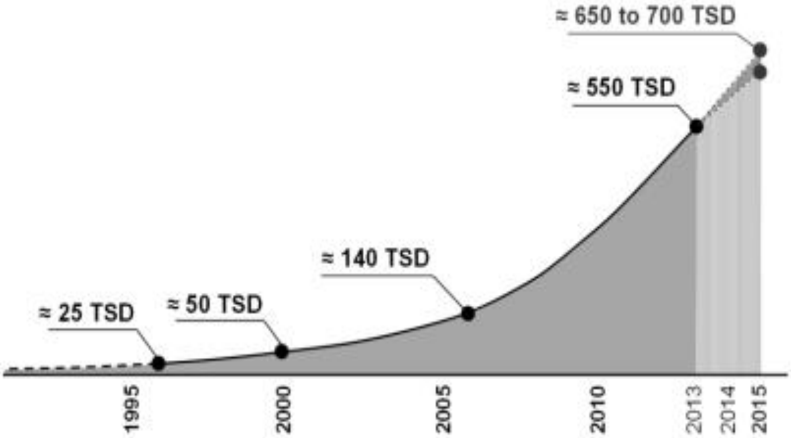


*Figure 10.2: Development of global production volume of CLT. 2013-2015 forecast (Brandner 2013).*

It was foremost the green building movement that increased CLT’s significance as a heavy construction material and the lack of knowledge was the main reason for its delayed impact on the construction industry (Stauder 2013).

CLT is considered a green building material and when used as a construction material it carries some environmentally sustainable benefits, such as carbon sequestration, reduced emissions and cost and time effectiveness when used on-site. Naturally, these benefits are associated with challenges in areas linked to logistics and other construction-related criteria. However, CLT is at the time considered as an alternative construction material, which not only vouch for the needs of solid structures but is also produced by a renewable and sustainable source (Stauder 2013).

## 10.2 The composition of cross-laminated timber

CLT is often composed by an uneven number of layers made of solid-sawn lumber, usually three, five, seven layers and sometimes more. The layers consist of solid-sawn lumber and each layer is orthogonally placed subsequent of the previous layers, thus creating a stronger structural rigidity in multiple directions. This is due to wood being an anisotropic material, which means that the material properties change depending on the direction of the force applied. The constitution of CLT panels benefits from the varying structural dynamics of the fibre directions in the solid wood boards. The combination of different layers homogenizes the board into a quasi-rigid body. The boards are glued together by an adhesive, which creates the CLT panels. The CLT panels can be modified in both length, width and thickness to fit specific needs (Brandner 2013; FPInnovations & Binational Softwood Lumber Council 2013).

*Figure 10.3: Solid sawn lumber placed orthogonally placed.(Reid Middleton 2017). CLT panel (Big Red Dog 2017).*

Figure 10.3 above illustrates the conventional cross-section of a CLT panel but it is possible to alter the arrangement of the solid wood boards to change the structural properties of the CLT panel to better fit certain specific structural requirements. The ongoing research and development of CLT also look at innovative methods for interlocking the solid-wood boards, one of these products being Interlocking Cross-Laminated Timber (ICLT) (FPInnovations & Binational Softwood Lumber Council 2013).

## 10.3 The manufacturing of cross-laminated timber

The typical manufacturing of a CLT panel can simplified be divided into the below stated steps, each of these steps may have several sub-steps included as shown below: (FPlnnovations & Binational Softwood Lumber Council 2013).

1. *Lumber selection*
    - Lumber moisture content and quality control inspection which involves visual grading and sometimes E-rating (elastic modulus). The results from the tests will broadly categorize the CLT into two groups; construction grade CLT and appearance grade CLT.
2. *Lumber grouping and planing*
    - Planing and grouping the CLT panels depending on its designated future use. Panels with aesthetical properties will be placed on the outmost layers and panels with higher structural values will be placed where the panel will be exposed to the most tension. The surface of the lumber also needs to be surfaced for a better adhesive application.
    - The lumber is cut to a specific length depending on application and client needs.
3. *Adhesive application*
    - The adhesive is applied in parallel lines in an airtight system with a constant rate. This is made to ensure that there are no holes or gaps that could reduce the glues adhesive ability.
4. *Panel lay-up and pressing*
    - The CLT layers are placed perpendicular to adjacent layers and pressed together with either vacuum or hydraulic pressure.
5. *Product cutting*
    - The finished CLT panels can be cut to fit certain demands, such as holes for doors, windows etcetera.
6. *Surface machining*
    - The CLT panel is later sanded and minor repairs are carried out by hand.

7. *Marking and packaging*
    - Finally, product marking ensures that the correct product is delivered and specified to the client. Additionally, certain stamps verify the different standards and certifications necessary for jurisdiction and authenticity of the produced product. It is important to keep the CLT panels dry, which entails weather protection, during shipping and on-site storage.

## 10.4 Advantages and limitations of cross-laminated timber

Sutton, Black and Walker (2011) highlight some of the advantages and limitations to CLT as shown below. These factors are correlated to CLT during its different applications, from manufacturing, logistics and on-site usage and provide an idea about the different possibilities and barriers that is associated with CLT (Sutton, Black & Walker 2011).

**Advantages**

- Renewable material
- Stores carbon during its lifespan
- Minimizes thermal bridging
- Contributes to an airtight building
- Lightweight construction which minimizes load on foundation
- Needs thorough design work which may improve overall design and performance
- Fast and simple on-site construction process
- Great architectural versatility which enable use in both non-visual and exposed finishes
- Vapour permeable wall-construction

**Limitations**

- Requires accurately set out groundworks
- Requires completed design work before project start due to offsite manufacturing
- Requires cladding to ensure weatherproof envelope of the building
- Risks associated with water and moisture during construction and usage

# Chapter 11 Architecture and construction materials

## 11.1 Architectural materiality

Architecture tend to separate materials and methods, suggesting that the one is not dependent on the other. Ballard Bell and Rand (2006) believes this misconception also hues the professional practice of architects. The authors further imply that materials are not included in the early stages of the design, rather conceived as a mere afterthought. This misconception, to consider design without material is a step towards a non-successful building.

*Materiality* is a term that intends to showcase the architect's design ideas in compliance with the properties of construction materials. Furthermore, the increase of new materials from an architectural perspective highly rests on the ideology of materiality, to successfully interpret, advance and revolutionize architecture (Ballard Bell & Rand 2006).

In a historical perspective, prior to the twentieth century, materials used in buildings was a product of the vicinity and abundance of construction materials considering the location of the building. During mid nineteenth century, Europe saw a rise of construction materials such as steel and glass in architecture, which symbolized industrialisation and technological development (Ballard Bell & Rand 2006).

The rapid development of the twentieth century combined materiality with the ideals of modernism thus the increased usage of concrete, not only as a replacement for stone, but also as a statement for the new architectural era.

One of the most famous architects from this era was Le Corbusier which used concrete’s superior properties to form his sculptural and innovative building impressions. No other material aside from concrete would be able to perform and construct the buildings the way Le Corbusier intended to (Ballard Bell & Rand 2006).

Ballard Bell and Rand (2006) later implies that the postmodern era of the 1980s denied materiality as a part of architecture, promoting imitation materials, faux material veneers, that neglected the true identity of construction and façade materials, one could no longer distinguish the materials’ true purpose within the building, neither structural nor architectural.

Today, materiality in construction materials is an expanding field, confining a steady inflow of new materials and ideologies in society. *Green* materials implementation in the construction sector is according to Ballard Bell & Rand (2006) considered mainstream. The authors also point out the paradigm shift with the advancement of technology in building materials, whereas today, technology can provide specific materials to cover specific needs within a building.

## 11.2 Traditional construction materials

### Concrete

By mixing Portland cement, water and stone aggregate, the robust qualities of concrete are created. Concrete has great compression strength compared to its tensile strength. When reinforcing concrete with steel it can also improve its lacking tensile strength. The shape of any concrete structure is limited by its casting, thus concrete can have many different shapes and forms (Ballard Bell & Rand 2006).

Concrete has a great variance of applicability in the construction sector, as it can be used in foundations, floors, and beams etcetera (Ballard Bell & Rand 2006).

### Wood

Wood has traditionally been the most conventional building material along with stone and clay. Wood is an anisotropic material, suggesting that the materials properties is dependent on the grain and fibre directions. Many different construction types are linked with wood, log construction and timber-frame constructions being some (Ballard Bell & Rand 2006).

### Steel

Structural steel was becoming popular and common in the early nineteenth century. When reinforced concrete was invented in the 1860s, the building sector was revolutionized providing tools for taller buildings and longer construction spans. Steel is a strong and reasonably priced metal used in almost all types of buildings and building applications. Steel, compared to other metals offer a high strength-to weight ratio and is most often used in light and heavy structural framing (Ballard Bell & Rand 2006).

## 11.3 Material usage comparison

Canadian Wood Council (2004), conducted a research that compared wood, steel and concrete structures in a three-storey building. It is hard to construct any building using only one certain building material and therefore were three different building types with varying construction solutions studied; a wood house, a sheet metal house and a concrete house. The main differences that separate the different building types are the floors and the exterior walls, which are made subsequently of the different construction materials. However, the roof and foundation wall were the same in all building types. The partition walls for the wood and concrete house were made of wood studs. In the sheet metal house, the partition walls were made of steel studs.

The research conducted from the Canadian Wood Council (2004), indicate some major differences on environmental performance between the three different building types as illustrated in table 11.1.

*Table 11.1: Relative to wood, steel and concrete produce, embody and emit the following Canadian Wood Council (2004).*

| Environmental factor | Steel [%] | Concrete [%] |
|---|---|---|
| **GHG** | 34 | 81 |
| **Air pollution** | 24 | 47 |
| **Energy** | 26 | 57 |
| **Water pollution** | 400 | 350 |
| **Solid waste** | 8 | 23 |

The main criterion which describes material consumption in different structural constructions based on material choice, derived from Canadian Wood Council (2004) indicate weighted resource use as shown in figure 11.1.

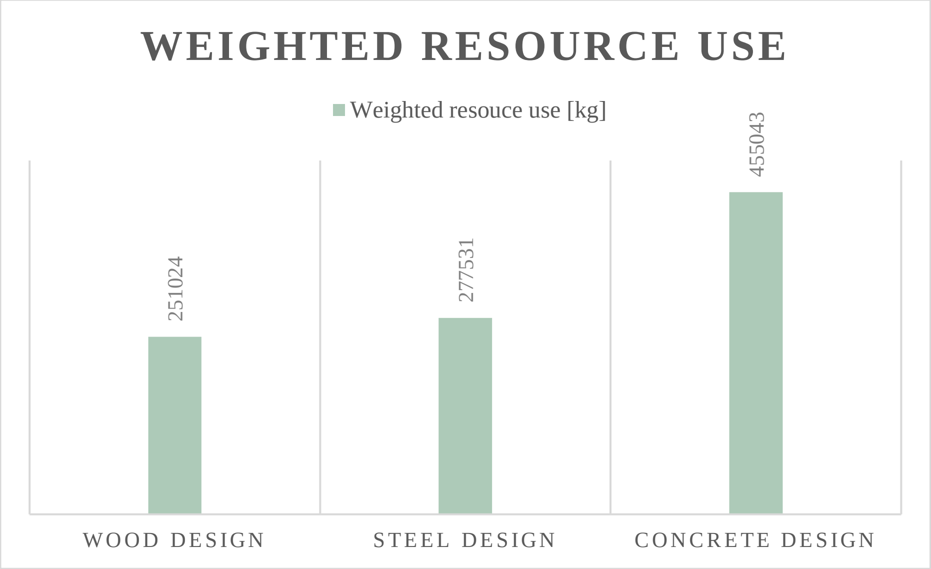


*Figure 11.1: Adapted representation of weighted material usage (Canadian Wood Council 2004),*

- Figure 11.1 indicates a weighted resource use of steel versus wood design to 1.11 kilogram steel equal 1 kilogram wood.
- Figure 11.1 indicates a weighted resource use of concrete versus wood design to 1.81 kilogram concrete equals 1 kilogram wood.

Another research, evaluating weighted resource use in different structural construction solutions indicate the following results, which are based on a comparison between a commercial building with two stories, the research was based on the exclusion of windows, doors and partition walls. All building types with wood, steel and concrete structure were presumed to have a concrete foundation (Continuing Education Center 2018)

- Figure 11.1 indicates a weighted resource use of steel versus wood design to 1.02 kilogram steel equals 1 kilogram wood.
- Figure 11.1 indicates a weighted resource use of concrete versus wood design to 2.3 kilogram concrete equals 1 kilogram wood.

Based on the above stated research, to further indicate different structural materials' environmental impact, the following weighting factors are implemented in the actual research study:

- Weighted resource use steel versus wood is 1 kilogram to 1 kilogram.
- Weighted resource use concrete versus wood is 2 kilograms to 1 kilogram.

This assumption is an effort to best describe wood, steel and concrete as structural construction materials and its environmental impacts. It is important to note, that any difference in weighting ratio will have impacts on the presented results in the actual research study.

To prevent any type of misguidance regarding weighted material use and its impact in LCA, in the actual research two types of results are shown for each evaluating criterion. The kilogram per kilogram environmental impact for each of the structural construction material (CLT, steel and concrete) and the environmental impact with the above stated weighted material usage for each of the structural construction materials (Canadian Wood Council 2004)

# Chapter 12 End of life scenarios and construction waste

Waste management is important for the overall sustainability of buildings throughout their life cycles. Waste disposal from a building after its service life can mainly be defined as either reuse, recycling or disposal. Policies and regulations strongly impact waste management strategies towards encouragement and incitements of reuse and recycling (Yu, Poon, Wong, Yip & Jaillon 2013).

For the Nordic countries, table 12.1 illustrates the amount of waste from the construction sector and how much waste that is recycled.

*Table 12.1: Construction and demolition waste in the Nordic countries.*

| **Country** | **Construction & Demolition waste/Total waste [%]** | **Recycled Construction and demolition waste [%]** | **Source** |
|---|---|---|---|
| **Sweden** | 31 | 56 | Boverket (2017) |
| **Denmark** | 25-50 | 80 | Yu et al. (2013) |
| **Finland** | 14 | 40 | Yu et al. (2013) |
| **Norway** | 30 | 7 | Yu et al. (2013) |

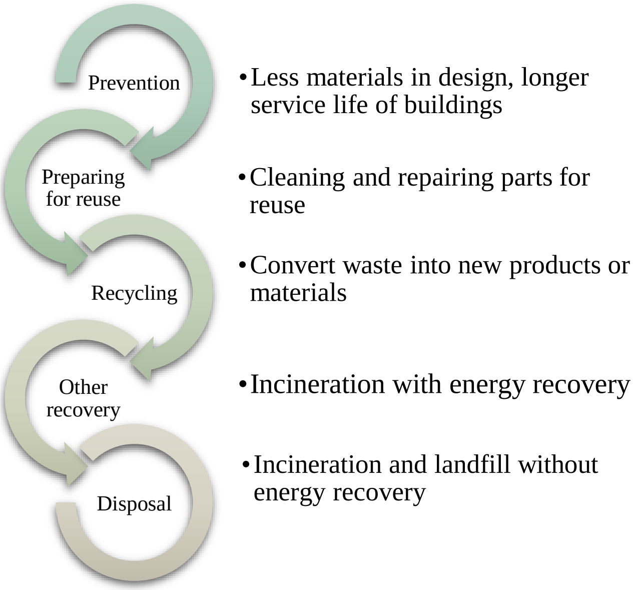
The EU Waste Directive 2008/98/EC Of the European Parliament and Of the Council, 19.11.2008 provides legislative framework concerning waste management and the handling of waste for the member states. The framework provides principles concerning waste and the environment, stating that each member state should handle waste in a way that does not harm the environment or human health. The legislative framework also encourages the use of waste hierarchy and the *polluter-pays-principle*. Broadly stating that the owner of the product that produces the waste should be responsible for the costs of waste disposal (Directive 2008/98/EC Of the European Parliament and Of the Council, 19.11.2008).

The EU Waste Directive 2008/98/EC Of the European Parliament and Of the Council, 19.11.2008 provides a priority for new legal framework and policies. The Swedish Environmental Protection Agency (2018b) states the following hierarchy for waste handling:

1. Pre-emptive waste reduction
2. Reuse
3. Material recycling
4. Other recycling (such as energy-recycling)
5. Disposal

The above list suggests that, firstly should waste pre-emptively be reduced, secondly reused, thirdly recycled and lastly disposed of as landfill.

To further illustrate the above-mentioned hierarchy, the following illustration shows the priorities more in detail and its application for buildings (Department for Environment, Food & Rural Affairs (DEFRA) 2011).



- Less materials in design, longer service life of buildings
- Cleaning and repairing parts for reuse
- Convert waste into new products or materials
- Incineration with energy recovery
- Incineration and landfill without energy recovery

*Figure 12.1: A systematic approach to waste prevention and waste management, adapted from DEFRA (2011).*

## 12.1 Waste management

According to Kralj & Markic (2008) there are different possible applications for the prevention of construction waste. As suggested before, the waste hierarchy strives mainly to prevent the excessive production of waste. The authors highlight some critical tasks to prevent waste:

- *Design*
  - Choose materials that easily can be dismantled after the building's service life.
  - Design for standardized sizes of the construction materials. Increase the usage of precast and prefabricated materials.
  - Increase the lifespan of materials to decrease the need of refurbishment and change of inbound materials.
  - Design areas and constructions for different uses, that can be changed and provide flexible solutions to further increase the usage rate of a building.

  - Increase the use of recycled materials as construction materials in new buildings.
- *Planning and waste management*
  - Include prevention of waste in waste management plans.
  - Increase the communication between stakeholders to raise the importance of preventing waste.
  - Use materials and tools on job-sites that can be reused and reduces the waste production.
- *Economic measures and on-site waste prevention*
  - Increase incitements for purchasing of recycled or partially recycled materials.
  - Keep an updated logistic plan on-site to reduce the time that materials are on-site which may contribute to the reduction of damage of the materials.
  - Use materials that require less alternatively no packaging.

According to Roth (2005) reuse is the overall term for many types of reuse activities. The mentioned subgroups in this case are *recirculation*, *upgrading* and *cascading*. These terms describe how the materials are used in an energy perspective, from high to lower energy materials.

- *Recirculation*
  - Could be described as direct reuse, the original material or product is not affected or reworked in any major way. Examples of this could be construction products such as doors and windows which is removed and reinstalled in another building structure.
- *Upgrading*
  - When adding energy to rework the used material to its original state. This upgrading of the used material can be divided into two subgroups; recycling and partial recycling. Where recycling refers to the added energy bringing the used material back to its original state, whereas partial recycling not fully corresponds to the original state of the material.
- *Cascading*
  - As the term implies, cascading refers to the degraded use of the original material in terms of energy state. An example of this could be crushed concrete used as filling material in road structures.

According to the EU Waste Directive 2008/98/EC Of the European Parliament and Of the Council, 19.11.2008, energy recovery is not defined as recycling. Energy recovery is the last step before landfill and defined as disposal. The EU Directive 2008/98/EC states the following concerning energy recovery in terms of incineration:

> *"It shall be a condition of any permit covering incineration or co-incineration with energy recovery that the recovery of energy take place with a high level of energy efficiency."*

*(EU Waste Directive 2008/98/EC*
*Of the European Parliament and Of the Council, 19.11.2008)*

The EU Directive further implies member states to, whenever possible aim for prevention, reuse or recycling of waste as described in the waste hierarchy. Member states should not support disposal of waste, landfill or incineration whenever possible.

## 12.2 Wood and end of life dependency

The overall sustainability of wood as a construction material is highly dependable on the end of life (EOL) scenario and if the wood is used for carbon sequestration or bio-storage. After the service life of wood used in a construction, which is approximately 80 years, the sequestrated carbon in the wood components can be recycled, thus the carbon will remain sequestrated. Alternatively, wood can be incinerated or decomposed and ultimately releasing the sequestrated carbon, only delaying the climate change impacts during the wood construction's service life. The measures to transform already used wood components with different EOL scenarios is fundamental to the mitigation of climate change (Brandão et al. 2013).

Biological sequestration can increase the carbon stocks of non-atmospheric reservoirs such as land and land-based products. Since the contained carbon is sequestered from, and retained outside, the atmosphere for a period, the concentration of carbon dioxide in the atmosphere is temporarily reduced and some radiative forcing is avoided (Brandão et al. 2013).

## 12.3 End of life scenarios for cross-laminated timber

The authors Darby, Elmualim and Kelly (2012) conclude in their research that different EOL methods for CLT have great impact on their overall sustainability. Below are some of the existing EOL scenarios for CLT different ways of waste treatment:

- Reuse in its existing form
- Partially reused by reworking the original product into smaller sections for reuse for different applications.
- Incineration with energy recovery
- Incineration without energy recovery
- Landfill

For all the above mentioned EOL scenarios, different combinations of ratios can appear. For example, 50% reuse and 50% incineration with energy recovery can be one possible EOL scenario (Darby, Elmualim & Kelly 2012).

The issue and opportunity of carbon sequestration is not itself an EOL scenario in the life cycle phases C1-C4 but rather connected to life cycle phase D. The ratio of the sequestration affects the overall sustainability of CLT as depicted in the table below (Darby, Elmualim and Kelly 2012):

*Table 12.2: GWP at End of construction with different levels of sequestration (Darby, Elmualim and Kelly 2012).*

| | **100% sequestration [Tonne $CO_2$-eq]** | **50% sequestration [Tonne $CO_2$-eq]** | **0% sequestration [Tonne $CO_2$-eq]** |
|---|---|---|---|
| **Growth** | -1192 | -596 | 0 |
| **Production and transport (A1-A4)** | 47 | 47 | 47 |
| **Construction** | 45 | 45 | 45 |
| **Total** | -1100 | -504 | 92 |

If the sequestration is included in the LCA, CLT gives a negative carbon emission. If carbon sequestration is not included, it gives a positive vale of carbon emission. Even ratios of sequestration depending on the LCA timeframe, as well as the service life of the building can affect the environmental impact values greatly concerning CLT.

The chosen EOL scenario also have a great impact on the sustainability of CLT. As Darby, Elmualim and Kelly (2012) further suggests in table 12.3. The different EOL scenarios chosen for CLT affects its overall sustainability.

*Table 12.3: GWP for CLT with different EOL scenarios (Darby, Elmualim and Kelly 2012).*

| | **Re-use [Tonne $CO_2$-eq]** | **Re-engineer [Tonne $CO_2$-eq]** | **Incineration [Tonne $CO_2$-eq]** | **Incineration with energy recovery [Tonne $CO_2$-eq]** | **Landfill [Tonne $CO_2$-eq]** |
|---|---|---|---|---|---|
| **To end of construction** | -1100 | -1100 | -1100 | -1100 | -1100 |
| **Demolition** | 22 | 22 | 22 | 22 | 22 |
| **Transport** | 12 | 12 | 12 | 12 | 12 |
| **Manufacture** | | 10 | | | |
| **Transport** | | 12 | | | |
| **Construction** | 45 | 45 | | | |
| **Combustion** | | | 1192 | 1192 | |
| **Energy from combustion** | | | | -628 | |
| **Emissions from landfill** | | | | | 1013 |
| **Total** | -1021 | -999 | 126 | -502 | -53 |

The increased demand of wood-based construction products relies on innovation and development within the timber industry. Improvements regarding cascading of reused and recycled timber are crucial to solidify environmentally beneficial EOL scenarios for wood products (Hafner 2014).

## 12.4 End of life scenarios for steel

Materials that have minimal material value, in terms of physical function or aesthetical value can be considered as waste products or even waste. These products most often disposed, incinerated or used as landfill and pose challenges in terms of transportation and waste handling for the end-user. Steel's material properties include high material value which exclude disposal options for steel scrap and enables EOL scenarios concerning reuse and recycling (Diener 2017).

However, there are some limitations regarding recycling of steel (United Nations Environment Programme 2013). Metals have become increasingly complex by mixing different alloys in numerous ways. Thus, creating increasingly complex situations for material recycling. The issues of steel recycling now reside in the separation and recovery of the different steel components.

Whenever metal compounds are cut or formed, slag will be produced. And with the increasingly complex metal compounds, the slag produced offers barriers concerning its recyclability (United Nations Environment Programme 2013).

Some of the slag produced can be used in roads as road fill, contemplating the degrading of function within metal compounds (Diener 2017).

Aside from the reuse of steel structures, metal compounds are recycled. Depending on the complexity of the metal compound, the recycling is affected. Some of the steel can be used as secondary steel in construction beams, while some other alloys might not be recycled and becomes scrap (Diener 2017).

## 12.5 End of life scenarios for concrete

Concrete is the most widely used material in the world (Royal Society of Chemistry 2008). Concrete creates the largest amount of construction and demolition (C&D) waste, hence highlighting the importance of the EOL scenarios for concrete in the construction sector (Di Maio, Hu, Lin & Roekel 2012).

The waste generated from concrete structures has recycling potential. The waste aggregate from concrete can be reused in other concrete structures (Vieira, Calmon, & Coelho 2016).

EOL scenarios for concrete (Sakai 2009):

- Reuse by cutting into smaller concrete structures
- Recycle as aggregate in road sub base
- Recycle as aggregate in underground stabilisation
- Recycle as aggregate in new concrete
- Landfill

A case study from the Netherlands show that the recycling of concrete, whereas 97% of demolished concrete is recycled as road structure aggregates. This poses challenges concerning the increase of constructed buildings against the constant demand of road structure aggregates. Concrete faces challenges concerning managing and processing the concrete at the EOL stage and finding new areas of recycling and reuse (Di Maio et al. 2012).

# Chapter 13 Buildings with cross-laminated timber

## 13.1 Murray Grove, United Kingdom

CLT was developed in the early 1990s, but it was not until 2009 that the Murray Grove project in Hackney, London was finished. Murray Grove is the first tall urban housing project that is completely constructed with prefabricated timber. Everything from floors, stairs and load-bearing walls is constructed with CLT. Although, the ground floor was constructed with reinforced concrete (Liu, Guo, Sun & Chang 2016).

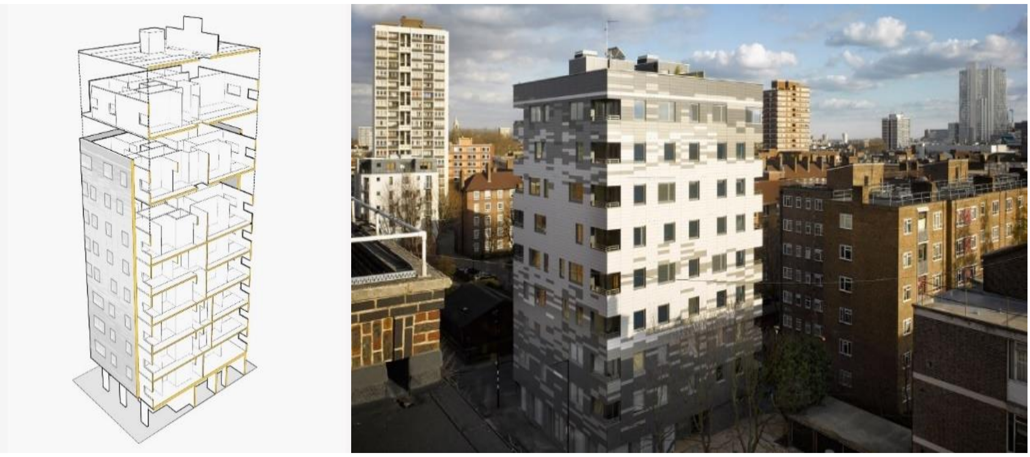


*Figure 13.1: Murray Grove CLT project (Waugh Thistleton Architects 2019a).*

The housing project resulted in a nine-storey tower and proved that CLT was a viable option in the aspects of environmental sustainability and economic viability as well as ensuring architectural values (Waugh Thistleton Architects 2019a).

## 13.2 Dalston Works, United Kingdom

The Murray Grove project was at the time of completion the tallest CLT building ever built until it later was surpassed by another London project, Dalston Works (Liu et al. 2016). Dalston Works is a ten-storey development project made entirely of CLT. Dalston Works is built on soil that cannot support an equally high building, with its 33, 8 meters, made of concrete due to the increased weight and force applied to the soil. The project was a solution to one of London’s residential development needs of high quality and high-density housing.

*Figure 13.2: Dalston works CLT project (Waugh Thistleton Architects 2019b)*

The carbon footprint of Dalston Works was reduced by the timber-technology which diminishes the environmental impacts in terms of material and energy usage, while improving on-site time efficiency (Waugh Thistleton Architects 2019b).

## 13.3 Najaden, Sweden

C.F. Møller and Slättö co-developed the winning competition proposal to design an urban area in Lund, Sweden, with sustainable residential buildings. The residential quarter called Najaden in Lund will be built with structural massive timber, CLT. The material choice is motivated by the properties of CLT regarding positive carbon footprint and being a renewable and sustainable construction material. The project is designed to incorporate a life cycle approach, circular processes and aims to be certified with Miljöbyggnad 3.0 grade silver (Slättö & C.F. Møller 2017).

*Figure 13.3: Visualization of the Najaden project in Lund, Sweden (Slättö & C.F. Møller 2017).*

The project's competition proposal design especially focuses on environmental and social sustainability. Environmental sustainability is expressed in terms of how sustainable transportation modes are promoted, urban agriculture, bike parking and bike workshop, greenhouses and waste disposal with recycle and reuse opportunities. The design of the buildings ensures efficient energy usage and the residents can keep track of their water usage. Raingardens are supposed to handle storm water and the buildings are expected to have green roofs. The outdoor environment in the residential quarter is characterized by vegetation which promotes ecological diversity (Slättö & C.F. Møller 2017).

Social sustainability is made sure through urban planning that enables spontaneous encounters and social areas that encourage interaction between the residents. There is a lot of recreational possibilities in the area due to the surroundings and natural landscape. Furthermore, there will be a restaurant and cafés in the neighbourhood (Slättö & C.F. Møller 2017).

## 13.4 Brock Commons Tallwood, Canada

The tallest mass-timber building today (2018) is the Brock Commons Tallwood House in Vancouver, Canada. The building reaches 53 metres above ground and is constructed of CLT structures as well as components of glulam and concrete. Brock Commons is a student residence building and houses 404 students for the University of British Columbia in Vancouver. As with the two previous projects, Murray Grove and Dalston Works, Brock Commons also report that mass-timber buildings can be erected at a lot faster than ordinary concrete buildings.

CLT buildings have also shown an economic viability and if the wood is provided based on sustainable forest management, the CLT building is an environmentally sustainable option to seriously consider (Forestry Innovation Investment 2019).

*Figure 13.4: Brock Commons Student Residence (Canadian Consulting Engineer 2016; Acton Ostry Architects and the University of British Columbia 2016).*

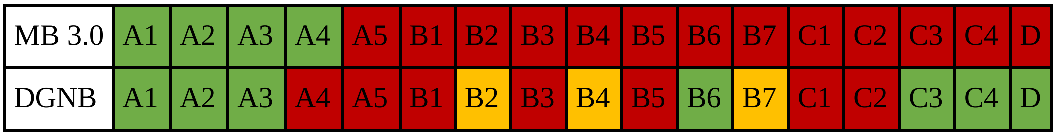
# Chapter 14 Methods for using the life cycle assessment tools in Miljöbyggnad 3.0 and DGNB

*To explore the available LCA tools in DGNB and Miljöbyggnad 3.0, the following sections aim to highlight step by step what considerations and actions that is needed to complete an LCA. The LCA tools are used to evaluate structural construction materials in Miljöbyggnad 3.0 and DGNB.*

## 14.1 Life cycle phases in Miljöbyggnad 3.0 and DGNB

The two sustainable building certifications Miljöbyggnad 3.0 and DGNB include different life cycle phases that are present in the standard EN 15804 in their respective LCA tools. Table 14.1 below illustrates the LCA phases included in the two certifications, visualized in green. If a life cycle phase is red it indicates that it is not measured in the LCA tool, while yellow means that it is taking into some consideration in the certification but not in the research study.

*Table 14.1: Included life cycle phases in the LCA tools for Miljöbyggnad 3.0 and DGNB.*



| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MB 3.0 | A1 | A2 | A3 | A4 | A5 | B1 | B2 | B3 | B4 | B5 | B6 | B7 | C1 | C2 | C3 | C4 | D |
| DGNB | A1 | A2 | A3 | A4 | A5 | B1 | B2 | B3 | B4 | B5 | B6 | B7 | C1 | C2 | C3 | C4 | D |

## 14.2 The Miljöbyggnad 3.0 life cycle assessment tool

*The LCA tool described for Miljöbyggnad 3.0 is called Ind 15 Klimatverktyg vers 15.4 180516 (Sweden Green Building Council 2019c).*

The LCA tool is used for indicator 15 in Miljöbyggnad 3.0, *called the Structure of the buildings environmental impact.* An overall motive from Sweden Green Building Council regarding the indicator is to increase the knowledge about the environmental impacts as a result from the usage of certain materials in buildings. To illustrate the environmental impacts in an accessible and comparable manner the global warming potential (GWP) is measured with the unit kilogram equivalent carbon dioxide ($CO_2$-e) per $A_{temp}$ is used. The indicator requires that the environmental impacts from the load bearing construction as well as the buildings foundation is presented**.** The construction material included in the LCA tool is horizontal and vertical load bearing components as well as load bearing components in the outer wall and material in the foundation.

## 14.3 Method for using the Miljöbyggnad 3.0 life cycle assessment tool

1. Regardless of which indicator grade that is aimed for, start by filling in the data for indicator grade bronze.
2. The certification grade bronze requires data regarding construction material weight and GWP from production stage phases A1-A3 in standard EN 15804. The three phases are environmental impact as a result from extraction and transportation of raw material, manufacturing and packaging.
3. To reach the indicator grade gold or silver, information from EPDs for the building materials must be used in the LCA tool. For silver, at least 50% of the total amount of information for each material environmental impact must be originated from an EPD and a reference for the EPD must be given. For gold, at least 70% of the environmental impact information must come from an EPD.
4. In addition to the phases A1, A2 and A3 in SS EN 15804, phase A4 is taken into consideration for indicator grade silver and gold. Phase A4 addresses

the transport required from the materials manufacturing site to the construction site.

5. Besides having a higher percentage EPDs, for gold the total environmental impact for life cycle phases A1- A4 must decrease with ten percent, by for example reducing the amount of material or change the mode of transport.
6. For indicator grade silver, generic data for the environmental impact for each mode of transport is given in the LCA tool.
7. For indicator grade gold, data for environmental impact from transportation must be extracted for each individual project and chosen mode of transport.

## 14.4 The DGNB life cycle assessment tool

Each of the numbers 1-12 below, indicate each of the available Excel sheets in the DGNB LCA tool used in the research study. In DGNB any LCA tool can be used if the LCA tool calculate according to and based on the rules specified in the DGNB Criteria. The LCA tool used in the research study has been approved to calculate according to the DGNB criteria and has been used in projects to certify with DGNB.

1. **ESUCO database**

In the first Excel sheet of the LCA tool of the Danish version of DGNB, there is a material inventory based on European Sustainable Council Construction Database (ESUCO). DGNB developed ESUCO based on Ökobaudat. Within this sheet, different construction materials are listed with their respective environmental properties. It also includes datasets for buildings and modes of transport as well as different production strategies in different countries. The purpose of developing Ökobaudat was to simplify building certifications in the international arena with specific data for building materials. ESUCO is free of charge to users of the DGNB international system.

## 2. Ökobaudat database

The second Excel sheet is based on Ökobaudat datasets of construction materials. Ökobaudat was first released 2009 and is provided free of charge by the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR). The data is especially linked to the German construction industry and market. It involves generic data along with EPD datasets from companies and associations. It addresses buildings and modes of transport as well as building materials.

Both the above-mentioned databases with building materials also consist of different EOL scenarios as well as environmental impact values of the different materials listed in the datasets. The environmental impacts are listed in ESUCO and Ökobaudat and the information is used in the DGNB LCA tool (DGNB System 2018).

*Table 14.2: Environmental impacts defined in DGNB.*

| Abbreviation | Environmental impact name | Unit | Environmental impact (short description) |
|---|---|---|---|
| **GWP** | Global Warming Potential | [kg $CO_2$-equivalents] | Anthropogenic greenhouse effect increases |
| **ODP** | Ozone Depletion Potential | *[kg R11 equivalents/$m^2$ (SA)·a] | Contribution to destruction of ozone layer |
| **POCP** | Photochemical Ozone Creation Potential | [kg Ethene-equivalents] | Contribution to destruction of ozone layer |
| **AP** | Acidification Potential | [kg $SO_2$-equivalents] (Sulfur dioxide equivalents) | Contribution to acidification of soil and water bodies |
| **EP** | Eutrophication Potential | [kg Phosphate equivalents] | Changed nutrient levels in waters, can lead to increased fish mortality and other consequences |

| | | | |
|---|---|---|---|
| **ADP** | Abiotic Depletion Potential | [kg Sb-equivalents] (Antimony - equivalents) | Depletion of non-renewable (abiotic) resources). |

**R11 is a chlorofluorocarbon (CFC), SA refers to comparison of reference building values for surface area (SA) and year.*

The environmental impacts in table 14.2 are accompanied in the LCA tool by three other criteria, which involves energy usage for all the materials in the inventory, as shown below:

### 2.1 Primary energy (non-renewable) MJ

Determined for life cycle phases; construction, repair, operation and dismantling/disposal. The demand for non-renewable primary energy is determined in relation to area and year and specified in [MJ/m$^2$ (SA) a].

### 2.2 Primary energy (renewable) MJ

Quantifies the amount of used renewable fuel.

### 2.3 Secondary fuel (MJ)

Could broadly be considered as fossil fuels.

## 3. Material database

The third Excel sheet is the material database for the specific project. In this sheet, different materials from the previous material dataset-sheets is selected and specified in the material database by inserting data from previous Excel sheets one and two. Materials can be chosen both from ESUCO and Ökobaudat. Additionally, the materials need to be specified with the correct functional unit for the calculations, therefore details concerning weight per square meter etcetera is specified. The sheet gathers all environmental impact values as shown in table 14.2. The last section of the material database sheet consists of an EOL section, which depicts which EOL scenario is chosen for the specific material listed in the material database for the specific project. This can be chosen by a drop-down menu with the available EOL scenarios for each material, which are specified in the ESUCO and Ökobaudat database.

## 4. EOL database

In the fourth sheet, the specific EOL scenarios is listed by choosing them from either Ökobaudat or ESUCO. This list is illustrated in the drop-down menu in the third sheet, which enables a greater range of possible EOL scenarios to choose from for the calculations. The EOL scenarios impact values are specified for one factor of each functional unit in the EOL database.

## 5. Energy database

The fifth Excel sheet gathers different energy alternatives for the energy usage in the building, the different options are directly taken from the ESUCO or Ökobaudat database. The calculated energy demand is inserted in a column to calculate the different environmental impact values, based on operational energy for the building.

## 6. Building components

The sixth Excel sheet consists of materials used in the building. Sheets one to five is basically the fundamental material database that all data derives from. Sheet number six now enhances the level of detail that the LCA tool uses. In sheet number six the specific construction details concerning fundament, exterior and interior walls, stairs, platforms and roof is specified. In Denmark, different construction parts are specified by a certain number in a system from Samarbetskommittén för Byggnadsfrågor (sfB), for instance exterior walls (21). From all the different construction and building components, a specific material type can be selected which has all the environmental impact values embedded from previous arcs. Combined with the specified area of each construction element; thickness, length and number of elements, the exact composition of the studied building can be specified.

From the above insertion of specified construction values and amounts, the Excel sheet calculates weight and volume to fit the needed functional units, as specified earlier for the environmental impact values. The user also needs to insert the lifespan of each construction element or material.

Criterion TEC1.6 is evaluated through two factors; dismantling construction elements and separation of materials. Here the user can specify from a scale (1, 3, and 5) how simple or difficult it is to dismantle and separate raw materials from the construction materials. From the evaluation a sum is created of how many specifications of user insertion is done as well as the sum of the specified scale-grade.

The user needs to specify where the material or waste ends up after its dismantling and separation. Reuse, incineration, landfill and special treatment are the four available options.

The sixth sheet later calculates the environmental impact values (GWP, ODP, POCP, AP, EP and ADP) for the construction of the specified building as well as the energy parameters. The sheet also calculates the environmental impact values for a fifty-year interval of material-change of all the construction materials, meaning that materials with a specified lifespan of fifty years gets changed once in a fifty-year time interval.

The sheet does the same calculation as above for all the construction materials over a 120-year period as well, meaning that materials with a specified lifespan of 50 years gets changed twice.

The sheet continues to calculate the environmental impact values from the End of Life scenario for two timespans, 50 and 120 years. For the 50-year calculation, only materials which have a lifespan of 50 years or less are involved in the calculation. The same logic is used for the 120-year calculation, where materials with a lifespan of 120 years or less are involved in the calculation.

### 7. Operational energy

This seventh parameter complies all the energy used for the usage of the building; heating, electricity, cooling and lighting. From these energy indications environmental impact values are calculated. The sheet also involves the production of energy from the building through renewable sources. All data is specified per year.

### 8. Results (page 1)

The eighth sheet illustrates the LCA-result over a 50-year period. In the sheet, the user can specify which environmental aspect to illustrate by selecting in a drop-down menu. The different graphs illustrate the total environmental impact value for the whole building, as well as per square meter multiplied with year value.

## 9. Results (page 2)

The ninth sheet illustrates the LCA-result over a 120-year period. The structure is the same as in sheet seven as described above.

## 10. Allocation of points

The grading sheet evaluates ENV1.1 and ENV2.1 from the DGNB criteria. The sheet weighs the values from the 50-year calculations to 70% and the 120-year calculations to 30%. The grading also takes a quota between ENV1.1 and ENV2.1. The calculation uses the results from Results (Page 1) and Results (Page 2) and insert them to calculate $P$, $E$ and $R$ with the $td$ which is the lifespan. This calculation is made for construction, operation and building.

From the calculated $P$, $E$ and $R$ the sheet also uses a German reference building to compare some of the values to grade the designed building. There are calculations made for both 50 and 120-year time horizon.

## 11. Glossary

Gives an explanation to all the sfB-system abbreviations used for the different types of construction elements in the building.

## 12. Criterion TEC 1.6

Basically, the exact same calculations as used in sheet 5 Building Components with some additional formatting.

# Chapter 15 Environmental impacts for cross-laminated timber

The included phases required in the LCA tool for Miljöbyggnad 3.0 is the production stage phases A1-A3 and phase A4 which is the required transport from factory gate to construction site. However, life cycle phase A4 is only required if the applicant aims for a higher grade than bronze in Miljöbyggnad 3.0. The following study is limited to only include the production stage phases A1-A3 and therefore the lowest possible grading in Miljöbyggnad 3.0. A later section includes a short research regarding the inclusion of life cycle stage A4.

The included phases in the LCA tool for DGNB is the production stage phases A1-A3, phase B6 which is operational energy, phase C3-C4 which is transport to waste processing and disposal and phase D, which represent benefits and loads beyond the system boundary. In the LCA tool in DGNB, the phases *B2 Maintenance* and *B4 Replacement* are also taken account of but excluded in this study. Life cycle phase *B7 Operational water use* is assessed in another evaluation criterion than the material evaluation criterion in DGNB.

The following chapters intend to highlight potential differences between the environmental impacts for Miljöbyggnad 3.0 and DGNB with different EOL scenarios. The assessed EOL scenarios for CLT in DGNB are reuse, recycling and incineration. All EOL scenarios assumes that the EOL scenario chosen is solely the EOL scenario for the material. Since Miljöbyggnad 3.0 does not include any phases from the end-of life stage, only phases A1-A3 is considered for Miljöbyggnad 3.0.

To be able to compare the two sustainable building certifications and their life cycle phases respectively, an EPD for CLT from Stora Enso is used (Stora Enso 2017). Generally, high environmental impact values in the EPD equals stronger negative impacts on the environment. Moreover, a low, negative value for the environmental impact is beneficial for the environment since it reduces the levels of the environmental impact. The evaluated environmental impacts are highlighted and described in the following section.

## 15.1 Global warming potential (GWP)

The greenhouse effect is dependent on the accumulations of greenhouse gases which warms the air in the atmosphere. The global warming potential of a substance is exclusively compared to the global warming potential of carbon dioxide, which ultimately results in emissions that contribute to the greenhouse effect are quantified as kilogram carbon dioxide equivalents ($CO_2$-eq). Since GHGs persists in the atmosphere over long time periods, the GWP value must be specified related to a certain period. The characteristic period for GWP is usually 100 years. Another term is impact factor, which describes how potent a substance is to contribute to the GWP. Over a 100-year period, one kilogram of methane (or other substance) has an impact factor of 25, which means that the carbon dioxide equivalent of methane is 25. A given mass of methane contributes to the greenhouse effects 25 times as the same amount of carbon dioxide, GWP value one, over the selected period (DGNB System 2018).

### 15.1.1 Global warming potential without sequestration

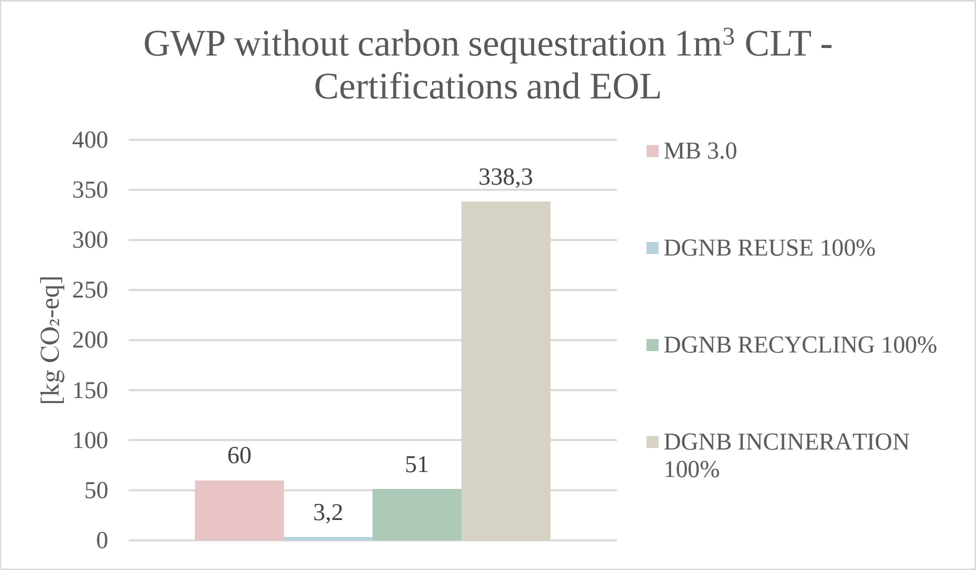


*Figure 15.1: Global warming potential without carbon sequestration in kilogram CO2-eq for one cubic metre CLT in Miljöbyggnad 3.0 and DGNB with varying EOL scenarios.*

Figure 15.1 illustrates that the worst certification option for CLT regarding GWP is DGNB with incineration 100% as EOL scenario. The best certification option for CLT regarding GWP is DGNB reuse 100%. The environmental impacts for CLT regarding GWP are relatively similar comparing DGNB Recycling and Miljöbyggnad 3.0.

*Table 15.1: The Global warming potential for one cubic metre CLT compared with the available certifications and EOL scenarios.*

| **Environmental certification** | **GWP [kg $CO_2$-eq]** | **Comparison [DGNB Reuse-eq]** |
|---|---|---|
| **MB 3.0** | 60,0 | 18,8 |
| **DGNB Reuse 100%** | 3,2 | 1 |
| **DGNB Recycling 100%** | 51,0 | 15,9 |
| **DGNB Incineration 100%** | 338,3 | 105,7 |

Figure 15.2 below illustrates the emitted GWP emissions during CLTs different life cycle stages as included in the different sustainable building certifications. One can identify that Miljöbyggnad 3.0, which only include production stage phases does not include the negative effects of life cycle phase C3, however, neither the beneficial effects of life cycle stage D. EOL scenarios recycling and reuse has decreased beneficial loads from stage D, which equivalently worsens the EOL scenarios overall GWP performance.

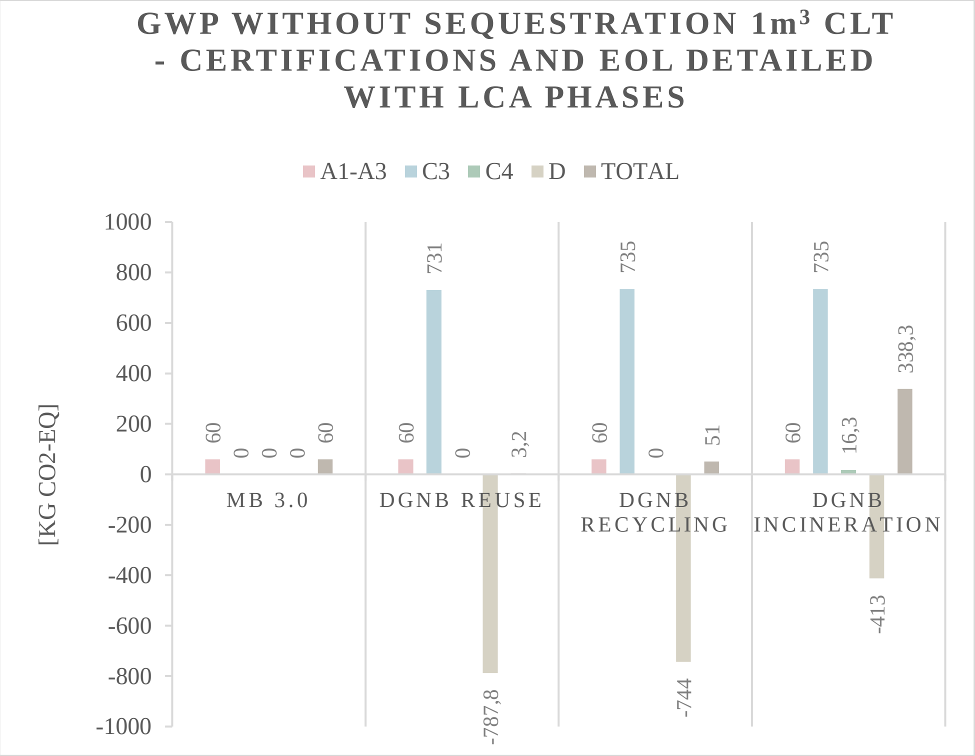


*Figure 15.2: Shows each certification and EOL scenario's Global warming potential contribution in each of the included LCA phases respectively.*

As the figure 15.2 above shows, production phases (A1-A3) are the same for every specific certification with varying EOL scenarios. The greatest differences between the different scenarios is the stage D variations observed from the EOL scenarios reuse, recycling and incineration. The stage D differences is the main factor that provides the total $CO_2$-eq differences between the scenarios. Worth to mention is the added stage C4 emissions in the EOL scenario incineration in DGNB (16.3 kg $CO_2$-eq). However, this value does not provide a major impact on the overall $CO_2$-eq emissions for DGNB incineration.

### 15.1.2 Global warming potential with sequestration

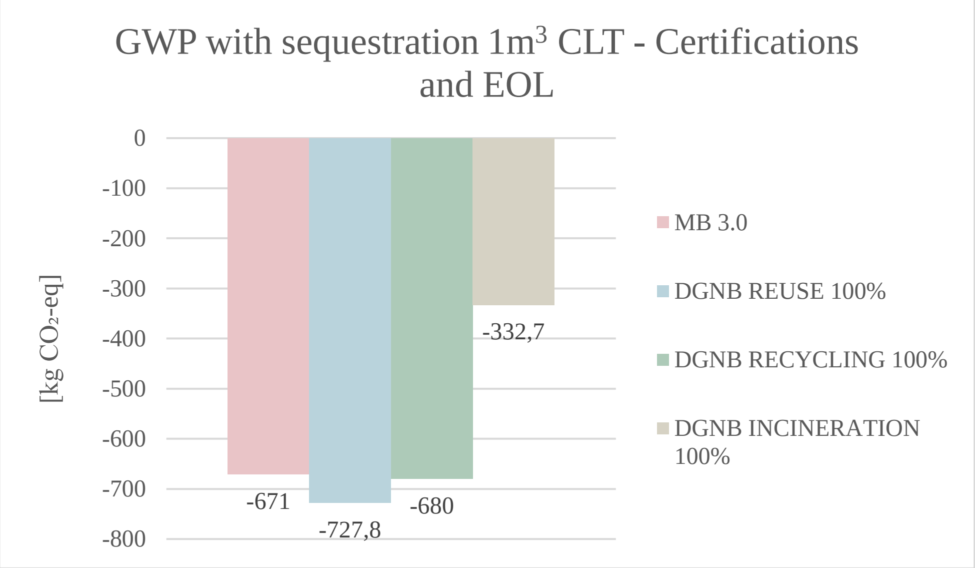


*Figure 15.3: Global warming potential with carbon sequestration in kilogram CO2-eq for one cubic metre of CLT in Miljöbyggnad 3.0 and DGNB with varying EOL scenarios.*

With the implementation of carbon sequestration in the life cycle of CLT, figure 15.3 above clearly demonstrate that all different certifications and EOL scenarios have a positive environmental impact regarding GWP. Since all values are negative. However, there is still some differences between the EOL scenarios and certifications. The best certification and EOL scenario regarding GWP and carbon sequestration for CLT is DGNB reuse. The worst scenario out of the four different alternatives present is DGNB incineration. However, this EOL scenario still offer a negative GWP value, which implies that the EOL scenario is still positive and beneficial for the environment.

The differences can be summed up by presenting that Miljöbyggnad 3.0, DGNB reuse and DGNB recycling has about the double amount of carbon sequestrated compared to DGNB incineration. Once again highlighting that all observed certifications and EOL scenarios offer a positive environmental impact regarding GWP for CLT.

*Table 15.2: The global warming potential with carbon sequestration for one cubic metre CLT compared with the available certifications and EOL scenarios.*

| **Environmental certification** | **GWP [kg $CO_2$-eq] with sequestration** | **Comparison [DGNB Reuse-eq]** |
|---|---|---|
| **MB 3.0** | -671,0 | 1,1 |
| **DGNB Reuse 100%** | -727,8 | 1 |
| **DGNB Recycling 100%** | -680,0 | 1,1 |
| **DGNB Incineration 100%** | -332,7 | 2,2 |

To further illustrate the differences between the observed certifications and EOL scenarios, figure 15.4 illustrates the carbon sequestration and carbon emissions of one cubic meter of CLT throughout its life cycle.

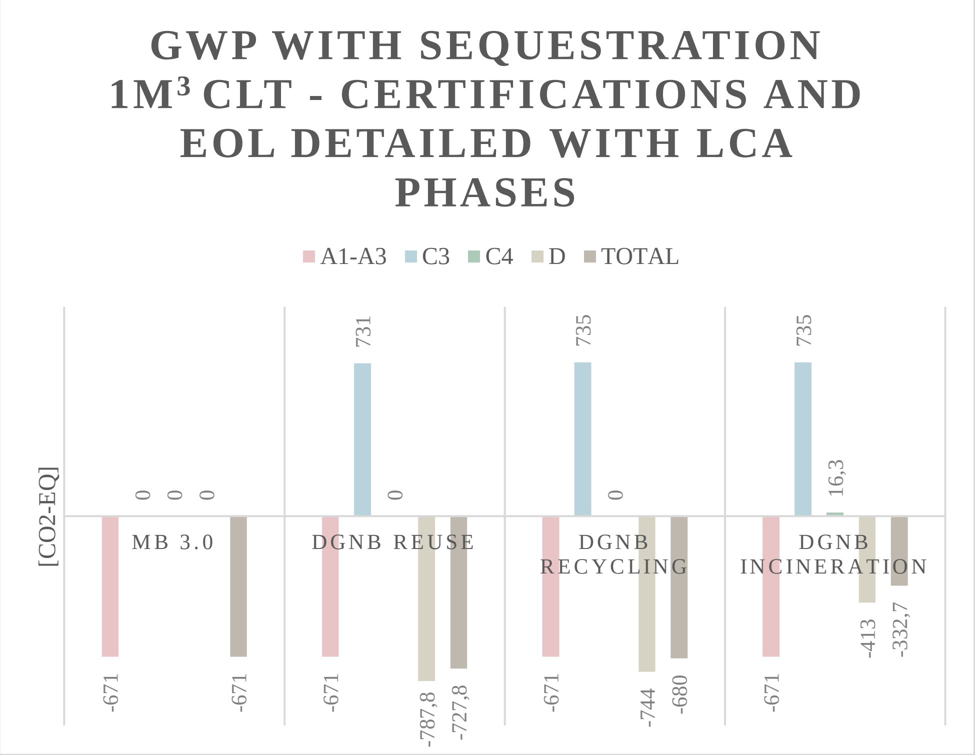


*Figure 15.4: Illustrates each certification and EOL scenario's global warming impact with carbon sequestration contribution in each of the included LCA phases respectively.*

For CLT in Miljöbyggnad 3.0, production stage phases A1-A3 depending on if carbon sequestration is included or not, both sequestrate 731 kg $CO_2$-eq and produce 60 kg $CO_2$-eq, finally creating a net debt of 671 kg $CO_2$-eq. The DGNB certification and its respective EOL scenarios acquire even more carbon savings by the respective net-value for the EOL scenarios of DGNB and CLT. The greatest positive environmental impacts regarding GWP for CLT, when implementing carbon sequestration derives from life cycle phase D and the carbon sequestration in production stage phases A1-A3.

DGNB reuse also have $CO_2$-eq emissions in life cycle phase C3. However, a lesser amount compared to the savings in stage life cycle stage D. DGNB reuse saves the most $CO_2$-eq in phase D, thus resulting in the most beneficial EOL scenario and certification whilst implementing carbon sequestration. DGNB recycling also saves carbon in LCA stage D and produces $CO_2$-eq emissions in C3, however not as much as DGNB reuse. The reduced carbon savings in DGNB recycling compared to DGNB reuse, results in DGNB recycling being the second-best alternative for GWP with consideration to carbon sequestration for CLT. The worst certification and EOL scenario comparing Miljöbyggnad 3.0 and DGNB, considering GWP and carbon sequestration for CLT is DGNB and incineration. For DGNB incineration, the carbon dioxide emissions in life cycle phase C3 are higher than the carbon savings in life cycle stage D, which explains the reduced positive environmental impact regarding GWP for CLT.

However, whilst implementing carbon sequestration in both Miljöbyggnad 3.0 and DGNB with varying EOL scenarios, all certification and EOL scenarios provide a positive environmental impact regarding GWP, with varying potency.

### 15.1.3 Comparison of GWP for CLT with and without carbon sequestration

The figure 15.5 below, illustrates the environmental impact carbon sequestration has on one tonne of CLT regarding GWP. In any EOL scenario for DGNB (reuse, recycling or incineration) and Miljöbyggnad 3.0, including carbon sequestration gives a negative GWP value. The sequestration value in $CO_2$-eq are the same for all different certification scenarios, it is only the respective EOL scenarios that have varying values for C3-C4 and D thus creating the differences as depicted in figure 15.5. By including carbon sequestration, one will radically improve the environmental impact considering GWP for CLT, no matter the certification or EOL scenario.

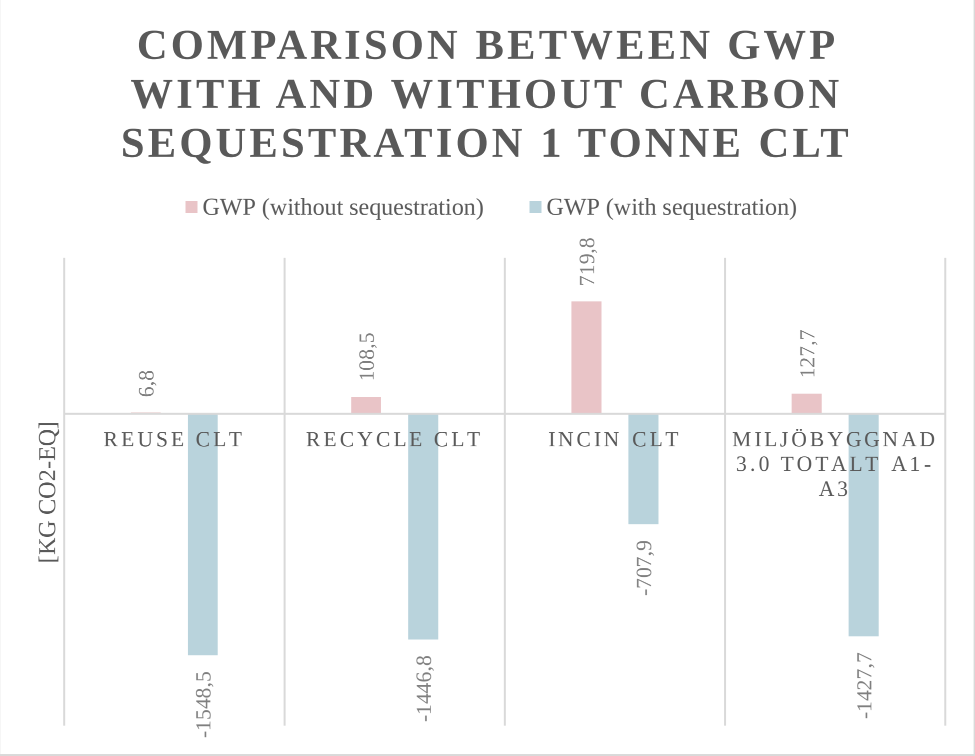


*Figure 15.5: The global warming potential in kilogram CO2-eq for each certification and EOL scenarios with and without the implementation of carbon sequestration.*

## 15.2 Ozone depletion potential (ODP)

The atmosphere contains low concentrations of ozone. However, ozone's shielding effects from harmful high-energy ultraviolet radiation is crucial for life on Earth. The chemical properties of ozone consist of three oxygen atoms, which forms the ozone molecule ($O_3$). Atmospherically ozone is present in the stratosphere between 15 and 50 kilometres above the Earth surface and without it, the Sun's harmful UV radiation would sterilize the surface on Earth. The weakening of the ozone layer has harmful effects on life on Earth, such as cancerous tumours in animals and humans (National Aeronautics and Space Administration (NASA) 2019; DGNB system 2018).

The ozone layer utilizes the *ozone-oxygen cycle* which continuously absorbs the high-energy short-wave UV radiation to split oxygen molecules ($O_2$) thus absorbing the UV radiation and splitting the oxygen molecule into two oxygen atoms. These oxygen atoms later react with other oxygen molecules ($O_2$) which is abundant in the atmosphere to form ozone ($O_3$) once again. This process releases shorter wavelengths of energy which is not harmful for animals and humans. The ozone-oxygen cycle is dependent on the same rate of destruction and creation of ozone in the stratosphere (NASA 2019).

The anthropogenic production of halogenated hydrocarbons, such as chlorofluorocarbons (CFCs) increases the rate of destruction of ozone in the stratosphere, thus shifting the balance of destruction and creation of ozone in the stratosphere. This is due to that free chlorine which is a halogen, reacts with ozone, creating chlorine monoxide (ClO) and leaving one oxygen molecule ($O_2$), destructing ozone. The chlorine monoxide later reacts with the single oxygen atoms (O) leaving free chlorine and an oxygen molecule ($O_2$), not creating ozone, hence the increased rate of ozone destruction. (NASA 2019).

The ozone depletion potential is specified in DGNB as kg R11 equivalents, which refers to the chlorofluorocarbon comparison substance CFC-11 (DGNB system 2018).

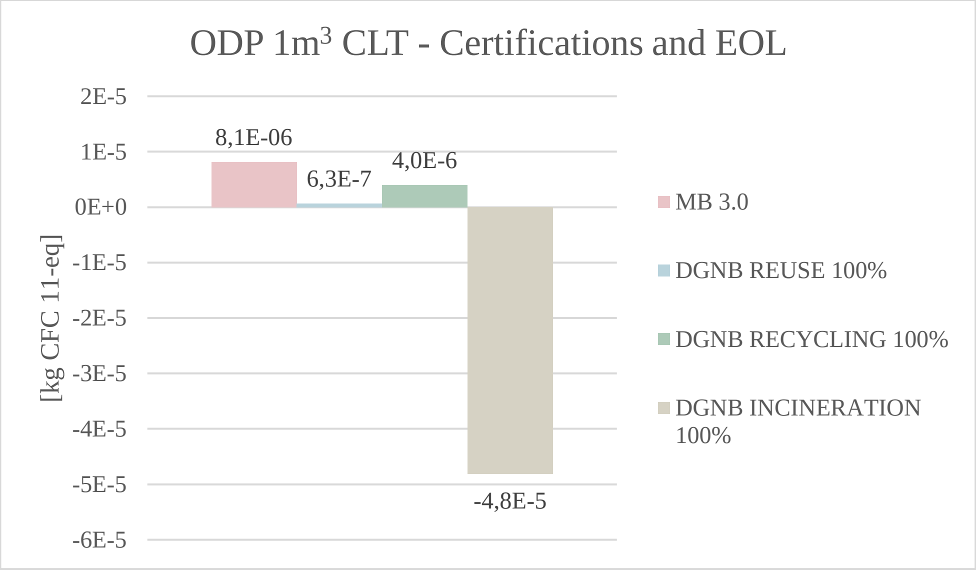


*Figure 15.6 – Ozone depletion potential in kilogram CFC 11-eq for one cubic metre of CLT in MB 3.0 and DGNB with varying EOL scenarios.*

DGNB incineration presents a negative value for CLT regarding ODP, which implies a positive environmental effect. Miljöbyggnad 3.0 is the most harmful certification for the environment regarding CLT and its ODP, since it shows the highest emission of kg CFC 11-eq. Since DGNB includes the same life cycle phases as Miljöbyggnad 3.0 as well as adding life cycle phase C3. Regarding life cycle phase C4 and D, all certifications and EOL scenarios produce the same value for ODP as Miljöbyggnad 3.0 in production stage phases A1-A3. However, DGNB compensates with environmental positive effects for the high value attained in production stage phases A1-A3 through the chosen EOL which generates a systematic lower ODP value for all EOL scenarios in DGNB regarding CLT.

*Table 15.3: The ozone depletion potential for one cubic metre CLT compared with the available certifications and EOL scenarios.*

| **Environmental certification** | **ODP [kg CFC 11-eq]** | **Comparison [DGNB Reuse-eq]** |
|---|---|---|
| MB 3.0 | $8{,}1\cdot10^{-6}$ | 12,9 |
| DGNB Reuse 100% | $6{,}3\cdot10^{-7}$ | 1 |
| DGNB Recycling 100% | $4{,}0\cdot10^{-6}$ | 6,3 |
| DGNB Incineration 100% | $-4{,}8\cdot10^{-5}$ | Positive environmental effect (-76,5) |

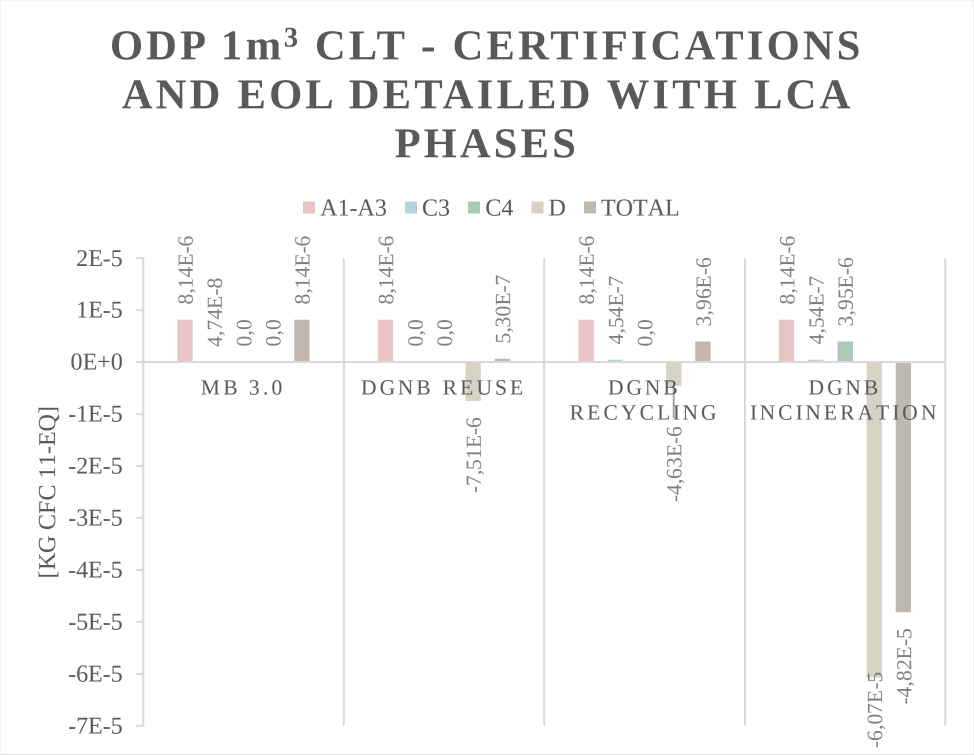


*Figure 15.6: Illustrates each certification and EOL scenario's ozone depletion potential contribution in each of the included LCA phases respectively.*

As figure 15.6 above illustrates, the improvement of ODP in DGNB resides mainly in the positive environmental impacts of stage D in reuse, recycling and incineration. One can clearly see the huge beneficial stage D in DGNB incineration providing a total positive environmental impact (aiding the ozone production) for

DGNB incineration. To clarify, negative values for the environmental impacts implies positive environmental effects. A negative value means a net uptake of emission, which is the opposite of emitting environmentally harmful emissions.

## 15.3 Acidification potential (AP)

Acidification is a problem caused by anthropogenic acidifying emissions, some of these emissions are sulfur dioxide ($SO_2$), ammonia ($NH_3$) and nitrogen oxide ($NO_x$). The acidification potential is measured in sulfur dioxide $SO_2$-equivalents. The acidifying emissions as mentioned above react with airborne water to form acids (sulfur acid and nitric acid) which later enters the ground from the air by *acid rain*. Acidification leaches the soil from important nutrients due to the increased rate of chemical breakdown of these nutrients. The acidification is harmful for plants and can lead to forest dieback as well as negative aquatic life impacts. The high acid concentration in the acid rain can also lead to damage on concrete structures due to the chemical acid attacks of $NO_x$ and $SO_2$ (Kim & Chae, 2016; DGNB System 2018).

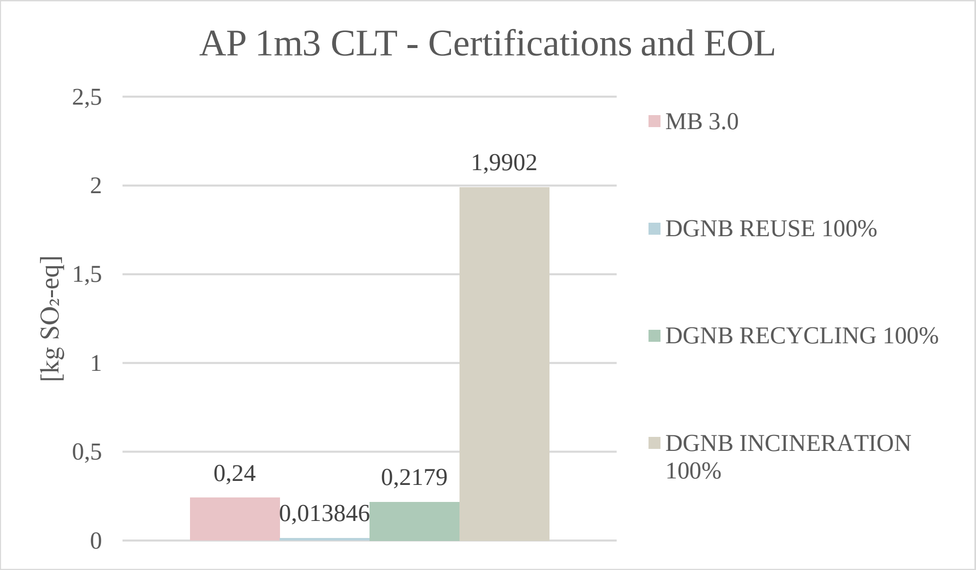


*Figure 15.7: Acidification potential in kilogram SO2-eq for one cubic metre of CLT in Miljöbyggnad 3.0 and DGNB with varying EOL scenarios.*

DGNB incineration is significantly the most harmful EOL scenario considering AP for CLT. Miljöbyggnad 3.0 and DGNB recycling illustrate basically the same values for AP regarding CLT. DGNB reuse is the best certification and EOL scenario to minimize harmful effects of AP for CLT.

*Table 15.4: The acidification potential for one cubic metre of CLT compared with the available certifications and EOL scenarios.*

| **Environmental certification** | **AP [kg Ethene-eq]** | **Comparison [DGNB Reuse-eq]** |
|---|---|---|
| MB 3.0 | 0,20 | 17,3 |
| DGNB Reuse 100% | 0,01 | 1 |
| DGNB Recycling 100% | 0,20 | 15,7 |
| DGNB Incineration 100% | 2,00 | 143,7 |

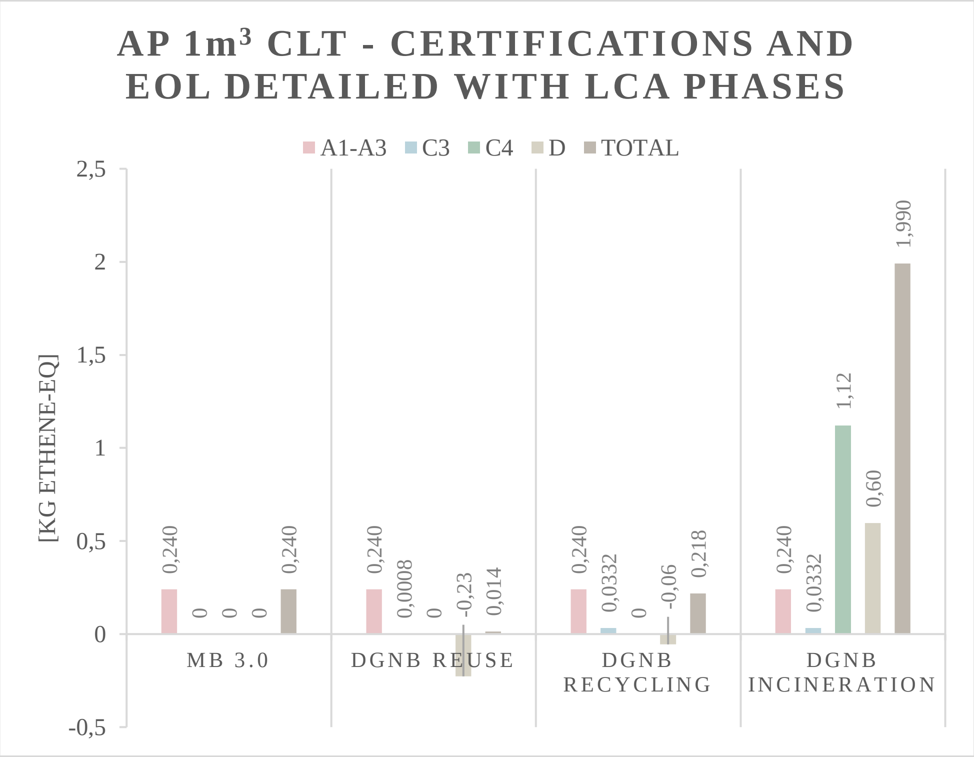


*Figure 15.8: Illustrates each certification and EOL scenario's acidification potential contribution in each of the included LCA phases respectively.*

As figure 15.8 illustrates, DGNB reuse shows the best results considering AP for CLT. AP for Miljöbyggnad 3.0 and DGNB recycling is about the same and DGNB incineration is by far the worst EOL scenario considering AP for CLT. In certification and EOL scenario DGNB reuse, life cycle stage D limit and reduce the overall emission and thus resulting in the best EOL scenario regarding CLT for AP. In DGNB incineration, both life cycle phases C4 and D emits $SO_2$-eq and accumulates into the highest and most harmful certification and EOL scenario regarding AP for CLT.

## 15.4 Eutrophication potential (EP)

When soils and waters are excessively loaded with nutrients from anthropogenic sources such as fertilizers or leakage of combustion pollutants from manufacturing and construction processes, rapid algae growth can occur in water bodies. This increased rate of algae growth poses a threat to aquatic life and can lead to increased fish mortality. The unit used for the environmental impact EP is kg $PO_4^{3-}$-equivalents, *phosphate ions* (Kim & Chae 2016; DGNB System 2018; Life Cycle Association of New Zealand 2010).

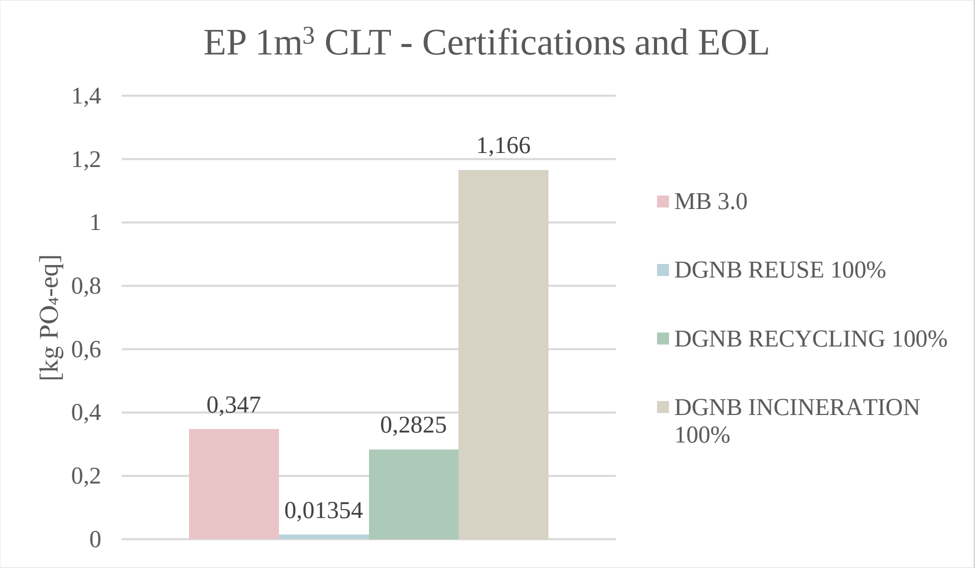


*Figure 15.9: Eutrophication potential in kilogram $PO_4$-eq for one kilogram of CLT in Miljöbyggnad 3.0 and DGNB with varying EOL scenarios.*

DGNB incineration presents the highest EP for CLT, followed by Miljöbyggnad 3.0 and DGNB recycling. The environmental impact regarding EP for DGNB reuse is comparatively low and the best certification for EP regarding CLT.

*Table 15.5: The Eutrophication potential for one cubic metre CLT compared with the available certifications and EOL scenarios.*

| **Environmental certification** | **EP [kg $PO_4^3$ eq]** | **Comparison [DGNB Reuse-eq]** |
|---|---|---|
| MB 3.0 | 0,35 | 24,8 |
| DGNB Reuse 100% | 0,014 | 1 |
| DGNB Recycling 100% | 0,28 | 20,2 |
| DGNB Incineration 100% | 1,17 | 83,3 |

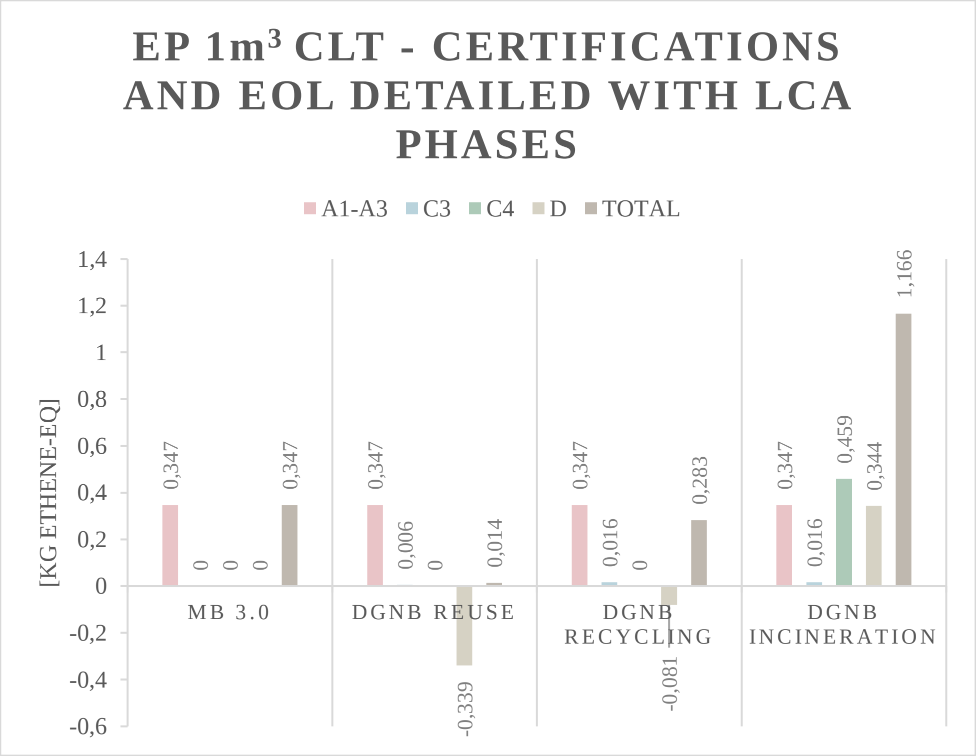


*Figure 15.10: Shows each certification and EOL scenario's eutrophication potential contribution in each of the included LCA phases respectively.*

As figure 15.10 above illustrates, DGNB reuse shows the best result considering EP for CLT. DGNB recycling is the second-best certification regarding EP for

CLT, followed by Miljöbyggnad 3.0. DGNB incineration is by far the worst certification and EOL scenario considering EP for CLT. In DGNB reuse, stage D limit and reduce the overall emission, thus resulting in the best certification and EOL scenario for AP regarding CLT. In DGNB incineration both life cycle phases C4 and D emits $PO_4^3$-eq and accumulates into the highest EP for CLT. Production stage phases for all different scenarios and EOL scenarios are relatively high, suggesting that raw material manufacturing contributes to EP regarding CLT the most, apart from life cycle phase C3 in DGNB incineration which show the highest EP for CLT out of all possible life cycle phases.

## 15.5 Photochemical ozone creation potential (POCP)

Ground-level ozone is known to be dangerous and harmful for the human health as well as for plants and animals. Ground-level ozone is formed by nitrogen oxides ($NO_x$) and VOC (volatile organic compounds) under the influence of sunlight (Altenstedt & Pleijel 1998).

These harmful reactions taking place on ground-level is often referred at as summer smog which are harmful to the respiratory organs. DGNB.

POCP values are often visualized and measured as the ratio between the VOCs produced ozone and the produced ozone of the same amount of emitted ethene. The following ratio describes the unit kilogram ethene-equivalents in POCP (Altenstedt & Pleijel 1998).

$$POCP_i = 100\ \times \frac{\text{ozone increment with the } i\text{th VOC}}{\text{ozone increment with ethene}}$$

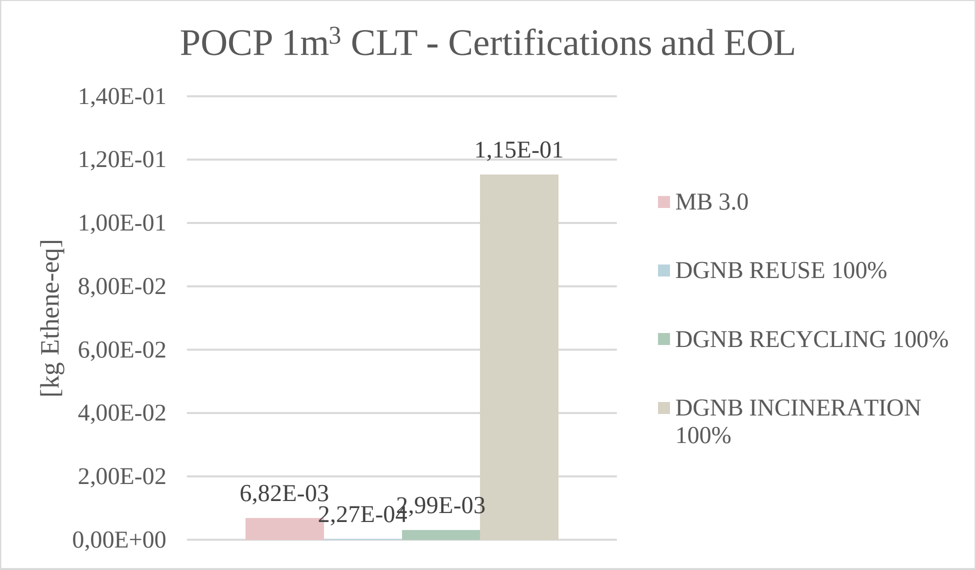


*Figure 15.11: Photochemical ozone creation potential in kg ethene-eq for one cubic metre of CLT in Miljöbyggnad 3.0 and DGNB with varying EOL scenarios.*

DGNB incineration is by far the least beneficial certification and EOL scenario considering POCP for CLT. The other certifications and EOL scenarios, compared to DGNB incineration are almost negligible, although they still pose negative environmental effects. DGNB reuse is the best certification and EOL scenario to minimize harmful effects of POCP regarding CLT.

*Table 15.6: The photochemical ozone depletion potential for one cubic metre CLT compared with the available certifications and EOL scenarios.*

| **Environmental certification** | **POCP [kg Ethene-eq]** | **Comparison [DGNB Reuse-eq]** |
|---|---|---|
| MB 3.0 | $6,8 \cdot 10^{-3}$ | 29,6 |
| DGNB Reuse 100% | $2,3 \cdot 10^{-4}$ | 1 |
| DGNB Recycling 100% | $3,0 \cdot 10^{-3}$ | 13,2 |
| DGNB Incineration 100% | 0,12 | 506,6 |

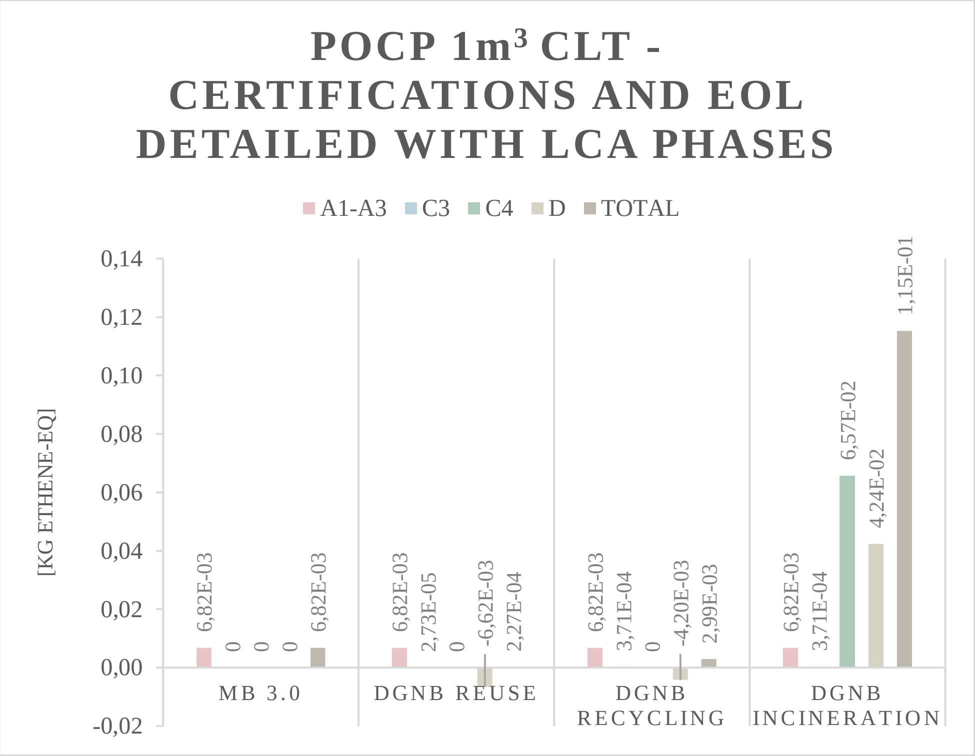


*Figure 15.12: Illustrates each certification and EOL scenario's photochemical ozone depletion potential contribution in each of the included LCA phases respectively.*

As shown in figure 15.12 above, DGNB reuse emits the least kilogram ethene-eq followed by DGNB recycling and Miljöbyggnad 3.0 regarding CLT for the environmental impact POCP. Life cycle phase D in both DGNB reuse and DGNB recycling is negative, thus resulting in a limited overall total value for POCP in the respective EOL scenarios. DGNB incineration regarding POCP for CLT is dominated by large ethene-eq emissions in life cycle stage C4 and D. The results clearly show that DGNB incineration is the least beneficial option considering ethene-eq emissions for POCP regarding CLT.

## 15.6 Abiotic depletion potential (ADP)

Abiotic means non-renewable and the ADP refers to the non-renewable resource consumption and more precisely the function between the existing natural reserve of the resources and the rate of their extraction. Abiotic resources are mineral resources, hence not from the biosphere. ADP is separated into two different subgroups. ADP elements (ADPE), which are minerals that does not include fossil fuels and ADP fossil fuels (ADPF), as the name implies contain the consumption rate of fossil fuels. Uranium is an example of an ADPE.

ADPE is quantified by using a function, which simplified can be explained as the ratio between the reserve of the resource and the extraction rate of the resource. This ratio is also compared to the extraction rate of a reference resource which is antimony (Sb) as kilogram per year. The reserve of the resource is described as the *ultimate reserve* and is defined as the total amount of the resource that can be found in the Earth's crust. (Pikon 2012; DGNB System 2018).

### 15.6.1 Abiotic depletion potential elements (ADPE)

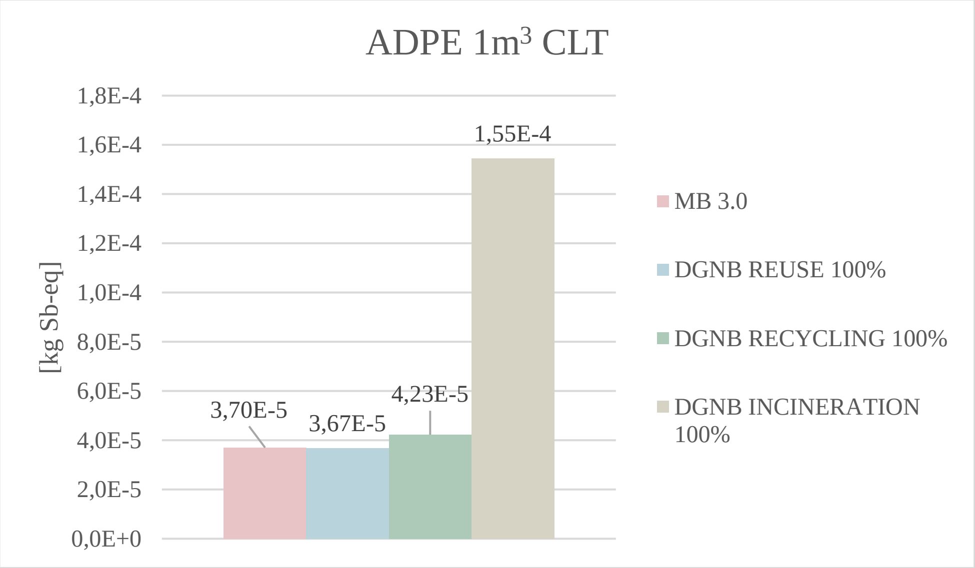


*Figure 15.13: Abiotic depletion potential elements in kg Sb-eq for one cubic metre of CLT in Miljöbyggnad 3.0 and DGNB with varying EOL scenarios.*

DGNB incineration presents the highest ADPE values regarding CLT, whereas Miljöbyggnad 3.0, DGNB recycling and DGNB reuse are rather similar regarding ADPE values for CLT.

*Table 15.7 - The abiotic depletion potential elements for one cubic metre CLT compared with the available certifications and EOL scenarios.*

| **Environmental certification** | **ADPE [kg Sb-eq]** | **Comparison [DGNB Reuse-eq]** |
|---|---|---|
| MB 3.0 | $3{,}7 \cdot 10^{-5}$ | 1 |
| DGNB Reuse 100% | $3{,}7 \cdot 10^{-5}$ | 1 |
| DGNB Recycling 100% | $4{,}2 \cdot 10^{-5}$ | 1,2 |
| DGNB Incineration 100% | $1{,}6 \cdot 10^{-4}$ | 4,2 |

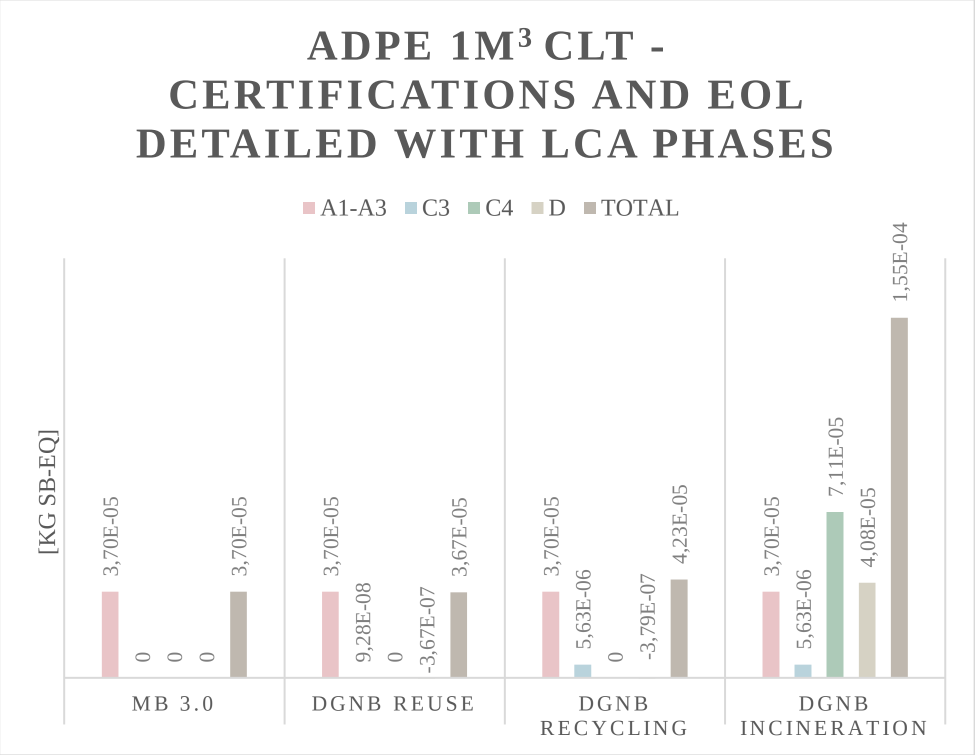


*Figure 15.14: Shows each certification and EOL scenario's abiotic depletion potential elements contribution in each of the included LCA phases respectively.*

The production stage phases A1-A3 for Miljöbyggnad 3.0, DGNB reuse and DGNB recycling are responsible for most Sb-eq emissions, with some minor differences in life cycle phases C3 and C4 for certification and EOL scenario Miljöbyggnad 3.0, DGNB reuse and DGNB recycling. For ADPE, DGNB incineration is the worst EOL scenario regarding CLT, with high emissions of Sb-eq values in both life cycle phase C4 and D.

### 15.6.2 Abiotic depletion potential fossil fuels (ADPF)

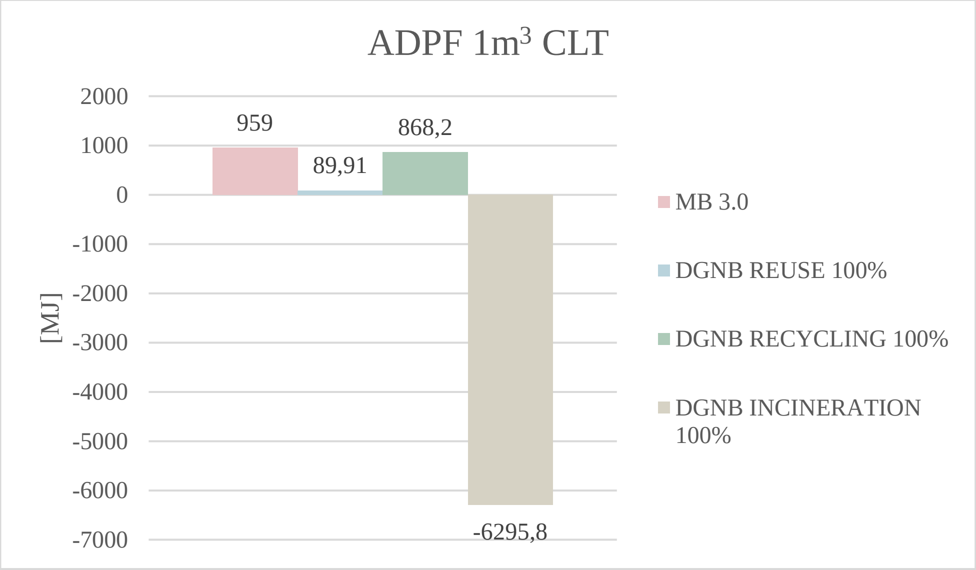


*Figure 15.15: Abiotic depletion potential fossil fuels in MJ for one cubic metre of CLT in Miljöbyggnad 3.0 and DGNB with varying EOL scenarios.*

DGNB incineration presents a negative value for ADPF which implies a positive environmental effect regarding CLT. Miljöbyggnad 3.0 is the most harmful certification for the environment regarding ADPF, considering that it shows the highest value (959 MJ). Since all presented EOL scenarios for DGNB include production stage phases A1-A3, as well as C3-C4 and D, figure 15.15 above suggests that the net value of C3-C4 and D for all EOL scenarios in DGNB are negative. The negative values in life cycle stages C3-C4 and D, inhibits Miljöbyggnad 3.0 to include the attractive values that will lower the overall ADPF emissions for CLT.

No matter the certification nor the possible EOL scenarios, one cubic meter of CLT produce the same value of ADPF in production stage phases A1-A3. However, DGNB compensates with positive environmental effects through the chosen EOL scenarios, which generates a systematic lower ADPF value for DGNB which include EOL scenarios. The effect of reduction of harmful values for ADPF regarding CLT, subsides in the life cycle phases C3, C4 and D, which are not included in Miljöbyggnad 3.0.  Finally, DGNB reuse does not require a lot of energy (89.9 MJ) in the total overall life cycle, whereas DGNB recycling demand more energy (868.2 MJ) and DGNB incineration gives a positive energy output, since it probably includes energy recycling when incinerating the CLT.

*Table 15.8: The Abiotic depletion potential fossil fuels for one cubic metre CLT compared with the available certifications and EOL scenarios.*

| **Environmental certification** | **ADPF [MJ]** | **Comparison [DGNB Reuse-eq]** |
|---|---|---|
| MB 3.0 | 959,0 | 10,7 |
| DGNB Reuse 100% | 89,9 | 1 |
| DGNB Recycling 100% | 868,2 | 9,7 |
| DGNB Incineration 100% | -6295,8 | Positive environmental effect (-70,0311) |

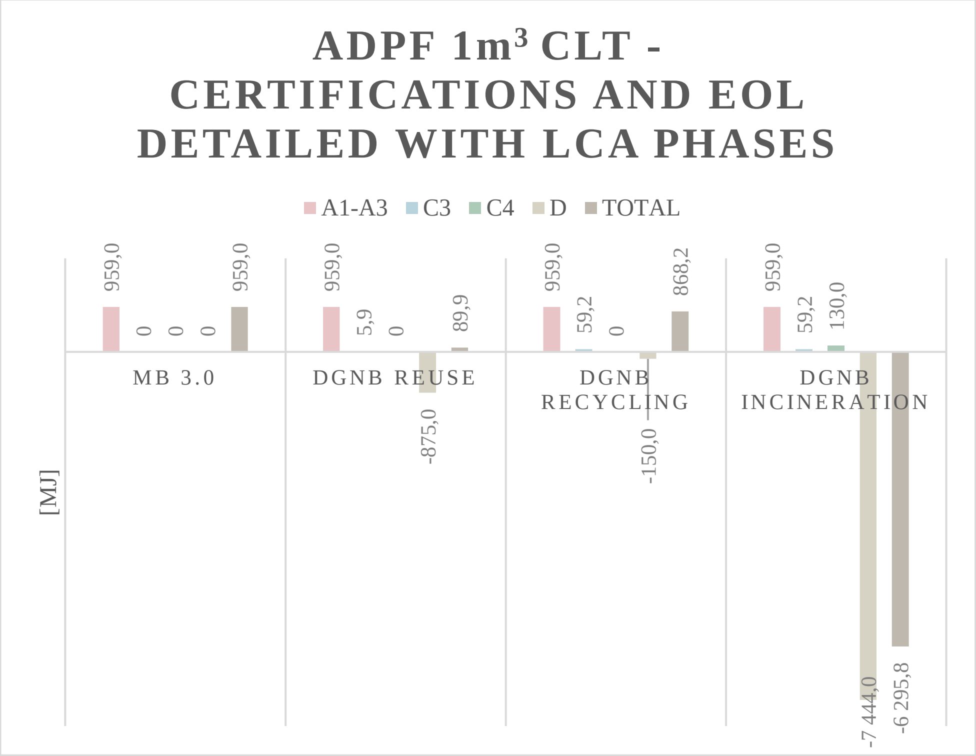


*Figure 15.16: Diagram over each certification and EOL scenario's abiotic depletion potential fossil fuels contribution in each of the included LCA phases respectively.*

The best EOL scenario considering ADPF for CLT is DGNB incineration, where the energy [MJ] released in production phases A1-A3, are overwritten by the positive effects in stage D, conclusively resulting in an overall positive environmental effect. Miljöbyggnad 3.0 and DGNB recycling is fairly comparable. DGNB reuse is the second-best certification and EOL scenario regarding ADPF for CLT, having the same characterizing effects as DGNB incineration, however not as powerful.

## 15.7 Summarized results: Environmental impacts for cross-laminated timber

*Table 15.9: Summarized results for chapter 15 and the total environmental impacts for different certification scenarios.*

| CLT [1 cubic metre] | MB 3.0 | DGNB Reuse | DGNB Recycling | DGNB Incineration | Declared Unit |
|---|---|---|---|---|---|
| **GWP (Without seq)** | 60,0 | 3,2 | 51,0 | 338,3 | **[kg CO2-eq]** |
| **GWP (With seq)** | -671,0 | -727,8 | -680,0 | -332,7 | **[kg CO2-eq]** |
| **ODP** | 0,0000081 | 0,0000006 | 0,0000040 | -0,0000482 | **[kg CFC11-eq]** |
| **AP** | 0,240 | 0,014 | 0,218 | 1,990 | **[kg SO2-eq]** |
| **EP** | 0,3470 | 0,0135 | 0,2825 | 1,1660 | **[kg PO4-eq]** |
| **POCP** | 0,00682 | 0,00023 | 0,00299 | 0,11500 | **[kg Ethene-eq]** |
| **ADPE** | 0,000037 | 0,000037 | 0,000042 | 0,000155 | **[kg Sb-eq]** |
| **ADPF** | 959,0 | 89,9 | 868,2 | -6295,8 | **[MJ]** |

Conclusions based on table 15.9:

- DGNB Incineration has the worst certification scenario regarding GWP (with and without carbon sequestration), AP, EP, POCP and ADPE.
- DGNB Incineration is the best certification scenario regarding ODP and ADPF.
- DGNB Reuse is the best certification scenario regarding GWP (with and without carbon sequestration), AP, EP, POCP and ADPE.

For details regarding environmental impacts during different life cycle phases for the certification scenarios, check the appropriate sections in chapter 15.

In general, the following conclusion can be made for the environmental impacts during different life cycle stages. Miljöbyggnad 3.0 only include production life cycle phases A1-A3, whereas DGNB include life cycle phases C3-C4 and D. This additional life cycle inclusion enables the opportunity for increases and decreases in total environmental impacts. In some cases, the results can be positive, depending on the added phases’ environmental benefits, alternatively, the effects can be negative due to the detrimental environmental impacts in the added life cycle stages.

Varying EOL scenarios can either act positively or negatively depending on the assessed environmental impact as well as the construction material. The inclusion of carbon sequestration significantly improves CLT’s GWP in all types of certification scenarios.

# Chapter 16 Construction material comparison

## 16.1 Environmental impacts for steel

Miljöbyggnad 3.0 presents the greatest environmental impact value for GWP compared to DGNB. This is due to the high environmental values for recycling and reusing steel which improves the environmental performance for steel in DGNB. Miljöbyggnad 3.0 only considers production stages A1-A3 reducing the materials properties to better its environmental ability.

For ODP both Miljöbyggnad 3.0 and DGNB have about the same values, however a slight benefit for Miljöbyggnad 3.0, this is the only value that are less than the correspondent value in DGNB.

Miljöbyggnad 3.0 does not include the positive effects for acidification potential that resides in life cycle stages C3 and D, thus resulting in a 1.6 times worse value in AP.

DGNB reuse, recovery and recycling potential offers better environmental impact values considering Eutrophication potential. This is also due to the extended inclusion of life cycle phases that contributes with positive effects considering eutrophication. Miljöbyggnad 3.0 offers 1.5 times more EP impact than DGNB.

Photochemical ozone creation potential in Miljöbyggnad 3.0 is 2.5 worse than in DGNB, with the same effect as mentioned before, inclusion of positive effects in C3 and D.

Abiotic depletion potential for elements and fossil fuels follows the previous results where Miljöbyggnad 3.0 offers 1.6 and 1.8 times worse environmental impacts considering ADPE and ADPF.

The steel EPD used in the research below is called *Structural steel: sections and plates* and it is from the Ökobaudat database. The EOL scenario is reuse, recovery and recycling potential, all mixed together as one using different weighing from different EOL scenarios.

*Table 16.1: Emission values for one tonne steel in Miljöbyggnad 3.0 without EOL and in DGNB with EOL scenario reuse, recovery and recycling. The table also illustrates the factors of emission for each environmental impact between the two certifications.*

| **Environmental Impact** | **MB 3.0** | **DGNB REUSE** | **MB 3.0 (compared to DGNB reuse)** | **DGNB** |
|---|---|---|---|---|
| GWP [kg $CO_2$-eq] | 1735 | 776 | 2,2 | 1 |
| ODP [kg R11-eq/$m^2$(SA)*a] | $1{,}39 \cdot 10^{-7}$ | $1{,}45 \cdot 10^{-7}$ | 1,0 | 1 |
| AP [kg $SO_2$-eq] | 3,52 | 2,2 | 1,6 | 1 |
| EP [kg Phosphate-eq] | 0,37 | 0,244 | 1,5 | 1 |
| POCP [kg Ethene-eq] | 0,698 | 0,284 | 2,5 | 1 |
| ADPE [kg Sb-eq] | $2{,}85 \cdot 10^{-4}$ | $1{,}74 \cdot 10^{-4}$ | 1,6 | 1 |
| ADPF [MJ] | $1{,}70 \cdot 10^{4}$ | $9{,}55 \cdot 10^{3}$ | 1,8 | 1 |

The two different certification scenarios for steel consists of MB 3.0 utilizing production stage phases A1-A3, whilst DGNB reuse also covers life cycle phases C3, C4 and D. In the table above, it is clearly stated that DGNB reuse provides a better alternative considering all environmental aspects except ODP. This effect depends mainly on the positive effects that can be utilized in the added life cycle phases C3, C4 and D. A summarizing statement is that DGNB reuse as chosen certification and EOL scenario serves as a twice as a good option when compared to Miljöbyggnad 3.0.

## 16.2 Environmental impacts for concrete

In this research a combination of EPDs for concrete is used. The first is an EPD from Norway and called *Kompaktvegg Opplandske Betongindustri AS*, this EPD is responsible for the values in the production stage phases A1-A3. Since there were no further info about the other life cycle phases another EPD, or series of EPDs were used. In Ökobaudat the life cycle stages C3-C4 and D for all different strength grades of concrete C20/30 etcetera have the same numerical values for the EOL stages.

In the research regarding concretes environmental impact in Miljöbyggnad 3.0 the first EPD from Norway was used. Equivalently for the environmental impact of concrete in DGNB the Norwegian EPD was used for the life cycle phases A1-A3 and the EOL phases C3, C4 and D was derived from the EPDs in Ökobaudat for different strength grades of concrete.

As table 16.2 illustrates, the differences between concrete in Miljöbyggnad 3.0 and DGNB is limited, for the environmental impacts; global warming potential, ozone depletion potential, acidification potential and abiotic depletion potential elements the environmental impacts are the same. The only differences between the certification scenarios is present for eutrophication potential, photochemical ozone creation potential and abiotic depletion potential fossil fuels. Whereas the first two, EP and POCP have lower environmental impacts in Miljöbyggnad 3.0 even while the included LCA stages are fewer, this is due to the included phases C3-C4 and D contribute with emissions thus increasing the emissions in DGNB considering EP and POCP. The emissions for EP and POCP are about ten percent lower than for the correspondent values for DGNB.

The opposite is actual for abiotic depletion potential fossil fuels, where the included phases C3-C4 and D in DGNB reduce the energy released, alternatively recycles some of the energy for the product. The emissions for Miljöbyggnad 3.0 are about ten percent higher than for the correspondent values in DGNB for concrete.

*Table 16.2: Emission values for one tonne concrete in Miljöbyggnad 3.0 without EOL and in DGNB with EOL scenario reuse. The table also illustrates the factors of emission for each environmental impact between the two certifications.*

| **Environmental Impact** | **MB 3.0** | **DGNB REUSE** | **MB 3.0 (compared to DGNB reuse)** | **DGNB** |
|---|---|---|---|---|
| GWP [kg $CO_2$-eq] | 157 | 148 | 1,1 | 1 |
| ODP [kg R11-eq/$m^2$(SA)*a] | $4{,}81 \cdot 10^{-6}$ | $4{,}77 \cdot 10^{-6}$ | 1,0 | 1 |
| AP [kg $SO_2$-eq] | 0,89 | 0,88 | 1,0 | 1 |
| EP [kg Phosphate-eq] | 0,14 | 0,15 | 0,9 | 1 |
| POCP [kg Ethene-eq] | 0,04 | 0,05 | 0,9 | 1 |
| ADPE [kg SB-eq] | $1{,}42 \cdot 10^{-4}$ | $1{,}41 \cdot 10^{-4}$ | 1,0 | 1 |
| ADPF [MJ] | 1039 | 944 | 1,1 | 1 |

The overall statement considering the difference between DGNB and Miljöbyggnad 3.0 for concrete is that there is a minimal difference by using one or the other.

Figure 16.1 shows the interconnected properties of GWP for one tonne of CLT, steel and concrete. The EOL scenarios for concrete and steel is reuse, recovery or recycling. The CLT is either reused, recycled or incinerated. For the research of Miljöbyggnad 3.0 only production stage phases are included and no EOL scenarios are included.

Since the comparison is made of three types of structural materials, CLT, steel and concrete, the material usage in a building needs to be attained. For this research, as shown previously, a material usage of 1x CLT, 1x steel and 2x concrete is used in weight. To further clarify, the previous connection suggests that in a type of building with structural materials consisting mainly of CLT, steel or concrete. The weight of each structural construction type and construction material result in different values of waste in kilogram. For every kilogram CLT as a structural material, one kilogram steel and two kilogram concrete is needed.

Steel has the highest emittance of $CO_2$-eq and contributes the most to the GWP. Even when the doubled amount of concrete in kilogram is used. In this research study, steel is being reused, recovered or recycled and it has been shown that steel is gained by stretching the included LCA life cycle phases. To clarify, the above example highlights the most beneficial scenarios for steel. If no EOL scenarios were included, the GWP emissions would have been doubled for steel. Concrete's global warming potential is slightly improved when reused or recycled thus only improving its quota in the actual case slightly.

Although the most advantageous prepositions exist for steel and concrete, CLT still produces great advantages considering GWP and CO2-eq emissions.

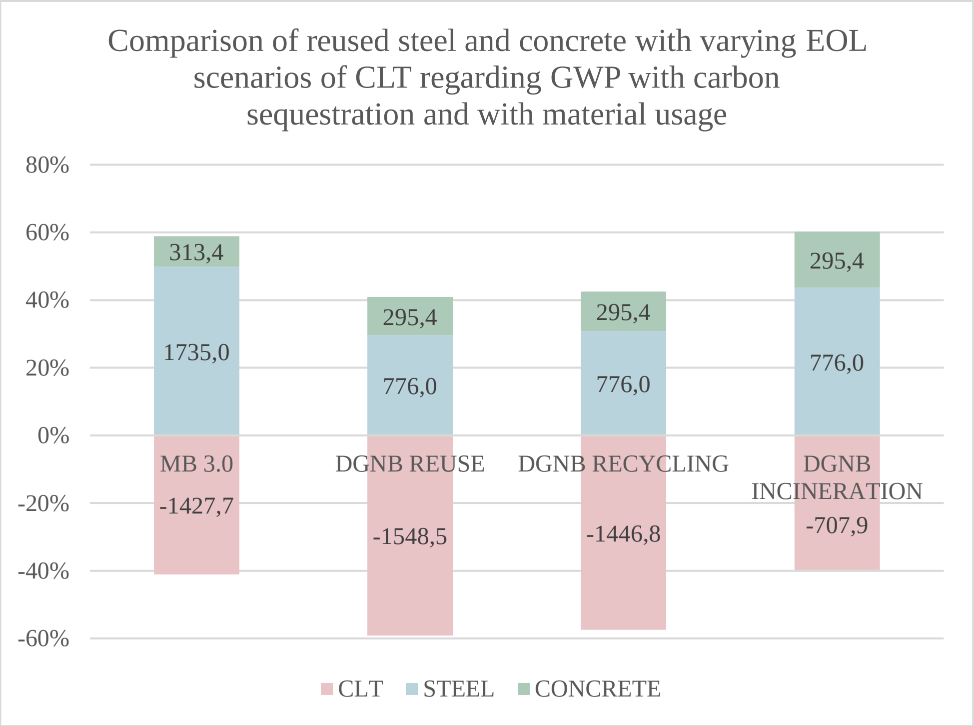


*Figure 16.1: The percentage distribution of global warming for each building certification and EOL scenario. Comparing CLT, steel and concrete with consideration of carbon sequestration and material usage for the materials in a type building as a structural construction material.*

Figure 16.1 shows the interconnected properties of global warming potential for 1 tonne of CLT, steel and concrete. The EOL scenarios for concrete and steel is reuse, recovery or recycling. The CLT is either reused, recycled or incinerated. For the research of Miljöbyggnad 3.0 only production stage phases are included, and no EOL scenarios are included.

Since the comparison is made of three types of structural materials, CLT, steel and concrete, one need to attain the material usage in a building. For this research, as shown previously, a material usage of 1x CLT, 1x steel and 2x concrete is used in weight. To further clarify, the previous connection suggests that in a type of building with structural materials consisting mainly of CLT, Steel or concrete. The weight of each structural construction type and construction material result in different values of waste in kilogram. For every kilogram CLT as structural material, one kilogram steel and two kilogram concrete is needed.

Steel has the highest emittance of $CO_2$-eq and contributes the most to global warming potential. Even when the doubled amount of concrete in kilogram is used. In this research, steel is being reuse, recovered or recycled and it has been shown that steel is gained by stretching the implemented LCA stages. To clarify, the above example highlights the most beneficial scenarios for steel. If no EOL scenarios were included, the GWP emissions would have doubled for steel. Concrete's global warming potential is slightly improved when reused or recycled thus only improving its quota in the actual case slightly.

Although, the most advantageous prepositions exist for steel and concrete, CLT still produces great advantages considering GWP and $CO_2$-eq emissions.

The figure 16.1 above aims to highlight the massive advantage CLT as a construction material obtains if carbon sequestration is included in the LCA. In all different scenarios CLT gets a negative $CO_2$-eq emission value, thus aiding and counterworking radiative forcing.

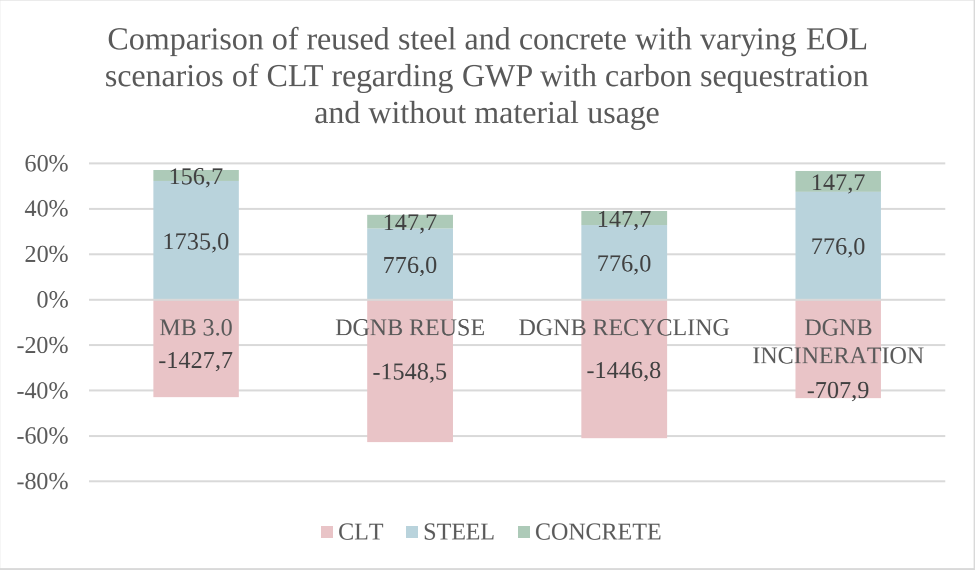


*Figure 16.2: The percentage distribution of global warming potential for each building certification and EOL scenario. Comparing CLT, steel and concrete with consideration of carbon sequestration and without material usage for the materials in a type building as a structural construction material.*

Following the same reasoning as the previous example, the actual case, see figure 16.2, highlights the global warming potential and $CO_2$-eq emission kilogram by kilogram for each of the studied structural construction materials. The results follow the same main line, that is, CLT is hugely rewarded when including carbon sequestration in the LCA regarding GWP. The actual case only improves the ratio between steel and concrete since the amount is equal in this case. Straying from the fact that, less steel and CLT is needed to construct a structure in a type building compared to concrete. This data can be used in further research where other buildings have different material usage between the different structural construction materials.

## 16.3 Comparison of environmental impacts of structural materials in Miljöbyggnad 3.0

The below figure 16.3 shows the percentage distribution of each environmental impact for Miljöbyggnad 3.0, only including production stage phases A1-A3. For the environmental aspects in Miljöbyggnad 3.0, the most beneficial structural construction materials are:

Environmental impacts most beneficial for CLT [1 kg] compared to steel [1 kg] and concrete [1 kg]:

- Global warming potential (without sequestration)
- Acidification potential
- Photochemical ozone creation potential
- Abiotic depletion potential elements

Environmental aspects most beneficial for steel [1 kg] compared to CLT [1 kg] and concrete [1 kg]:

- Ozone depletion potential

Environmental aspects most beneficial for concrete [1 kg] compared to CLT [1 kg] and steel [1 kg]:

- Eutrophication potential
- Abiotic depletion potential fossil fuels

For all the above statements, the material usage is regarded as one to one to one in kilogram between CLT, steel and concrete.

From the above simplification some further context is added, the GWP for steel is much greater than the GWP for CLT and concrete. One explanation could be that the material value in terms of waste and properties of steel is higher than CLT and concrete. Steel is much more recyclable than CLT and concrete and is correlated to the core material value being higher for metals than wood and stone.

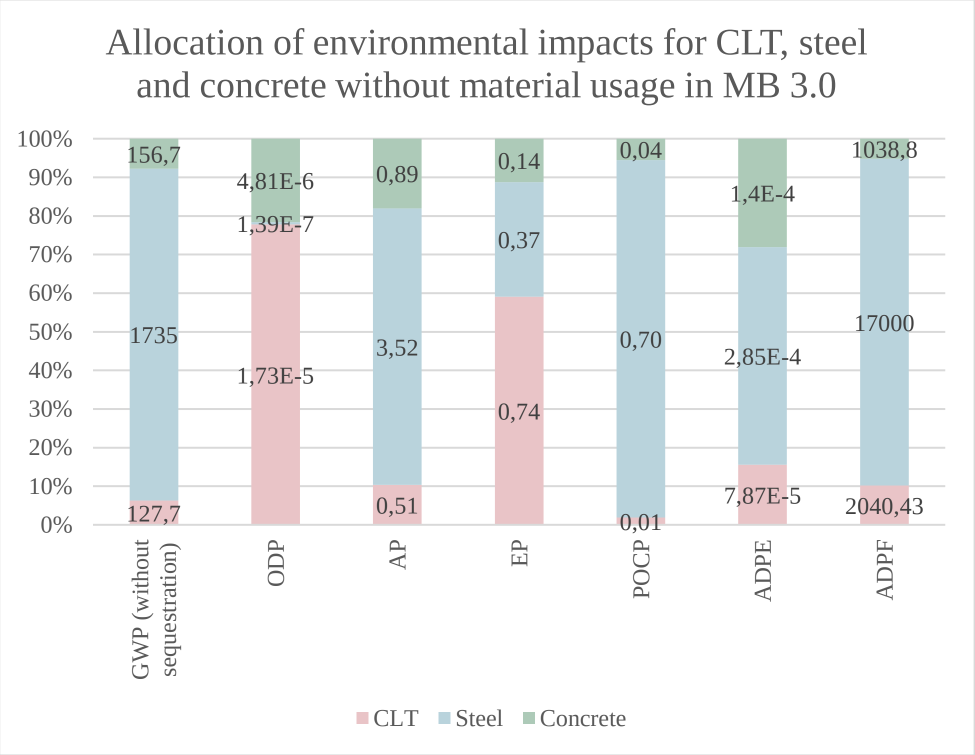


*Figure 16.3: The percentage distribution for each environmental impact, comparing CLT, steel and concrete without consideration of carbon sequestration and material usage for the materials in a type building as a structural construction material. Life cycle stages A1-A3 are assessed.*

For the below figure 16.4 the following underlying properties subside, that the material usage between CLT, steel and concrete is 1 to 1 to 2 [kg]. Increasing concrete's environmental impact for all the environmental impacts. The figure shows the percentage distribution of each environmental impact for Miljöbyggnad 3.0, only including production stage phases A1-A3. For the environmental aspects in Miljöbyggnad 3.0, the most beneficial structural construction materials are (according to each structural construction material's material usage in a type building):

Environmental aspects most beneficial for CLT [1 kg] compared to steel [1 kg] and concrete [2 kg]:

- Global warming potential (without sequestration)
- Acidification potential
- Photochemical ozone creation potential
- Abiotic depletion potential elements
- Abiotic depletion potential fossil fuels

Environmental aspects most beneficial for steel [1 kg] compared to CLT [1 kg] and concrete [2 kg]:

- Ozone depletion potential

Environmental aspects most beneficial for concrete [2 kg] compared to CLT [1 kg] and steel [1 kg]:

- Eutrophication potential

The only difference for Miljöbyggnad 3.0 when comparing the different structural construction materials with and without the independent material usage for a type building is that ADPF shifts from concrete to CLT, further improving CLT regarding concrete.

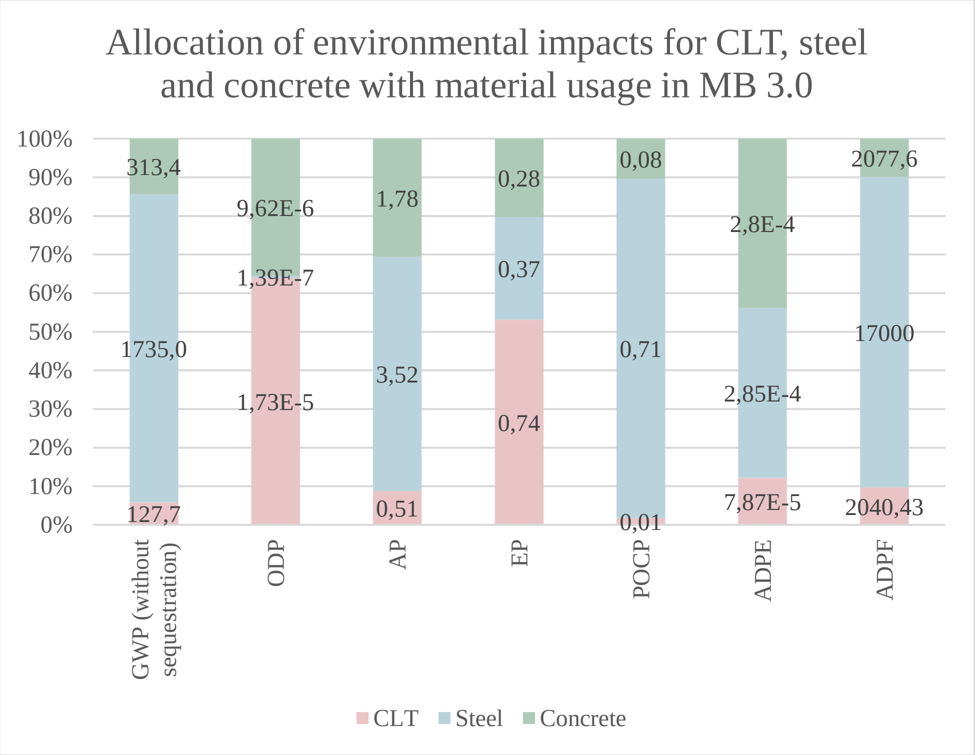


*Figure 16.4: The percentage distribution for each environmental impact, comparing CLT, steel and concrete without consideration of carbon sequestration and with consideration to material usage for the materials in a type building as a structural construction material. Life cycle stages A1-A3 are assessed.*

## 16.4 Comparison of environmental impacts of structural materials in DGNB

In the following section, interconnections between EOL scenarios for DGNB is researched. What differs in the actual case of comparing the materials in DGNB is the inclusion of life cycle phases C3, C4 and D. This type of comparison aims to illustrate how the different materials benefits from the extensive LCA cycle, alternatively inhibits its overall sustainability.

For the six figures 16.5-16.10, the materials environmental impacts are researched through the construction of six cases. The different combinations of EOL scenarios for the materials is illustrated in the table below:

*Table 16.2: Summary of the criteria combination for the six scenarios.*

| **Scenario** | **Material usage** | **Figure** | **CLT** | **Steel** | **Concrete** |
|---|---|---|---|---|---|
| 1 | NO | 16.5 | Reused | Reused, recovered or recycled | Reused |
| 2 | NO | 16.6 | Recycled | Reused, recovered or recycled | Reused |
| 3 | NO | 16.7 | Incinerated | Reused, recovered or recycled | Reused |
| 4 | YES | 16.8 | Reused | Reused, recovered or recycled | Reused |
| 5 | YES | 16.9 | Recycled | Reused, recovered or recycled | Reused |
| 6 | YES | 16.10 | Incinerated | Reused, recovered or recycled | Reused |

### 16.4.1 Scenario 1

*Table 16.3: The combination of evaluated conditions for scenario 1.*

| Scenario | Material usage | Figure | CLT | Steel | Concrete |
|---|---|---|---|---|---|
| 1 | NO | 16.5 | Reused | Reused, recovered or recycled | Reused |

For the actual case (scenario 1), the following criteria is set: steel is reused, recovered and recycled, concrete is reused and CLT is reused. Figure 16.5 shows how the total environmental impact for all different environmental impact categories are impacted by the EOL stages of each material.

In the actual case the material use of each of the structural construction materials are neglected, looking at the same amount of weight for each material.

Figure 16.5 shows the percentage distribution of each environmental impact for DGNB including production stage phases A1-A3 and EOL phases C3-C4 as well as stage D.

The environmental impacts most beneficial for reused CLT [1 kg] compared to reused, recovered or recycled steel [1 kg] and reused concrete [1 kg] is:

- Global warming potential (without sequestration)
- Acidification potential
- Eutrophication potential
- Photochemical ozone creation potential
- Abiotic depletion potential elements
- Abiotic depletion potential fossil fuels

The environmental impacts most beneficial for reused, recovered or recycled steel [1 kg] compared to reused CLT [1 kg] and reused concrete [1 kg] is:

- Ozone depletion potential

There are no environmental impacts most beneficial for reused concrete [1 kg] compared to reused CLT [1 kg] and reused, recovered or recycled steel [1 kg] in DGNB.

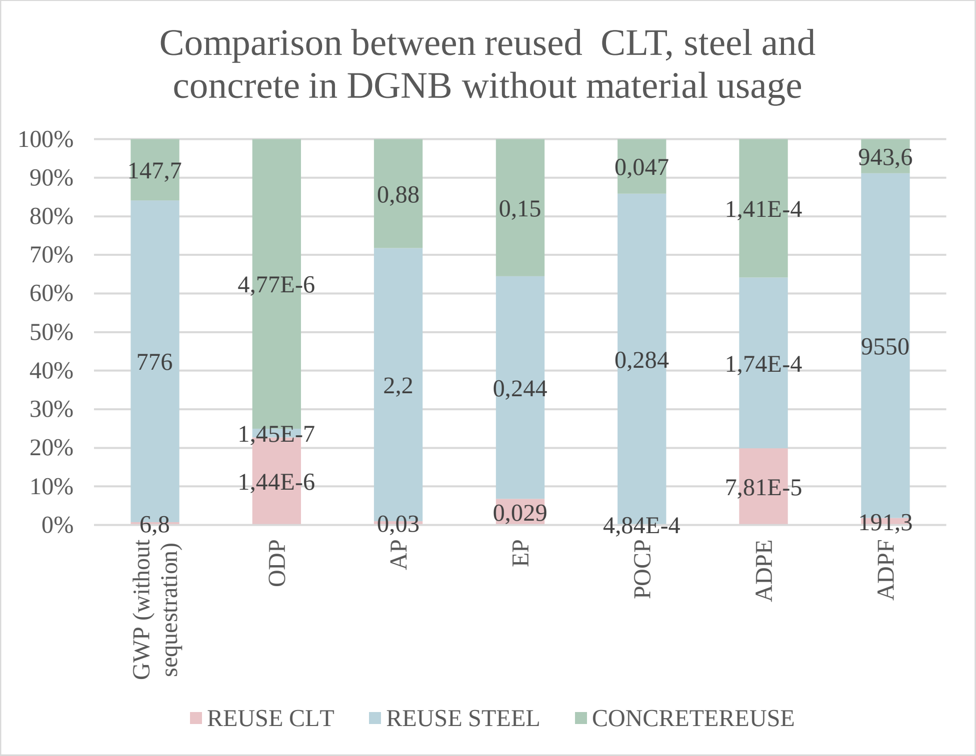


*Figure 16.5: Percentage distribution of every environmental impact for each of the construction materials (CLT, steel and concrete). Scenario 1, where CLT is reused, steel is reused, recovered or recycled and concrete is reused. With no consideration of material usage for the structural construction materials in a type building.*

### 16.4.2 Scenario 2

*Table 16.4: The combination of evaluated conditions for scenario 2.*

| **Scenario** | **Material usage** | **Figure** | **CLT** | **Steel** | **Concrete** |
|---|---|---|---|---|---|
| 2 | NO | 16.6 | Recycled | Reused, recovered or recycled | Reused |

For the actual case (scenario 2), the following criteria is set: steel is reused, recovered and recycled, concrete is reused and CLT is recycled. Figure 16.6 shows how the total environmental impact for all different environmental impact categories is impacted by the EOL-stages of each material.

In the actual case the material use of each of the structural construction materials is neglected, looking at the same amount of weight for each material.

Figure 16.6 shows the percentage distribution of each environmental impact for DGNB including production stage phases A1-A3 and EOL phases C3-C4 as well as stage D.

The environmental impacts most beneficial for recycled CLT [1 kg] compared to reused, recovered or recycled steel [1 kg] and reused concrete [1 kg] is:

- Global warming potential (without sequestration)
- Acidification potential
- Photochemical ozone creation potential

The environmental impacts most beneficial for reused, recovered or recycled steel [1 kg] compared to recycled CLT [1 kg] and reused concrete [1 kg] is:

- Ozone depletion potential

The environmental impacts most beneficial for reused concrete [1 kg] compared to recycled CLT [1 kg] and reused, recovered or recycled steel [1 kg] is:

- Eutrophication potential
- Abiotic depletion potential elements
- Abiotic depletion potential fossil fuels

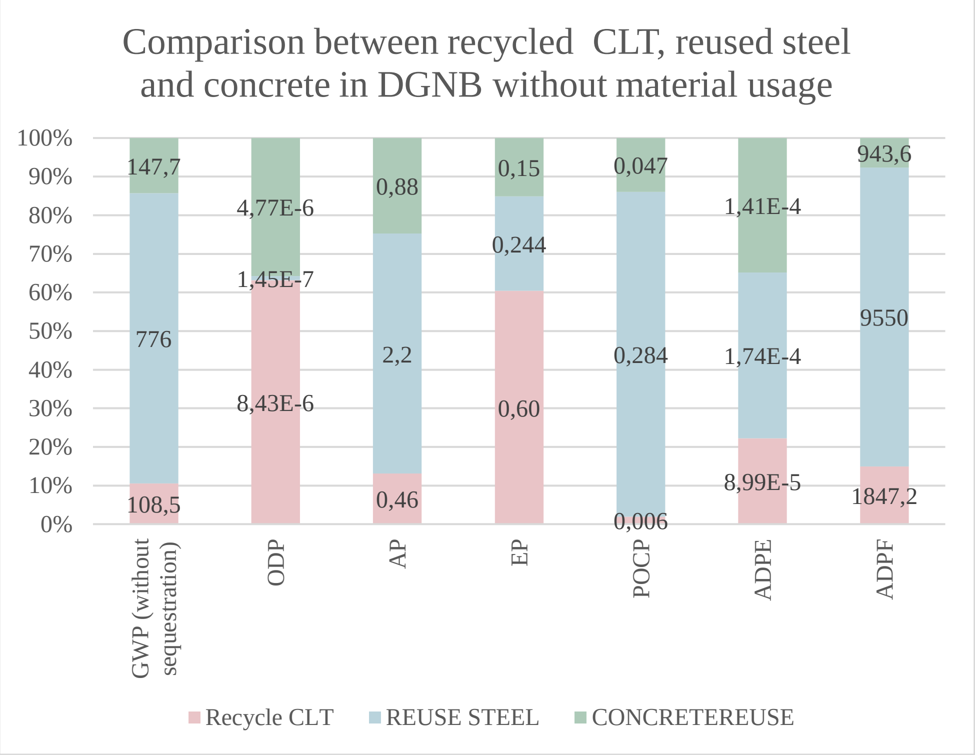


*Figure 16.6: Percentage distribution of every environmental impact for each of the construction materials (CLT, steel and concrete). Scenario 2, where CLT is recycled, steel is reused, recovered or recycled and concrete is reused. With no consideration of material usage for the structural construction materials in a type building.*

### 16.4.3 Scenario 3

*Table 16.5: The combination of evaluated conditions for scenario 3.*

| **Scenario** | **Material usage** | **Figure** | **CLT** | **Steel** | **Concrete** |
|---|---|---|---|---|---|
| 3 | NO | 16.7 | Incinerated | Reused, recovered or recycled | Reused |

For the actual case (scenario 3), the following criteria is set: steel is reused, recovered and recycled, concrete is reused and CLT is incinerated. Figure 16.7 shows how the total environmental impact for all different environmental impact categories is impacted by the EOL stages of each material.

In the actual case the material use of each of the structural construction materials is neglected, looking at the same amount of weight for each material.

Figure 16.7 shows the percentage distribution of each environmental impact for DGNB including production stage phases A1-A3 and EOL phases C3-C4 as well as stage D.

The environmental impacts most beneficial for incinerated CLT [1 kg] compared to reused, recovered or recycled steel [1 kg] and reused concrete [1 kg] is:

- Abiotic depletion potential fossil fuels
- Ozone depletion potential

There are no environmental impacts most beneficial for reused, recovered or recycled steel [1 kg] compared to incinerated CLT [1 kg] and reused concrete [1 kg] in DGNB.

The environmental impacts most beneficial for reused concrete [1 kg] compared to incinerated CLT [1 kg] and reused, recovered or recycled steel [1 kg] is:

- Global warming potential (without sequestration)
- Acidification potential
- Eutrophication potential
- Photochemical ozone creation potential
- Abiotic depletion potential elements

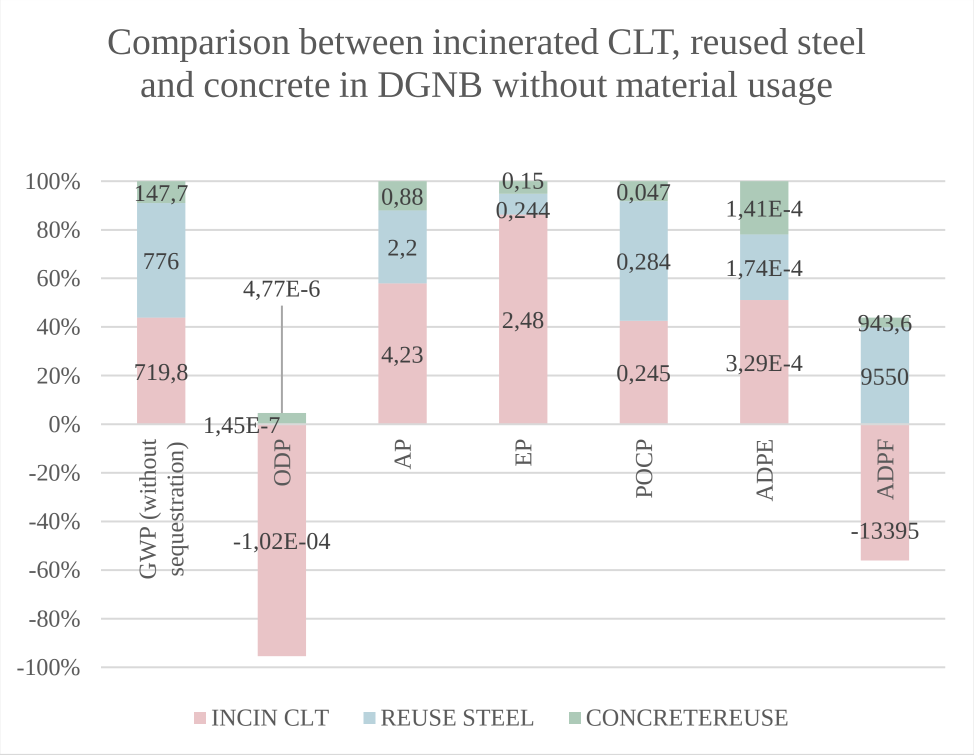


*Figure 16.7: Percentage distribution of every environmental impact for each of the construction materials (CLT, steel and concrete). Scenario 3, where CLT is incinerated, steel is reused, recovered or recycled and concrete is reused. With no consideration of material usage for the structural construction materials in a type building.*

### 16.4.4 Scenario 4

*Table 16.6: The combination of evaluated conditions for scenario 4.*

| Scenario | Material usage | Figure | CLT | Steel | Concrete |
|---|---|---|---|---|---|
| 4 | YES | 16.8 | Reused | Reused, recovered or recycled | Reused |

For the actual case (scenario 4), the following criteria is set: steel is reused, recovered and recycled, concrete is reused and CLT is reused. Figure 16.8 shows how the total environmental impact for all different environmental impact categories is impacted by the EOL stages of each material.

In the actual case the material use of each of the structural construction materials is included, looking at the weight ratio of one kilogram CLT to one kilogram steel and two kilogram concrete.

Figure 16.8 shows the percentage distribution of each environmental impact for DGNB including production stage phases A1-A3 and EOL phases C3-C4 as well as stage D.

The environmental impacts most beneficial for reused CLT [1 kg] compared to reused, recovered or recycled steel [1 kg] and reused concrete [2 kg] is:

- Global warming potential (without sequestration)
- Acidification potential
- Eutrophication potential
- Photochemical ozone creation potential
- Abiotic depletion potential elements
- Abiotic depletion potential fossil fuels

The environmental impacts most beneficial for reused, recovered or recycled steel [1 kg] compared to reused CLT [1 kg] and reused concrete [2 kg] in DGNB is:

- Ozone depletion potential

There are no environmental impacts most beneficial for reused concrete [2 kg] compared to reused CLT [1 kg] and reused, recovered or recycled steel [1 kg] in DGNB.

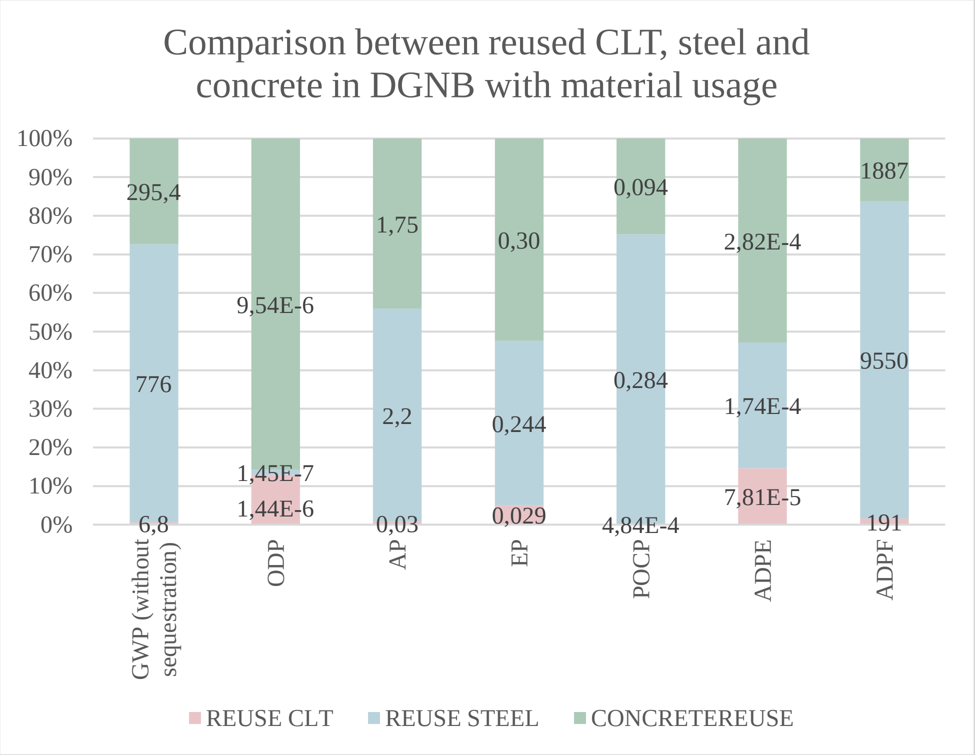


*Figure 16.8: Percentage distribution of every environmental impact for each of the construction materials (CLT, steel and concrete). Scenario 4, where CLT is reused, steel is reused, recovered or recycled and concrete is reused. With consideration of material usage for the structural construction materials in a type building.*

### 16.4.5 Scenario 5

*Table 16.7: The combination of evaluated conditions for scenario 5.*

| Scenario | Material usage | Figure | CLT | Steel | Concrete |
|---|---|---|---|---|---|
| 5 | YES | 16.9 | Recycled | Reused, recovered or recycled | Reused |

For the actual case (scenario 5), the following criteria is set: steel is reused, recovered and recycled, concrete is reused and CLT is recycled. Figure 16.9 shows how the total environmental impact for all different environmental impact categories is impacted by the EOL stages of each material.

In the actual case the material use of each of the structural construction materials is included, looking at the weight ratio of one kilogram CLT to one kilogram steel and two kilogram concrete.

Figure 16.9 shows the percentage distribution of each environmental impact for DGNB including production stage phases A1-A3 and EOL phases C3-C4 as well as stage D.

The environmental impacts most beneficial for recycled CLT [1 kg] compared to reused, recovered or recycled steel [1 kg] and reused concrete [2 kg] is:

- Global warming potential (without sequestration)
- Acidification potential
- Photochemical ozone creation potential
- Abiotic depletion potential elements
- Abiotic depletion potential fossil fuels

The environmental impacts most beneficial for reused, recovered or recycled steel [1 kg] compared to recycled CLT [1 kg] and reused concrete [2 kg] in DGNB is:

- Ozone depletion potential
- Eutrophication potential

There are no environmental impacts most beneficial for reused concrete [2 kg] compared to recycled CLT [1 kg] and reused, recovered or recycled steel [1 kg] in DGNB.

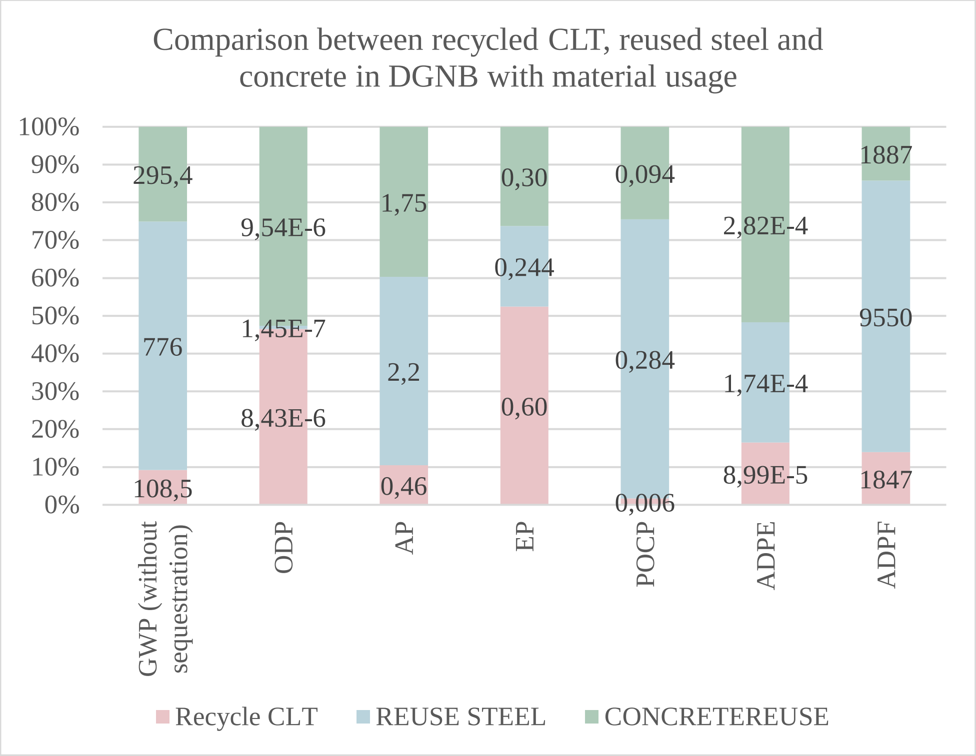


*Figure 16.9: Percentage distribution of every environmental impact for each of the construction materials (CLT, steel and concrete). Scenario 5, where CLT is recycled, steel is reused, recovered or recycled and concrete is reused. With consideration of material usage for the structural construction materials in a type building.*

### 16.4.6 Scenario 6

*Table 16.8: The combination of evaluated conditions for scenario 6.*

| Scenario | Material usage | Figure | CLT | Steel | Concrete |
|---|---|---|---|---|---|
| 6 | YES | 16.10 | Incinerated | Reused, recovered or recycled | Reused |

For the actual case (scenario 6), the following criteria is set: steel is reused, recovered and recycled, concrete is reused and CLT is incinerated. Figure 16.10 shows how the total environmental impact for all different environmental impact categories is impacted by the EOL stages of each material.

In the actual case the material use of each of the structural construction materials is included, looking at the weight ratio of one kilogram CLT to one kilogram steel and two kilogram concrete.

Figure 16.10 shows the percentage distribution of each environmental impact for DGNB including production stage phases A1-A3 and EOL phases C3-C4 as well as stage D.

The environmental impacts most beneficial for incinerated CLT [1 kg] compared to reused, recovered or recycled steel [1 kg] and reused concrete [2 kg] is:

- Ozone depletion potential
- Abiotic depletion potential fossil fuels

The environmental impacts most beneficial for reused, recovered or recycled steel [1 kg] compared to incinerated CLT [1 kg] and reused concrete [2 kg] in DGNB is:

- Eutrophication potential
- Abiotic depletion potential elements

The environmental impacts most beneficial for reused concrete [2 kg] compared to incinerated CLT [1 kg] and reused, recovered or recycled steel [1 kg] in DGNB is:

- Global warming potential (without sequestration)
- Acidification potential
- Photochemical ozone creation potential

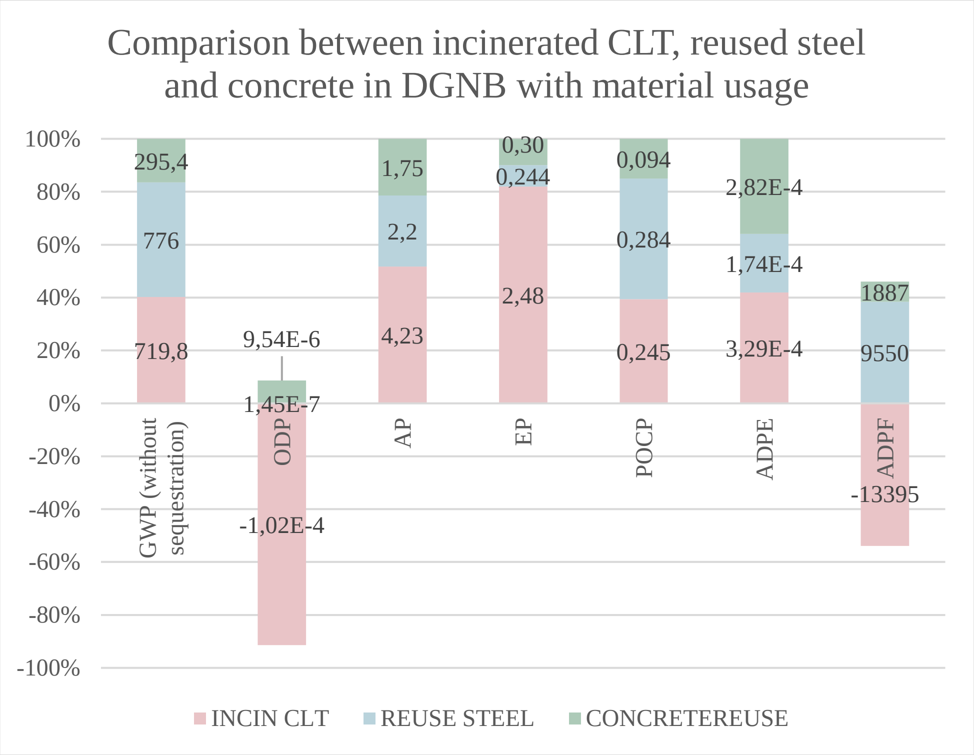


*Figure 16.10 - Percentage distribution of every environmental impact for each of the construction materials (CLT, steel and concrete). Scenario 6, where CLT is incinerated, steel is reused, recovered or recycled and concrete is reused. With consideration of material usage for the structural construction materials in a type building.*

## 16.5 Transport

LCA phase *A4 Transport*, which include transport from factory gate to construction site may have varying transport emissions regarding fossil fuels and more precisely CO2-eq emissions. The varying transport emissions depends on mode of transport. From the EPD of CLT from Stora Enso, transportation from the factories in Austria (Bad St. Leonhard or Ybbs) to Sweden is approximately 34 kilogram $CO_2$-eq for one cubic meter of CLT with a transportation distance of 1890 kilometres (Stora Enso 2017).

For concrete and the EPD for *Kompaktvegg*, it is shown that the distance from the concrete factory and construction site is 50 kilometres (EPD-Norge 2016). In this case, it can be approximated that the nearest concrete factory in Sweden is far less than the distance from the CLT factory and is assumed to be 50 kilometres.

For steel, 250 kilometres transportation is used from factory to construction site, this value can be found on a steel EPD citing that Sävsjö is the place where production takes place (EPD-Norge 2016b). The following analysis is shown to implicate that CLT has some negative regards due to its producing factories not being in Sweden. The aim of this part of the research study is to evaluate if *A4 Transport* can be considered a *hotspot* for CLT.

### Environmental impact of *A4 Transport* in Miljöbyggnad 3.0

*Table 16.9: The generic data for each mode of transport respectively. Generic data regarding transportation of 1 tonne CLT.*

| **Mode of transport** | **Generic data [kg$CO_2$/tonne*km]** |
|---|---|
| Road | 0,18 |
| Water | 0,05 |
| Rail | 0,05 |

Table 16.9 illustrates the generic values used in Miljöbyggnad 3.0 for the different transportation types. The generic values describe the carbon dioxide emission per tonne of transported material each kilometre.

CLT is mainly produced in southern Europe (Austria) which provide issues regarding CLT's implementation in the Swedish and Danish construction sector, due to the added environmental impacts of transportation. In Miljöbyggnad 3.0 life cycle stage A4 is included for the higher grades which will damage the overall sustainability of CLT due to the necessary long transportation distance. In the research study, CLT, steel and concrete are further analysed with the inclusion of life cycle stage *A4 Transport*, to give a fairer picture of CLT's environmental impact when assessed in Miljöbyggnad 3.0. Worth to mention is that in certification grade bronze in Miljöbyggnad 3.0 only life cycle phases A1-A3 are included. However, to attain higher certification grades (silver and gold) transportation stage *A4 Transport* is included.

The transport assessment aims to compare the environmental impact measured in carbon dioxide equivalents through different transportation types for one tonne of structural construction material. Using the EPD from Stora Enso regarding CLT, the transportation distance from factory to Sweden is approximated to 1890 kilometres. For steel, 500 kilometres is approximated. Concrete manufacturers are approximated to be located within 50 km. These values are approximated; however, the aim is to highlight the choice of transportation methods environmental impact. Table 16.10 highlight the calculations for carbon dioxide emissions per transportation mode.

*Table 16.10: Illustrates the environmental impact calculations made for life cycle phase A4 Transport regarding the chosen mode of transport, road transport, for CLT, steel and concrete.*

| **Road transport** | **Distance [km]** | **Generic data [kg$CO_2$/tonne*km]** | **Environmental impact [kg $CO_2$/tonne]** |
|---|---|---|---|
| CLT | 1890 | 0,18 | 1890·0,18=340,2 |
| Steel | 500 | 0,18 | 500·0,18=90 |
| Concrete | 50 | 0,18 | 500·,18=9 |

*Table 16.11: Illustrates the environmental impact calculations made for life cycle phase A4 Transport regarding the chosen mode of transport, water transport, for CLT, steel and concrete.*

| **Water transport** | **Distance [km]** | **Generic data [kg $CO_2$/tonne*km]** | **Environmental impact [kg $CO_2$/tonne]** |
|---|---|---|---|
| CLT | 1890 | 0,05 | 1890·0,05=94,5 |
| Steel | 500 | 0,05 | 500·0,05=25 |
| Concrete | 50 | 0,05 | 50·0,05=2,5 |

*Table 16.12: Illustrates the environmental impact calculations made for life cycle phase A4 Transport regarding the chosen mode of transport, rail transport, for CLT, steel and concrete.*

| **Rail transport** | **Distance [km]** | **Generic data [kg $CO_2$/tonne*km]** | **Environmental impact [kg $CO_2$/tonne]** |
|---|---|---|---|
| CLT | 1890 | 0,05 | 1890·0,05=94,5 |
| Steel | 500 | 0,05 | 500·0,05=25 |
| Concrete | 50 | 0,05 | 50·0,05=2,5 |

Figure 16.11 illustrates how the GWP is influenced by choice of transportation mode for different structural construction materials. The only factor that differentiates between the construction materials is the approximated transport distance.

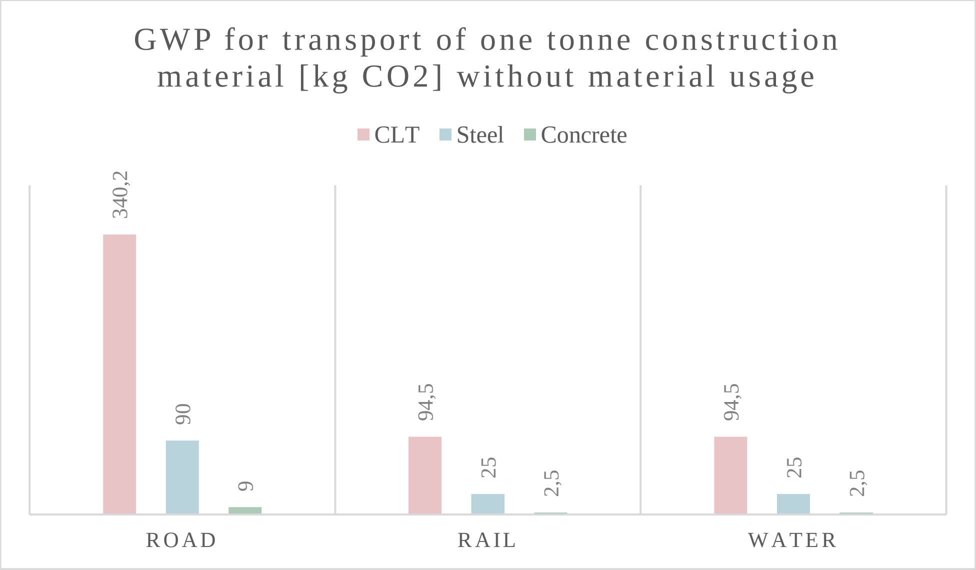


*Figure 16.11: The impact on GWP due to selected mode of transport, without material usage consideration for CLT, steel and concrete. Only life cycle phase A4 Transport is shown.*

Regarding on-site material consumption for the structural construction materials, figure 16.12 highlights the limited impact, material consumption has on GWP for *A4 Transport*. The material consumption only indicates a doubled amount of material usage of concrete per kilogram of CLT and steel, doubling the GWP impact for concrete. Since concrete's transportation distance is the shortest, 50 kilometres, the effect on concrete's environmental impact in life cycle phase A4 is limited in comparison of CLT's and steel's GWP in life cycle phase A4.

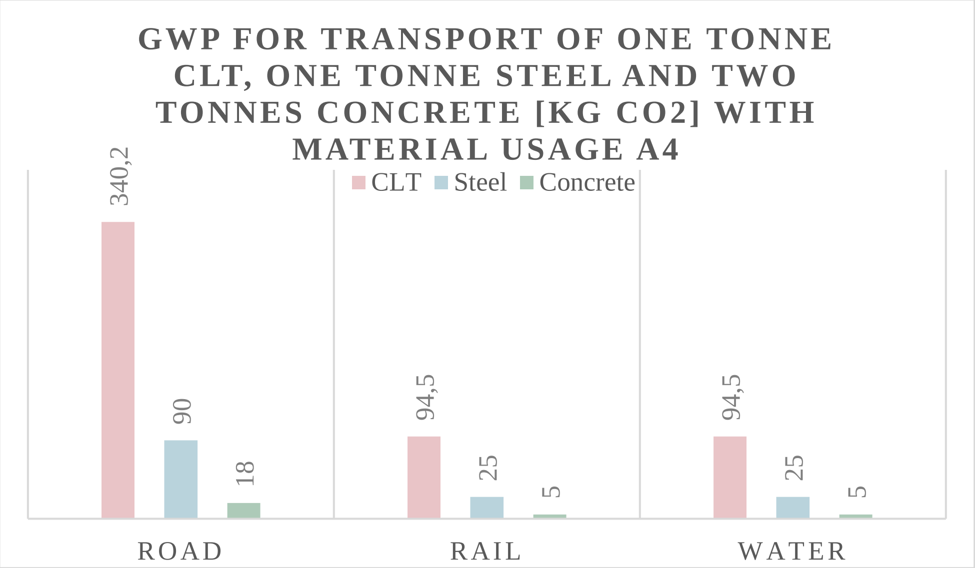


*Figure 16.12: The impact on GWP due to selected mode of transport, with material usage consideration for CLT, steel and concrete.*

For the section below, the included life cycle phase A4 is added to the GWP for each of the structural construction materials with production life cycle phases A1-A3 for the scenarios including Miljöbyggnad 3.0. The aim is to calculate the transportations impact on GWP for each of the structural construction materials.

*Table 16.13: Overview of the different calculation scenarios regarding A4 Transport.*

| **Scenario** | **Material usage** | **Carbon Sequestration for CLT** | **MB 3.0** | **DGNB with all EOL scenarios** | **Figure** |
|---|---|---|---|---|---|
| A | YES | YES | A1-A4 | A1-A3+C3-C4+D | 16.13 |
| B | NO | YES | A1-A4 | A1-A3+C3-C4+D | 16.14 |
| C | YES | NO | A1-A4 | A1-A3+C3-C4+D | 16.15 |
| D | NO | NO | A1-A4 | A1-A3+C3-C4+D | 16.16 |

*Table 16.14: The combination of evaluated conditions for scenario A.*

| **Scenario** | **Material usage** | **Carbon sequestration for CLT** | **MB 3.0** | **DGNB with all EOL scenarios** |
|---|---|---|---|---|
| A | YES | YES | A1-A4 | A1-A3+C3-C4+D |

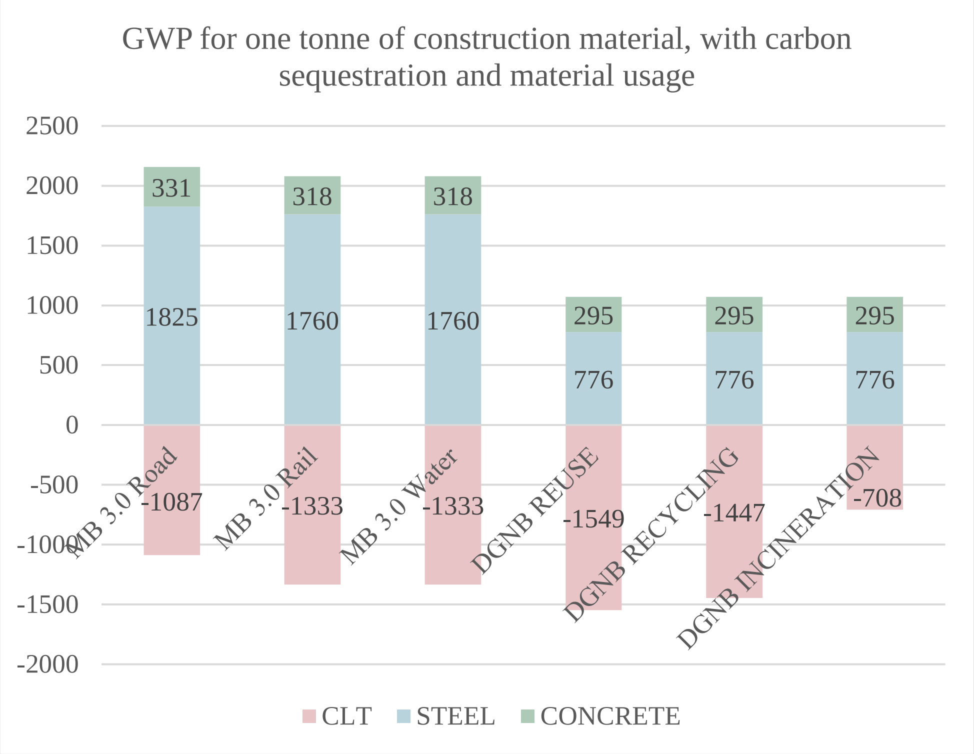


*Figure 16.13: Representation of GWP for one tonne of CLT for Miljöbyggnad (A1-A4) and DGNB (A1-A3+C3-C4+D) for scenario A.*

Figure 16.13 above shows that with the inclusion of life cycle stage *A4 Transport*, road transport is the worst transportation mode regarding GWP, resulting in limited positive environmental effects for CLT. Road transportation for concrete and steel also result in greater negative environmental impacts and GWP. Since the only evaluating factor is GWP, there are no results considering other environmental impacts.

Figure 16.13 shows, it is environmentally more beneficial for CLT regarding GWP including A1-A4, with road transport compared to incineration in DGNB incineration. For transportation modes, water and rail, GWP is the same for structural construction materials in both transportation modes.

*Table 16.15: The combination of evaluated conditions for scenario B.*

| **Scenario** | **Material usage** | **Carbon sequestration for CLT** | **MB 3.0** | **DGNB with all EOL scenarios** |
|---|---|---|---|---|
| B | NO | YES | A1-A4 | A1-A3+C3-C4+D |

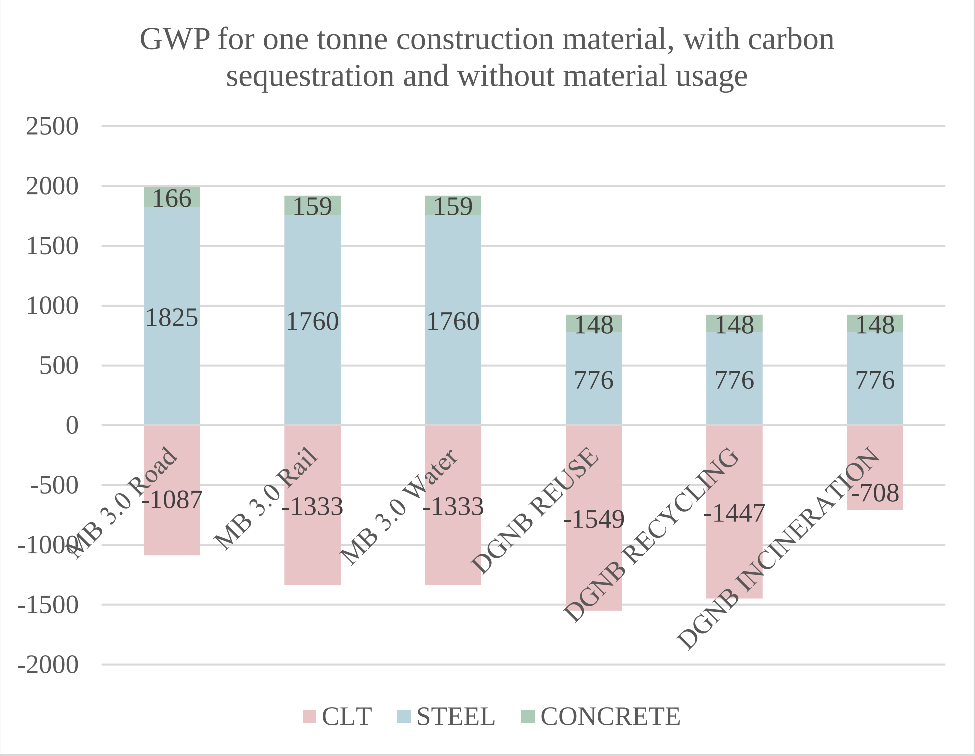


*Figure 16.14: Representation of GWP for one tonne of CLT for Miljöbyggnad (A1-A4) and DGNB (A1-A3+C3-C4+D) for scenario B.*

The only difference between scenario A and B, is the added material usage for concrete, which conclusively result in halved GWP for concrete in this case. Following the reasoning that road transportation effect the GWP values negatively for all construction materials. For Miljöbyggnad 3.0 Rail and Miljöbyggnad 3.0 Water, GWP is the same for the individual structural construction materials. The worst certification scenario for CLT is still DGNB incineration compared to other EOL scenarios within DGNB or the added life cycle stage *A4 Transport* for Miljöbyggnad 3.0.

*Table 16.16: The combination of evaluated conditions for scenario C.*

| **Scenario** | **Material usage** | **Carbon sequestration for CLT** | **MB 3.0** | **DGNB with all EOL scenarios** |
|---|---|---|---|---|
| C | YES | NO | A1-A4 | A1-A3+C3-C4+D |

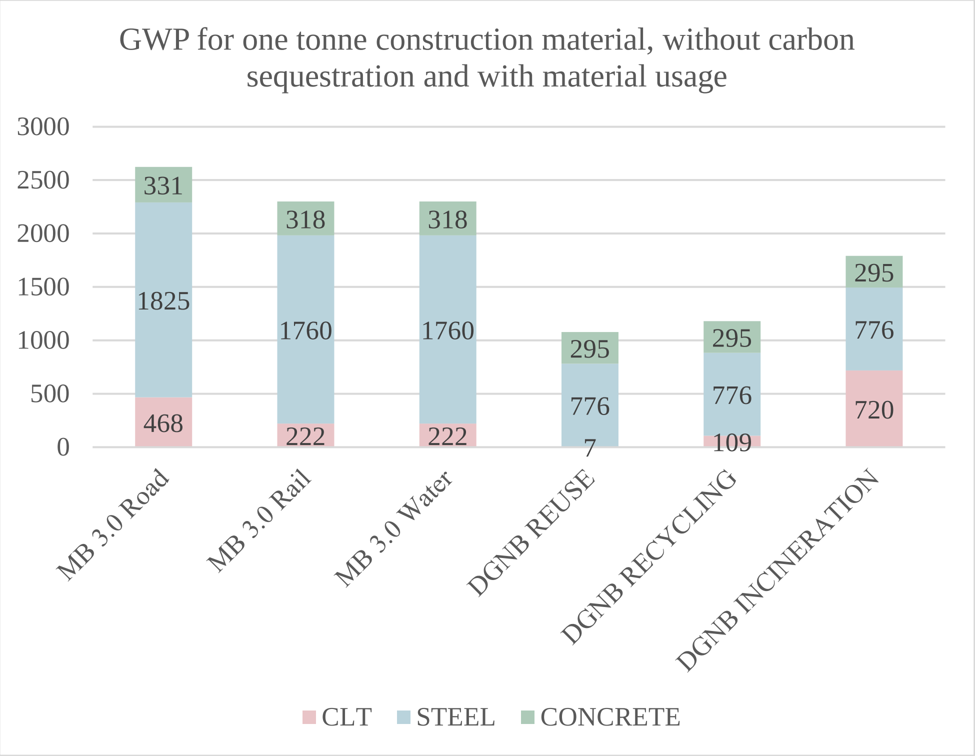


*Figure 16.15: Representation of GWP for one tonne of CLT for Miljöbyggnad (A1-A4) and DGNB (A1-A3+C3-C4+D) for scenario C.*

Regarding life cycle phase road transportation A4 for Miljöbyggnad 3.0, each individual construction material produces the greatest GWP. It is still observed that life cycle phases A1-A4 for Miljöbyggnad 3.0 road transportation have lesser GWP than DGNB incineration. Rail and water transport have the same environmental impact regarding GWP for each individual construction material.

*Table 16.17: The combination of evaluated conditions for scenario D.*

| **Scenario** | **Material usage** | **Carbon sequestration for CLT** | **MB 3.0** | **DGNB with all EOL scenarios** |
|---|---|---|---|---|
| D | NO | NO | A1-A4 | A1-A3+C3-C4+D |

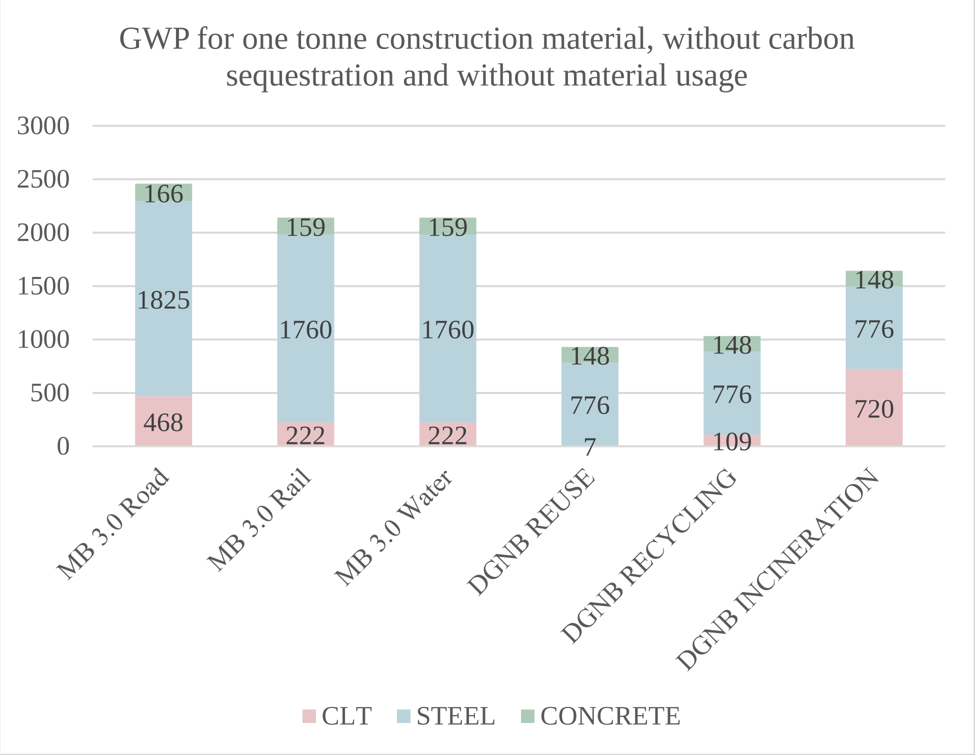


*Figure 16.16: Representation of GWP for one tonne of CLT for Miljöbyggnad (A1-A4) and DGNB (A1-A3+C3-C4+D) for scenario D.*

The only difference between scenario C and D is the added material usage factor, which halves the GWP for concrete since the present scenario compares all the construction materials by the same mass. Road transport in life cycle phase *A4 Transport* produce the highest carbon dioxide emissions for each construction material compared by the different transportation modes. Rail and water transport for the construction materials show no difference in GWP.

Even with the inclusion of transport phase A4, road transport which is the result in the highest carbon dioxide emissions in Miljöbyggnad 3.0, DGNB incineration still generate the highest carbon dioxide emissions for CLT and steel. For concrete, Miljöbyggnad 3.0 (A1-A4, all transportation methods) has less GWP compared to DGNB (A1-A3+C3-C4 +D, all EOL scenarios).

Figures 16.17 and 16.18 below show all possible scenarios regarding CLT and GWP, both with and without sequestration. The calculations are based on previous data regarding Miljöbyggnad 3.0 and life cycle phases A1-A3 combined with different EOL scenarios (C3-C4 + D) for the DGNB scenarios.

Regarding CLT without carbon sequestration in Miljöbyggnad 3.0, the inclusion of transport phase A4, only increases the GWP, with road transportation being the worst transport option. Rail and water transportation both contribute to the same amount of GWP.

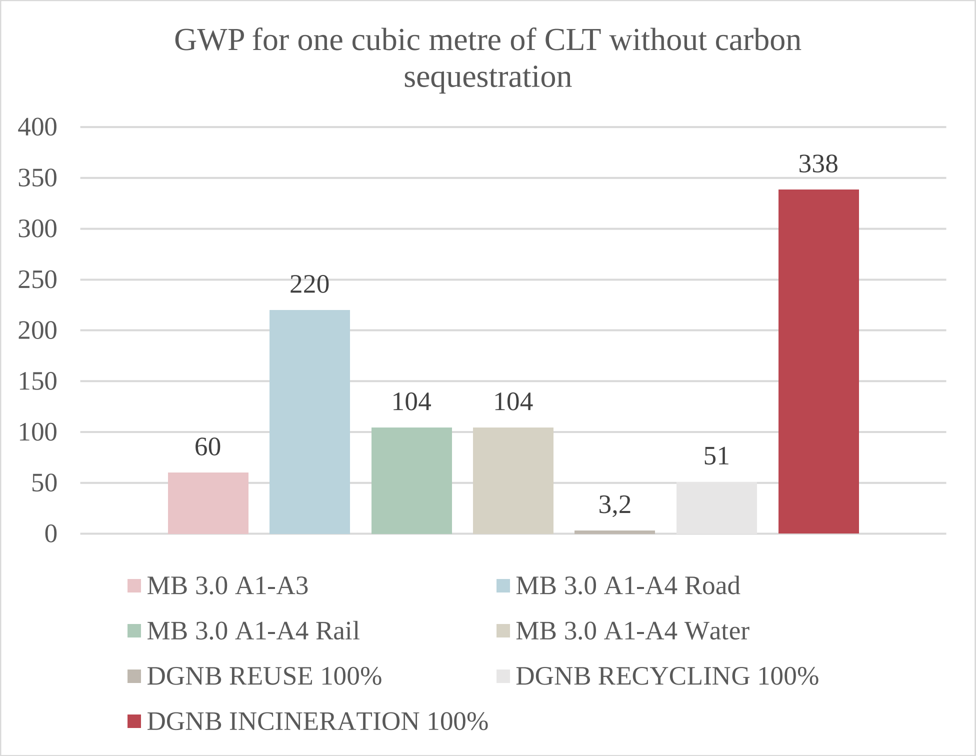


*Figure 16.17 – All evaluated scenarios for Miljöbyggnad 3.0 and DGNB without sequestration for one cubic metre of CLT. The CLT production is based in Austria with transportation distance 1890 km.*

DGNB reuse is the best certification scenario, where the positive EOL effects reduce the overall GWP. As figures 16.17 and 16.18 illustrates, Miljöbyggnad 3.0 (A1-A4) is a far worse option regarding CLT compared to Miljöbyggnad 3.0 (A1-A3), this is due to the long transportation distance of 1890 kilometre which is responsible for the carbon dioxide emissions. Even with the included life cycle phase A4, DGNB incineration is responsible for the highest GWP.

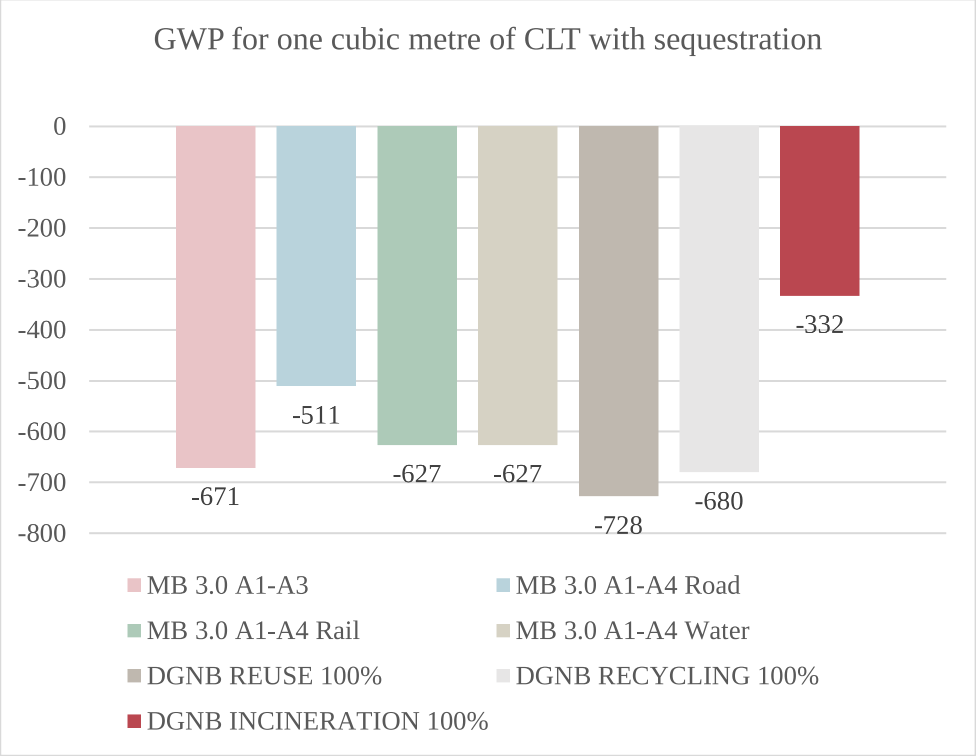


*Figure 16.18: All evaluated scenarios for Miljöbyggnad 3.0 and DGNB with sequestration for one cubic metre of CLT. The CLT production is based in Austria with transportation distance 1890 km.*

Regarding CLT with carbon sequestration in Miljöbyggnad 3.0, the inclusion of transportation phase A4, only decreases the otherwise positive environmental impact effects. The GWP for CLT with carbon sequestration, with road transportation being the worst transport option. Rail and water transportation both contribute to the same amount of sequestrated GWP. DGNB reuse is the best certification scenario, where the positive EOL effects reduce the overall GWP. As the figure illustrates, Miljöbyggnad 3.0 (A1-A4) is a far worse option regarding CLT compared to Miljöbyggnad 3.0 (A1-A3), this is due to the long transportation distance of 1890 kilometres which is responsible for the carbon dioxide emissions. Even with the included life cycle phase A4, DGNB incineration are responsible for the least beneficial GWP.

### Effects of reduction of transportation distance of CLT

Future CLT production in Scandinavia will dramatically decrease the transportation distance. This transportation distance reduction will impact the life cycle phase A4 regarding CLT and GWP. Figures 16.19 and 16.20 illustrate the GWP for one cubic meter of CLT when the distance to the manufacturing factory is reduced to 500 kilometres, with and without carbon sequestration. Stora Enso is building a third CLT factory in Gruvön, Sweden which will be completed in 2019. The other two factories are in Austria located in Bad St. Leonhard and Ybbs (Jauk 2017b).

The same systematic values for the moved manufacturing of CLT and show equivalently the decreasing performance of GWP for CLT with including transportation phase A4. For Miljöbyggnad 3.0 A1-A4 Rail and Miljöbyggnad 3.0 A1-A4 water have the same GWP since the carbon dioxide emission per kilometre and tonne material is the same for both transportation modes. However, the decreased performance of GWP for CLT is limited with shorter transportation distances.

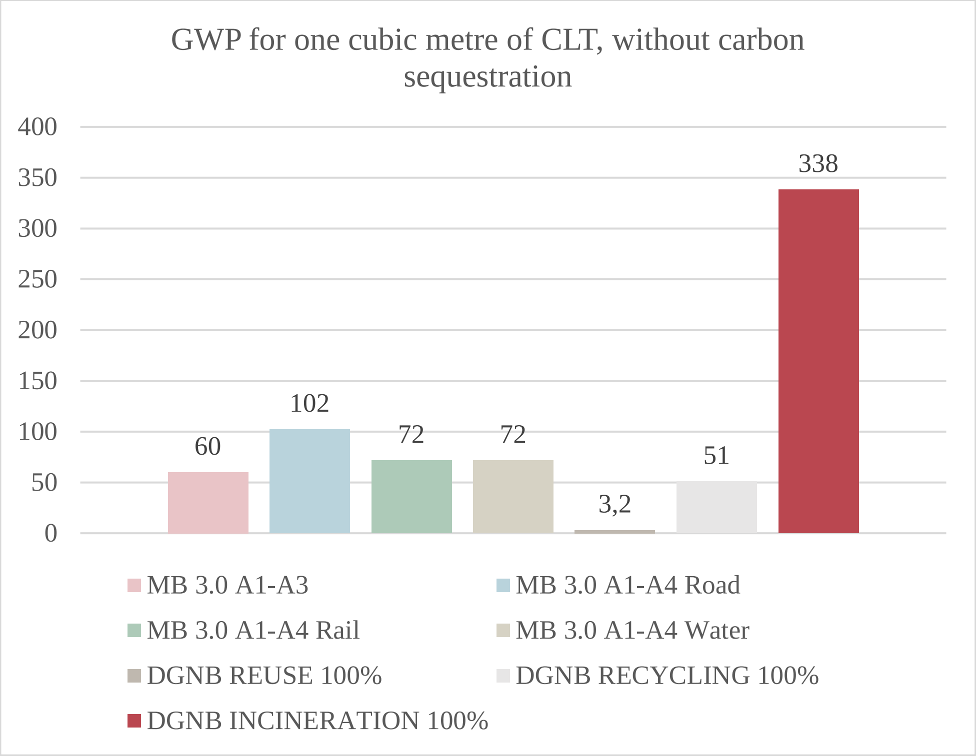


*Figure 16.19: All evaluated scenarios for Miljöbyggnad 3.0 and DGNB without sequestration for one cubic metre of CLT. The CLT production has a transportation distance of 500 km.*

The same analogy can be made for the shorter transportation distance regarding GWP for CLT with consideration to carbon sequestration. Any inclusion of transportation phase A4, will decrease the GWP-performance, moreover, decreasing the positive environmental effects of CLT with carbon sequestration. The worst certification scenario is still DGNB incineration. With reduced transportation distances, DGNB incineration becomes increasingly a worse option regarding GWP for CLT.

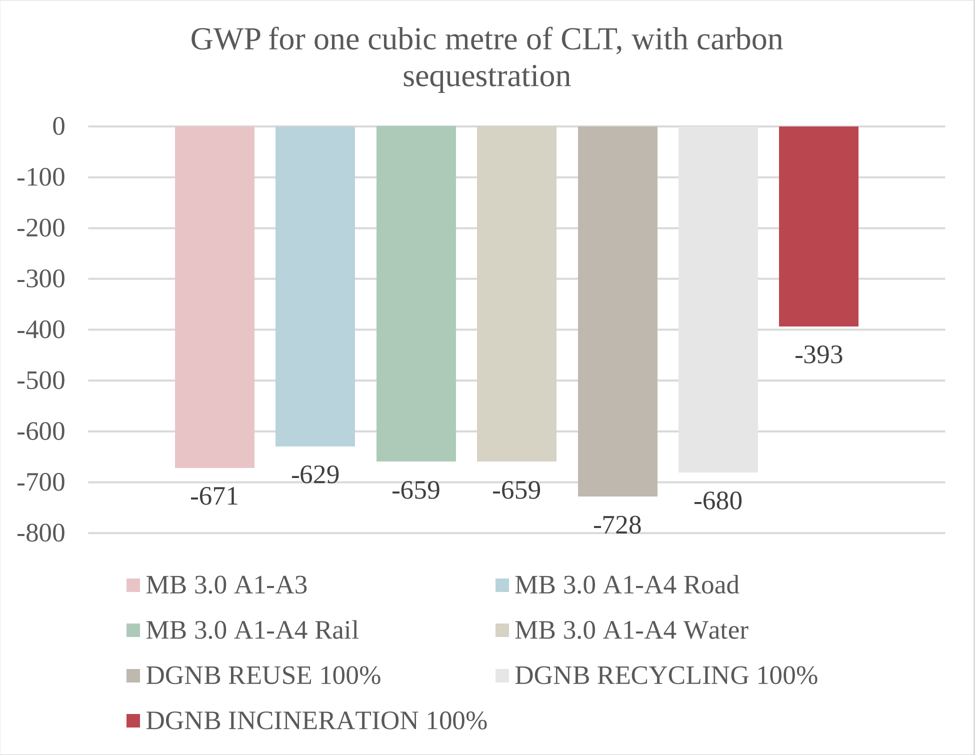


*Figure 16.20: All evaluated scenarios for Miljöbyggnad 3.0 and DGNB with sequestration for one cubic metre of CLT. The CLT production has a transportation distance of 500 km.*

## 16.6 Summarized results: Construction material comparison

Steel has a beneficial material structure for reuse and recycling. Overall, steel in DGNB with life cycle phases C3, C4 and D obtain about two times overall better environmental impact values for all environmental impacts.

Comparing concrete’s environmental performance in Miljöbyggnad 3.0 and DGNB with the added life cycle phases C3, C4 and D, the overall average improvement is negligible. With the same EOL scenario reuse and recycling compared to Miljöbyggnad 3.0, concrete’s performance even worsens with the added EOL scenario. This concludes concrete inability to improve its environmental sustainability with added life cycle phases.

### 16.6.1 Material comparison for GWP *with* carbon sequestration for CLT

*Table 16.18: Illustration of the studied structural construction material’s GWP. With material usage and with carbon sequestration for CLT. The comparison is conducted for all construction materials within a certain sustainable building certification.*

| **GWP [kg CO2-eq]** | **CLT [1 tonne]** | **Steel [1 tonne]** | **Concrete [2 tonnes]** | **Concrete [1 tonne]** |
|---|---|---|---|---|
| **MB 3.0** | -1428 | 1735 | 313 | 157 |
| **DGNB Reuse** | -1549 | 776 | 295 | 148 |
| **DGNB Recycling** | -1447 | 776 | 295 | 148 |
| **DGNB Incineration** | -708 | 776 | 295 | 148 |

As table 16.18 indicates, CLT with carbon sequestration is by far more environmentally beneficial, regardless of what sustainable building certification that is used. Carbon sequestration in DGNB incineration limits the beneficial effects due to the incineration limiting the time that the carbon is sequestrated. Steel is heavily impacted beneficially by certifying in DGNB with including beneficial EOL phases. The GWP for concrete is slightly improved with adding EOL scenario.

## 16.6.2 Material comparison for GWP without carbon sequestration for CLT

*Table 16.19: Illustration of the studied structural construction material's GWP. With material usage and without carbon sequestration for CLT. The comparison is conducted for all construction materials within a certain sustainable building certification.*

| GWP [kg CO2-eq] | CLT [1 tonne] | Steel [1 tonne] | Concrete [2 tonnes] | Concrete [1 tonne] |
|---|---|---|---|---|
| **MB 3.0** | 128 | 1735 | 313 | 157 |
| **DGNB Reuse** | 7 | 776 | 295 | 148 |
| **DGNB Recycling** | 109 | 776 | 295 | 148 |
| **DGNB Incineration** | 720 | 776 | 295 | 148 |

By not including carbon sequestration for CLT, the environmental performance regarding GWP suffers. As table 16.19 indicate, CLT still has a lesser GWP for Miljöbyggnad 3.0 and certification and EOL scenario DGNB Reuse and DGNB Recycling. However, DGNB Incineration performs badly compared to concrete, and compares evenly compared to steel.

Regarding the comparison of the structural construction materials' other environmental impacts, see chapter 16.3-16.4.

## 16.6.3 Summarized results for the six scenarios, comparing structural construction materials.

The tables 16.19-16.21 and 16.23-16.25 below illustrate the environmental impact based on the six scenarios that include different EOL scenarios for CLT and both include and exclude material usage factors. The results with an inclusion of carbon sequestration is presented in section 16.6.1. In tables 16.19-16.21 and 16.23-16.25, the EOL scenario for steel is reuse, recovery or recycling. The EOL scenario for concrete is reuse.

Tables 16.22 and 16.26 also represent the obtained result for comparisons of structural construction materials in Miljöbyggnad 3.0 only regarding production stage phases A1-A3

The figures show CLT's environmental impact as a fix value of one, the other values of environmental impact should be considered as a factor of environmental impact compared to CLT. All comparisons are made within each of the individual environmental impacts. To further describe the results, the following example are applicable in all presented scenarios below:

**Explanation of scenario 1 DGNB Reuse:**

According to table 16.19, GWP without sequestration for CLT is equal to one for any mass of the construction material. Steel's GWP compared to CLT is 114 times larger. Concrete's GWP compared to CLT is 21.7 times larger.

### Obtained results for scenario 1, 2 and 3

Scenarios 1, 2 and 3 below, represented in table 16.19, 16.20 and 16.21, presents a part of the obtained results in section 16.4.

*Table 16.19: Summarized results based on calculations where CLT is reused in DGNB, steel is reused, recovered or recycled and concrete is reused. All values should be interpreted as factors compared to CLT. Calculations are made without material usage.*

| | **Scenario 1 DGNB Reuse** | | |
|---|---|---|---|
| **Without material usage** | **CLT** | **Steel** | **Concrete** |
| GWP without sequestration [kg CO2-eq] | 1,0 | 114,0 | 21,7 |
| ODP [kg CFC11-eq] | 1,0 | 0,1 | 3,3 |
| AP [kg SO2-eq] | 1,0 | 74,7 | 29,7 |
| EP [kg PO4-eq] | 1,0 | 8,5 | 5,2 |
| POCP [kg Ethene-eq] | 1,0 | 586,8 | 97,0 |
| ADPE [kg Sb-eq] | 1,0 | 2,2 | 1,8 |
| ADPF [MJ] | 1,0 | 49,9 | 4,9 |

*Table 16.20: Summarized results based on calculations where CLT is recycled in DGNB, steel is reused, recovered or recycled and concrete is reused. All values should be interpreted as factors compared to CLT. Calculations are made without material usage.*

| | **Scenario 2 DGNB Recycling** | | |
|---|---|---|---|
| **Without material usage** | CLT | Steel | Concrete |
| GWP without sequestration [kg CO2-eq] | 1,0 | 7,2 | 1,4 |
| ODP [kg CFC11-eq] | 1,0 | 0,0 | 0,6 |
| AP [kg SO2-eq] | 1,0 | 4,7 | 1,9 |
| EP [kg PO4-eq] | 1,0 | 0,4 | 0,2 |
| POCP [kg Ethene-eq] | 1,0 | 44,6 | 7,4 |
| ADPE [kg Sb-eq] | 1,0 | 1,9 | 1,6 |
| ADPF [MJ] | 1,0 | 5,2 | 0,5 |

*Table 16.21: Summarized results based on calculations where CLT is incinerated in DGNB, steel is reused, recovered or recycled and concrete is reused. All values should be interpreted as factors compared to CLT. Calculations are made without material usage.*

| | **Scenario 3 DGNB Incineration** | | |
|---|---|---|---|
| **Without material usage** | CLT | Steel | Concrete |
| GWP without sequestration [kg CO2-eq] | 1,0 | 1,1 | 0,2 |
| ODP [kg CFC11-eq] | -1,0 | 0,0 | 0,0 |
| AP [kg SO2-eq] | 1,0 | 0,5 | 0,2 |
| EP [kg PO4-eq] | 1,0 | 0,1 | 0,1 |
| POCP [kg Ethene-eq] | 1,0 | 1,2 | 0,2 |
| ADPE [kg Sb-eq] | 1,0 | 0,6 | 0,4 |
| ADPF [MJ] | -1,0 | 0,7 | 0,1 |

## Obtained results for Miljöbyggnad 3.0, without material usage

Table 16.22, present the obtained result where the three structural construction materials without material usage are evaluated in Miljöbyggnad 3.0, only including production stage phases A1-A3.

*Table 16.22: Summarized results based on calculations where CLT, steel and concrete are evaluated in production stage phases A1-A3. All values should be interpreted as factors compared to CLT. Calculations are made without material usage.*

| | **Miljöbyggnad 3.0** | | |
|---|---|---|---|
| **Without material usage** | CLT | Steel | Concrete |
| GWP without sequestration [kg CO2-eq] | 1,0 | 13,6 | 1,2 |
| ODP [kg CFC11-eq] | 1,0 | 0,0 | 0,3 |
| AP [kg SO2-eq] | 1,0 | 6,9 | 1,7 |
| EP [kg PO4-eq] | 1,0 | 0,5 | 0,2 |
| POCP [kg Ethene-eq] | 1,0 | 48,1 | 2,9 |
| ADPE [kg Sb-eq] | 1,0 | 3,6 | 1,8 |
| ADPF [MJ] | 1,0 | 8,3 | 0,5 |

## Obtained results for scenario 4, 5 and 6

Scenarios 4, 5 and 6 below, represented in table 16.23, 16.24 and 16.25, presents a part of the obtained results in section 16.4.

*Table 16.23: Summarized results based on calculations where CLT is reused in DGNB, steel is reused, recovered or recycled and concrete is reused. All values should be interpreted as factors compared to CLT. Calculations are made with material usage.*

| | **Scenario 4 DGNB Reuse** | | |
|---|---|---|---|
| **With material usage** | CLT | Steel | Concrete |
| GWP without sequestration [kg CO2-eq] | 1,0 | 114,0 | 43,4 |
| ODP [kg CFC11-eq] | 1,0 | 0,1 | 6,6 |
| AP [kg SO2-eq] | 1,0 | 74,7 | 59,5 |
| EP [kg PO4-eq] | 1,0 | 8,5 | 10,4 |
| POCP [kg Ethene-eq] | 1,0 | 586,8 | 194,0 |
| ADPE [kg Sb-eq] | 1,0 | 2,2 | 3,6 |
| ADPF [MJ] | 1,0 | 49,9 | 9,9 |

*Table 16.24: Summarized results based on calculations where CLT is recycled in DGNB, steel is reused, recovered or recycled and concrete is reused. All values should be interpreted as factors compared to CLT. Calculations are made with material usage.*

| | **Scenario 5 DGNB Recycling** | | |
|---|---|---|---|
| **With material usage** | CLT | Steel | Concrete |
| GWP without sequestration [kg CO2-eq] | 1,0 | 7,2 | 2,7 |
| ODP [kg CFC11-eq] | 1,0 | 0,0 | 1,1 |
| AP [kg SO2-eq] | 1,0 | 4,7 | 3,8 |
| EP [kg PO4-eq] | 1,0 | 0,4 | 0,5 |
| POCP [kg Ethene-eq] | 1,0 | 44,6 | 14,8 |
| ADPE [kg Sb-eq] | 1,0 | 1,9 | 3,1 |
| ADPF [MJ] | 1,0 | 5,2 | 1,0 |

*Table 16.25: Summarized results based on calculations where CLT is incinerated in DGNB, steel is reused, recovered or recycled and concrete is reused. All values should be interpreted as factors compared to CLT. Calculations are made with material usage.*

| | **Scenario 6 DGNB Incineration** | | |
|---|---|---|---|
| **With material usage** | CLT | Steel | Concrete |
| GWP without sequestration [kg CO2-eq] | 1,0 | 1,1 | 0,4 |
| ODP [kg CFC11-eq] | -1,0 | 0,0 | 0,1 |
| AP [kg SO2-eq] | 1,0 | 0,5 | 0,4 |
| EP [kg PO4-eq] | 1,0 | 0,1 | 0,1 |
| POCP [kg Ethene-eq] | 1,0 | 1,2 | 0,4 |
| ADPE [kg Sb-eq] | 1,0 | 0,6 | 0,9 |
| ADPF [MJ] | -1,0 | 0,7 | 0,1 |

## Obtained results for Miljöbyggnad 3.0, with material usage

Table 16.26, present the obtained result where the three structural construction materials with material usage are evaluated in Miljöbyggnad 3.0, only including production stage phases A1-A3.

*Table 16.26: Summarized results based on calculations where CLT, steel and concrete are evaluated in production stage phases A1-A3. All values should be interpreted as factors compared to CLT. Calculations are made with material usage.*

| | **Miljöbyggnad 3.0** | | |
|---|---|---|---|
| **With material usage** | CLT | Steel | Concrete |
| GWP without sequestration [kg CO2-eq] | 1,0 | 13,6 | 2,5 |
| ODP [kg CFC11-eq] | 1,0 | 0,0 | 0,6 |
| AP [kg SO2-eq] | 1,0 | 6,9 | 3,5 |
| EP [kg PO4-eq] | 1,0 | 0,5 | 0,4 |
| POCP [kg Ethene-eq] | 1,0 | 48,1 | 5,7 |
| ADPE [kg Sb-eq] | 1,0 | 3,6 | 3,6 |
| ADPF [MJ] | 1,0 | 8,3 | 1,0 |

## Conclusion of tables 16.19-16.26

Reuse is the most beneficial EOL scenario for CLT followed by recycling. CLT with EOL scenarios reuse and recycling can be considered more environmentally sustainable compared to steel and concrete. CLT with EOL scenario Incineration can be considered more environmentally harmful compared to steel and concrete. Miljöbyggnad 3.0 with life cycle stages A1-A3 limits the beneficial and harmful environmental effects of CLT, depending on EOL scenario. Incineration is the worst EOL scenario for CLT.

### Transport conclusions

Since there is no manufacturing of CLT in Sweden and Denmark currently in 2018, the environmental impact and carbon dioxide emission will be higher in the LCA phase *A4 Transport* for CLT when comparing with steel and concrete. This is clearly shown in figure 16.11-16.12. The results also indicate that including life cycle phase A4 in Miljöbyggnad 3.0 for higher grades can be detriment for CLT and its environmental impact.

With the four available transport comparison scenarios, the lowest GWP of CLT, steel and concrete implemented in Miljöbyggnad 3.0 and DGNB, will be CLT with DGNB Reuse as certification scenario. Even if carbon sequestration is excluded. The highest GWP of the three studied construction materials is steel with Miljöbyggnad 3.0 road as *A4 Transport*.

Regarding CLT, the worst certification scenario will be DGNB Incineration. CLT in Miljöbyggnad 3.0 with road as mode of transport has a lower GWP compared to DGNB Incineration.

By moving manufacturing of CLT to Sweden and Denmark, the transportation emissions of carbon dioxide would be reduced and impact Miljöbyggnad 3.0 (higher grades) significantly for CLT. The total A1-A4 emissions for one tonne CLT manufactured in Austria would yield 220 kilogram carbon dioxide equivalents, one tonne CLT manufactured in Sweden would yield 102 kilogram carbon dioxide equivalents, which is an improvement of 54%. Transportation of CLT by road will still be a worse alternative compared to water and rail considering GWP.

# Chapter 17 Interviews

## 17.1 Certification interview with Sweden Green Building Council

*The interviewed representative from Sweden Green Building Council (SGBC) will from now on be referred to as respondent one (R1 SGBC).*

**Sustainable building certifications**

When considering new production of buildings, R1 SGBC mentions that the most important element in a green building certification depends on which aspects impact the environment the most. With new buildings, the yearly energy usage affects the environment the most. Regarding the environmental impact of construction materials, the effect occurs once during the building's life cycle, whereas energy usage is a reoccurring constant occasion.

In accordance with the national environmental goals, the legal framework is adapted to include certain minimum-requirements for the built environment. In Sweden a *good built environment* is a national environmental goal which aims to improve environmental aspects in the urban environment. There are other environmental goals which aims to reduce chemical usage in the construction sector. There is an obligation for developers to follow the building regulations which adapt the environmental goals, hence the importance of green building certifications. Green building certifications serves as a quality indicator for property developers and buyers. If a building is certified, the certification implies that the building has a high standard in accordance with the certification criteria.

R1 SGBC thinks that the number of available certifications available today is positive. Property developers wants to distinguish themselves and their buildings from others and brand themselves in a certain way. Consequently, it is good to have several available building certifications on the market. Furthermore, R1 SGBC highlights that different building certifications are more apt in different countries, depending on how they are designed and which aspects they emphasize. Since Miljöbyggnad 3.0 is developed for Swedish conditions, Miljöbyggnad 3.0 supports the Swedish national environmental goals. LEED and BREEAM on the other hand, is not originally developed for Swedish conditions. However, some adaptions have been made in the Swedish versions of LEED and BREEAM.

Miljöbyggnad 3.0 focuses on environmental sustainability and the property of the building. R1 SGBC suggests that it is hard to measure social sustainability when only focusing on the building. BREEAM and LEED has a larger system boundary which include other aspects of the building that allows to include social sustainability easier. However, economical sustainability is somewhat easier to include in a certification. For instance, economical incitements can work as an enabler to incorporate economical sustainability in the certification. The certification grading gold is achievable with the latest available building techniques, which can result in higher costs. Larger investments in the building will over time generate energy and other savings as well as increase property values, hence reducing the investment costs over time.

Architectonical values are not explicitly included in Miljöbyggnad 3.0. The aesthetical aspect of architectural values is not included. Regarding functional architectural values, for instance how furnishable a building is and the availability are regulated in Swedish building regulations.

### LCA tool in sustainable building certifications

The designing process of the LCA tool was rather complex for Miljöbyggnad 3.0 since many aspects needed to be considered. The main idea with the LCA tool in Miljöbyggnad 3.0 was to only include the life cycle phases that can be calculated consistently in one way. It is only life cycle phases A1-A4 that can be calculated consistently, according to SGBC. This idea aims to limit the possible interpretations of calculating certain areas. The purpose of the LCA tool is to increase the knowledge about LCA and the environmental impacts of construction materials and increase the amount of available EPDs on the market. The LCA tool only include the construction elements with the highest carbon dioxide equivalents, which is the building foundation and the structural construction. Generally, there are less EPDs available for non-loadbearing elements. The current LCA tool in Miljöbyggnad 3.0 will evolve in later versions of Miljöbyggnad 3.0, since it is a dynamic indicator that can be changed in other versions of the third generation of Miljöbyggnad. In later versions of the LCA tool it is likely that the focus from generating more EPDs on the market will shift. The design of the tool and the included phases may also change.

In Miljöbyggnad 3.0 the LCA tool is simple, which is a conscious decision that aims to educate certification users in LCA and increase the demand for EPDs from manufacturers. The big challenge in an environmental perspective is to reduce to carbon dioxide emissions and that is why GWP is the only included environmental impact factor in Miljöbyggnad 3.0.

In the beginning of the LCA tool’s existence on the market, there were no reference values that could be compared to given material solutions. R1 SGBC says that as the certification gets used increasingly, reference values can be extracted from the material data and emission data from submitted LCA tool calculations. The purpose of the Miljöbyggnad 3.0 LCA tool is not to stay within a certain boundary, but rather to learn how to use an LCA and estimate quantities of required material. As soon as the market understands and uses the LCA tools to assess their buildings, reference values can be introduced to increase the minimum accepted values of carbon emissions.

According to R1 SGBC, the selection of LCA phases included in the LCA tool, was decided by LCA standards. The majority of EPDs include production stage phases A1-A3 and they are therefore included in the Miljöbyggnad 3.0 LCA tool. The calculation for life cycle phases A1-A3 is consistently the same, according to standard LCA methods. Generic values are simple to use in an LCA tool, whilst assuring that all calculations are based on the same values. The generic values can be considered average values for each construction material category. When other areas of the LCA stages are standardized, they can be used in the Miljöbyggnad 3.0 LCA tool as well.

All EPDs are third party verified and SGBC must trust in the reliability of the EPDs. Although, there are still some differences in the quality of EPDs between different manufacturers.

R1 SGBC mentions that LEED does not take chemical consumption into account since the American chemical industry has made it their mission to exclude restrictions of chemical usage in LEED. Miljöbyggnad 3.0 include the reduction of chemicals in the construction sector as it is a national environmental goal.

According to R1 SGBC, BREEAM and Miljöbyggnad 3.0 for new production of buildings both consider restrictions of chemical use.

Miljöbyggnad 3.0 demands a journal of inbound materials in the building. For different certification grades, the amount and location of materials is also required. This is a good way to have information about future sanitation costs of certain specific materials regarding indicator 14 *(phasing out of hazardous substances)* in Miljöbyggnad 3.0.

### Construction material

R1 SGBC points out that carbon sequestration of timber is a sensitive and a somewhat controversial matter. The origin of the question regarding carbon sequestration is an interpretation of a standard that can be interpreted as if the benefits of sequestration can be included in an LCA. Carbon sequestration is not allowed or considered in Miljöbyggnad 3.0. R1 SGBC suggests that there are ongoing actions to mitigate carbon sequestration, hence eliminating the possible positive interpretation of the standard. The main argument from R1 SGBC is that carbon sequestration is accounted of too far into the future and therefore not relevant.

### General comments

There has been a shift during the last ten years towards prioritizing environmental aspects in building projects. Ten years ago, the environmental issues were often neglected, today the environmental aspects and sustainable building certifications are often central in a project.

The general tendency is that banks are more willing to loan money for acquiring and building certified buildings. The trend could be explained in two different ways, either they regard the certification as a quality brand and a good investment, or they can apply it in their corporate social responsibility (CSR). It is expensive for the manufacturers to produce EPDs and it costs approximately 10 000 euro.

The initiative from banks regarding loans have had effects on the manufacturers strive to lower the carbon dioxide emissions. Consequently, the manufacturers are working hard to increase environmental sustainability aspects of their production to acquire more market shares. The construction material manufacturers in Sweden tend to be transparent with inbound chemicals and materials in their products and EPDs. Other European construction material manufacturers are not always as prone to transparency and often demands confidentiality along with viewing their EPDs. This reluctance to share information about the content of construction materials act as a hinder on the Swedish market and the increased availability of EPDs.

## 17.2 Certification interview with Green Building Council Denmark

*The interviewed representative from Green Building Council Denmark (DK-GBC) will from now on be referred to as respondent two (R2 DK-GBC).*

**Sustainable building certifications**

R2 DK-GBC highlights the holistic approach and that all different aspects are important in a green building certification. R2 DK-GBC also refers to sustainable certifications rather than green building certifications, since the goal is to build sustainable buildings. In DGNB the overall sustainability is made up of five main areas which are: economic quality, environmental quality, socio-cultural and functional quality, technical quality and process quality.

According to R2 DK-GBC, sustainable certifications is a sort of sustainable framework and works as a mean for the construction industry to compete. The DGNB system offers stricter building regulations which improves the overall sustainability for the building. Sustainable certifications should initially work as a positive incitement for early adapters to push the sustainable border in the construction sector. Sustainable certifications also aim to educate stakeholders in the construction sector in building sustainable buildings. In the future when more companies and building owners certificate buildings, the regular building regulations and demands in DGNB can be tightened up to further move the frontier of sustainable buildings.

R2 DK-GBC highlight that there is a lot of building certifications available on the market and that it is not necessarily a bad thing. Due to the fact, that building regulations differ between countries, it is important to have sustainable certifications based on the building regulations in the actual country where the building will be erected. At the same time, it is important to not have too many certifications available, since clients tend to choose the cheapest one.

All the aspects of sustainability, economic, environmental and social sustainability, are incorporated in DGNB. Different indicators within DGNB evaluate the three aspects of sustainability.

Due to the difficulty to define and measure architectural values, there is no direct criterion that evaluates architectural values. However, embedded in some criteria are sustainable architectural aspects such as; availability, indoor climate etcetera. In Germany, DGNB has introduced DGNB diamond which awards architectural values and design.

### LCA tool in sustainable building certifications

DK-GBC did not develop the LCA tool originally. DK-GBC took the German LCA tool and in cooperation with SBi, DK-GBC developed a similar LCA tool which is used in Denmark. The most important factors in the LCA tool is to exclude life cycle phases that does not impact the environmental impact of the building. DK-GBC believes that life cycle phases A1-A3 for construction materials is an important aspect of the LCA tool and transport, life cycle phase A4, is not. DGNB includes *cradle-to-gate* phases A1-A3 and EOL phase D. DGNB also include energy and usage phases, B4 and B6, in the certification. However, the usage is parted from the topic of construction materials. A long lifespan is also preferable according to R2 DK-GBC. At the moment, the LCA tool looks at a 50-year lifespan, however there is actions towards increasing the lifespan to 100-years. This expansion of lifespan rests on the improvement of energy calculations in the future. An energy mix today which has an environmental impact will not be the same in 100 years, it is therefore important to develop assumptions on future energy mixes used in buildings.

A more detailed LCA tool will include more negative environmental impacts compared to a simplistic LCA tool. However, the more complex LCA tool will give a more accurate result on the actual emission of a construction material. A simplified LCA tool aims to educate and get stakeholder involved in using LCA tools. There is a balance between achieving correct environmental impacts and getting stakeholders to use LCA tools. Regarding the different environmental impacts, a more complex LCA tool can adjust the inclusion or exclusion of new and old environmental impacts. In the future, ODP will be excluded from the German LCA tool since there is research implying that the ozone layer is healing. A more complex LCA tool is seemingly more prone to better adjust and adapt to new trends. One of which is the product environmental footprint (PEF) which include other environmental impacts and scales the impacts differently based on the general conception and scientists weighing. It is the R2 DK-GBC's belief that PEFs and EPDs will eventually converge and form a more complex and thorough background about material emissions. It is a possibility that DGNB in the future will base LCA calculations on PEFs.

Reference values for GWP and energy is the most important ones, with three times more strict references compared to the other environmental impacts. R2 DK-GBC that initially strict reference values inhibit the consumer's ambition to use certifications and EPDs. However, in a later stage when stakeholders have adapted LCA tools and understand how it works, the reference values can be made stricter to push the development in decreasing emissions.

The decisions of what LCA phases that should be included was not made by DK-GBC. The LCA phases included in the German DGNB was used. However, DK-GBC thought about and considered the limitations surrounding the choices of what LCA phases that should be included. Some LCA phases are easier to get a clear picture on what to include in calculations, other are more complex and could lead to misinterpretations and misunderstandings.

An issue with DGNB is that the values are mainly based on the Ökobaudat database which does not give the correct background and context when certifying in Denmark. R2 DK-GBC wishes that the EPDs in Ökobaudat were more relevant for the Danish building sector. By getting a building certified it is a third-party verification of a sustainable building. The client may now know all the aspects of what it means to get certified, however it's like a quality assurance for the building that can be understood easily.

### Construction material

By using DGNB the inclusion of LCA gives an accurate description of the building's environmental impact. LEED and BREEAM only asks for the EPD without any grading of the EPDs values. The emissions from the EPDs can be high or low and LEED and BREEAM does not reward or punish based on values. This approach of not valuing EPDs could lead to a more widespread use of EPDs. However, DGNB look at the EPDs and their reference values, only to use it as an instrument for moving the frontier of emissions in a later stage. DGNB, LEED and

BREEAM all have the same goal. However, the sustainable building certifications use different approaches regarding EPDs.

If you look at CLT over a long enough lifespan, the material should always be carbon neutral. By sequestrating carbon in a building over its service life, the effect should still be carbon neutrality. However, about 50% of the wood cut down in Denmark are incinerated without it being sequestrated in a building. If you look at it this way, it should be better to use new timber for buildings and used timber for incineration. Depending on the construction material, the emissions of carbon dioxide is different. Concrete has very high carbon emission during production stage phases (A1-A3), whereas CLT has it at the end of its service life. Another aspect highlighted by R2 DK-GBC was that the carbon dioxide uptake today, when sequestrating carbon in a timber building is preferable to positive environmental effects in 100-years. Concrete during decarbonatization takes up carbon dioxide, however this only occurs when the concrete is crushed, which implies a time-span of 100-years. Considering CLT, the timber sequestrates differently depending on if the carbon uptake takes place during the growth of the forest or the regrowth. When mentioning CLT it is important not to forget sustainable forestry. For CLT to be sustainable, it is crucial that there is no deforestation and that the cut lumber is replanted.

**General comments**

Projects under a budgeted value of 2 000 000 euro is not recommended to certify with DGNB since the certification is expensive for small scale projects. However, for bigger projects the percentage cost is very low. Smaller scale projects could still benefit from DGNB certification since parts of DGNB can be used to assure sustainable values.

The building ministry is working towards introducing *Frivillig Bæredygtighedsklasse* which is a voluntary extension to the building regulations to capture projects below 2 000 000 euro, with a motivation to build sustainably. Since all EPDs are third-party evaluated, DGNB choose to trust these values. Most EPDs only include production stage phases A1-A3 and not EOL, some of the EPDs are also outdated. However, the available EPDs from Ökobaudat is the best option available.

## 17.3 Architectural interview with C.F. Møller

*The interviewed representative from C.F. Møller will from now on be referred to as respondent three (R3 C.F. Møller).*

**Sustainable building certifications**

R3 C.F. Møller is familiar with DGNB, Active House and BREEAM. An architect working in Denmark does not have any authority to make decisions concerning sustainable building certifications. However, suggestions can be made by the architect to encourage the client to certify their building with DGNB. It is most often decided in an earlier stage whether the building should be certified with a sustainable building certification. As a part of a company's CSR, DGNB can be used. Acquisition of ground, owned by the municipality, may include a clause that the buildings constructed on the ground must be certified with DGNB with a certain grade.

R3 C.F. Møller's opinion about the amount of available sustainable building certifications is that it should be a balance between complex, detailed certifications and simplified certification systems. The different certifications with varying complexity cover the full spectra of construction projects. DGNB is a complex, extensive and expensive sustainable building certification. In general, a certification costs 50 000 euro and the construction cost are estimated to be 1-2 million DKK more expensive for a 5000-15 000 square meter building, compared to a non-certified building. Compared to DGNB, a simplified certification does not offer the same level of detail and do not include all environmental effects. There is reason to believe that a more comprehensive certification system should be more environmentally sustainable in contrast to a simpler version. There is an initiative in Denmark right now with the aim to develop a method called *Frivillig Bæredygtighedsklasse* for buildings with voluntarily regulations, stricter than the Danish building regulations, to encourage property developers to build more sustainable buildings without being forced to. The method includes for example LCA and life cycle cost (LCC) calculations. *Frivillig Bæredygtighedsklasse* is presumed to include the adopter category *Early Adopters* according to E.M. Rogers Diffusion of Innovation Theory, as shown in figure 7.1. While, DGNB captures the first adopter category, *Innovators*.

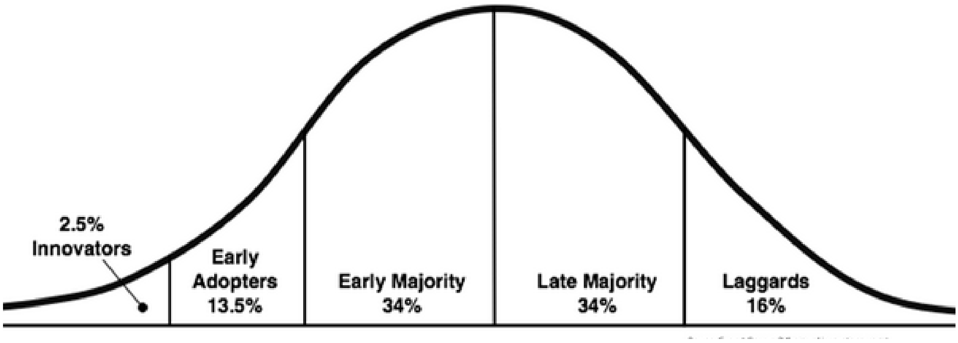


*Figure 17.1: Illustrates the different adopter categories according to E.M. Rogers (Boston University School of Public Health 2018).*

If the decision to certify the building project according to DGNB is made before the design work starts it is easy to map the points given by each criterion in DGNB. However, if the decision is made later in the design process or even in the initial phases of the construction work the DGNB certification process becomes more time consuming and complex. The chosen construction design usually remains the same even if the decision to certify with DGNB is made later in the design process. Nevertheless, the focus becomes to find other criteria rather than the criteria related to the construction material to collect points within the certification system.

The determination to certify a building with DGNB in one aspect may in other aspects compromise the overall sustainability of the building. For instance, if the focus is to reduce operational energy usage, a solution could be to add more insulation in the building envelope. As a result of more insulation higher operative temperatures than preferred may occur inside the building, thus resulting in a worse indoor climate. Consequently, it is essential to think of the building as a system and that one criterion can impact another. To for example use an expensive façade material with a long lifespan is mostly not beneficial in DGNB as LCC is also considered. The LCC calculation used in DGNB is static but the expensive façade material might be considered a sustainable construction solution if the LCC model is dynamic, given thought to its long lifespan.

## Construction material

The limitations of CLT as a construction material in Denmark is primarily fire resistance and building regulations hindering multi-storey buildings from being higher than four floors high. The limitations of steel as a construction material in Denmark is that it is rather expensive and there is limited experience and tradition of steel buildings. Since construction steel is only used as hybrid construction solutions, steel and concrete combinations, it is simpler to only use concrete, due to the lack of experience in Denmark. There are no mentioned limitations about concrete since it is easy to construct and most construction projects in Denmark uses concrete as structural construction material.

The material choice for buildings is not highly dependent on DGNB. According to R3 C.F. Møller it is possible to get DGNB gold for a typical concrete building. There is also a tendency towards increased reuse of bricks in new buildings, which reduces the production energy and dramatically improves the environmental impact values. Timber frame modules are also beneficial to use in the LCA tool. Generally, construction materials that do not need maintenance and replacement too often is advantageous to choose to get a higher grade in DGNB.

In recent years the focus of building sustainability has been operational energy savings. Furthermore, the trend moves towards focusing and improving energy usage in relation to construction materials in a life cycle perspective. The observed time perspective differs when comparing operational energy savings and effects of construction material. Operational energy calculations and EOL scenarios is based on future assumptions whereas sequestration is imminent. R3 C.F. Møller is very positive towards including carbon sequestration in the DGNB LCA tool. However, the how carbon sequestration should be incorporated in DGNB is not suggested by R3 C.F. Møller.

## General comments

C.F. Møller is involved in several initiatives in conjunction with the timber industry and the academia. The initiative intends to increase the number of timber buildings in Denmark and advert changes towards using timber and reduce carbon dioxide emissions. Another challenge concerning the increased use of timber is the present fire regulations in Denmark, which is beneficial for concrete.

# Chapter 18 Discussion

## 18.1 Environmental impacts for construction materials

For steel, an inclusion of an EOL scenario that reuses and recycles steel after its service life as construction material, improves the environmental impact broadly with a factor two for the different evaluated environmental impacts. This results in any inclusion of the EOL scenario reuse and recycling will broadly halve the environmental impact for steel.

Regarding concrete, an inclusion of EOL scenario reuse and recycling, results in that the environmental impacts stays about the same for all the environmental impacts. Suggesting a none-factor of environmentally beneficial effects at life cycle phases C3, C4 and D.

On this note, that different materials have different environmental impacts during different life cycle phases is something that needs to be further addressed. When designing any LCA tool, the included life cycle phases will have a great effect on the overall sustainability for the researched construction material. In this research study, environmental impacts in different life cycle phases for different construction materials have been observed. There is a great variance of environmental impact emphasis in life cycle stages depending on which material and environmental impact that is observed. Further concluding the importance of which life cycle stages and environmental impacts that are included in any sustainable building certifications LCA tool.

The number of environmental impacts included in Miljöbyggnad 3.0 and the Danish version of DGNB differ. Miljöbyggnad only assess global warming potential. According to R1 SGBC, global warming potential is the most important environmental impact which need an urgent decrease, thus the emphasis on GWP. DGNB on the other hand assess other environmental impacts in addition to GWP. DGNB assesses acidification potential (AP), ozone depletion potential (ODP), eutrophication potential (EP), photochemical ozone creation potential (POCP), abiotic depletion potential- elements (ADPE) and abiotic depletion potential-fossil fuels (ADPF).

The effect of having different life cycle phases available in different sustainable building certifications, is the main factor of the differences obtained in environmental impacts of the same material in two different sustainable building certifications. The inclusion of life cycle phase *A4 Transport* affects CLT in Miljöbyggnad 3.0 negatively and other construction materials are barely affected since the manufacturing are more closely based nationally. However, CLT in DGNB do not have any carbon emissions in life cycle phase A4, since life cycle phase A4 is not included in the LCA tool. Completely neglecting the impact of transport of the construction material.

## 18.2 Environmental impacts for cross-laminated timber

By summarizing all environmental impacts in the life cycle stages, as stated in EN standard 15804; *Production stage A1-A3, Construction stage A4-A5, Use stage B1-B7, End of Life stage C1-C4 and Benefits and Loads beyond the System Boundary D*, the environmental impact of CLT can be determined. There will be slight differences in environmental impact regarding CLT depending on manufacturer, environmental product declarations used, type of energy used in the different life cycle stages etcetera. However, within this system boundary, the environmental impacts of CLT can be identified. Due to the fact of lacking knowledge regarding how to quantify the environmental impacts from certain life cycle stages, most EPDs do not include values on environmental impacts for all life cycle stages.

In the research study, the aim was to identify and measure the environmental impacts of CLT when implemented in sustainable building certifications Miljöbyggnad 3.0 and the Danish version of DGNB. Depending on the different included life cycle phases in the sustainable building certifications, the environmental impacts of CLT depends on which certification that is used. In its extension, the environmental impact of CLT depends on which life phases that are included in the calculations.

By using an EPD from Stora Enso (2017), the environmental impacts from the included life cycle stages; *Product stage A1-A3, Construction stage A4 Transport, End of life stage C1-C4* and *Benefits and loads beyond the system boundary D* was presented. The data was presented for each life cycle phase and each environmental impact individually, as shown in chapter 15.

Depending on which EOL scenario that is included in an LCA calculation, the environmental impact of CLT will differ. Since each type of EOL scenario, will impact the environment differently, as seen in section 16.6.3.

## 18.3 Bio-mass and wood-based products

The carbon cycle shows that atmospheric carbon is embodied by vegetation due to photosynthesis. This stored carbon in bio-mass will eventually by natural processes, such as decay, be re-released as atmospheric carbon. Therefore, this concludes that over long-enough timespans any bio-mass product will be carbon neutral. This phenomenon also goes for CLT and CLT as a construction material.

However, the carbon neutrality of wood-based products is dependable on the constant and preserved bio-mass on Earth. If the amount of plants and forests should decrease, the embodied carbon would be released and thus increasing the atmospheric carbon. Equivalently, if the amount of bio-mass in vegetation on Earth should increase, more atmospheric carbon would be embodied in bio-mass and thus decreasing the atmospheric carbon.

The understanding of the carbon cycle is paramount to be able to understand and evaluate the positive environmental effects of carbon sequestration. In line with previous descriptions, any wood-based product will be carbon neutral over a long enough time-span, depending on the preserved and constant regrowth of the harvested wood material. However, regarding radiative forcing which is the balance of incoming solar energy and outgoing reflected infra-red radiation, the abundance of greenhouse gases affects the ratio of outgoing energy and ultimately the Earth’s temperature. The greenhouse effect is the driver for radiative forcing and depends on the amount of greenhouse gases in the atmosphere. Carbon sequestration’s ability to retain atmospheric carbon as embodied carbon will reduce the concentration of greenhouse gases in the atmosphere, as long as the bio-mass sequestrates carbon. During the time of any wood-product’s carbon sequestration, some radiative forcing is avoided due to the prolonged time of carbon storage in the bio-mass.

To exemplify the positive effects on the environment of carbon sequestration, the following deduction goes in line with the response from R2 DK-GBC. If bio-mass is incinerated, which the research study regard as an unsustainable EOL scenario, embodied carbon emissions transform into atmospheric carbon and energy is recycled during the process. According to R2 DK-GBC, about 50% of the wood cut down in Denmark are incinerated immediately without having any type of functional use as a wood product. This raises the following question; would it not be better to first use the wood as a construction material, sequestrating carbon and avoiding some radiative forcing and after the product’s lifespan use incineration as EOL scenario? The theoretical framework is not clear on the environmental effects of carbon sequestration therefore, any implementation in an LCA will be debated. By using global temperature potential (GTP), a possible representation of the avoided radiative forcing could be quantified, thus accrediting carbon sequestration further.

## 18.4 Cross-laminated timber and carbon sequestration

Regarding the ongoing discussion of the debated term carbon sequestration, there is no denying the beneficial results for wood-based products in LCAs with the implementation of carbon sequestration. The empirical part of the research study undoubtedly presents a significant improvement concerning the performance of CLT in sustainable building certifications, with the inclusion of carbon sequestration regarding GWP. Darby, Elmualim and Kelly (2012), present the same fundamental findings in their research, showing that including carbon sequestration will dramatically decrease the GWP for CLT.

In a given scenario, where sustainable building certification and EOL scenario is chosen for a wood-based product, the inclusion of carbon sequestration will decrease the product’s GWP and reduce the carbon dioxide emissions. The above scenario is based on the misconception and misinterpretation of an EN standard, according to R1 SGBC. For the ongoing discussion Hafner (2014) suggests that there seems to be diverging opinions regarding if carbon sequestration should be included or not, from an LCA perspective and the framework of ISO-standards. Hafner (2014) also mentions different life cycle phases that may be able to include carbon sequestration such as *B1 Use* or *D Benefits and Loads beyond the System Boundary*. Depending on which sustainable building certification and LCA tool that is used, this may exclude carbon sequestration even though the ISO-standard allows it. Furthermore, as the research study shows, varying inclusions of life cycle phases in different sustainable certifications LCA tools can have great impact on the performance of the observed construction material.

The actual research study does not provide any objective description of the potential inclusion of carbon sequestration, it only highlights the environmental effects that can be observed in the results of an LCA regarding CLT. The theoretical framework proves the existence of different opinions and results regarding the actual environmentally benefits carbon sequestration can have on climate change.

## 18.5 Material comparison

Regarding included environmental impacts such as global warming potential, ozone depletion potential etcetera in sustainable building certifications, the weighing of each included environmental impact needs to be addressed. In the research study, empirical evidence suggests that some structural construction materials environmental performance increases based on some specific environmental impacts. CLT has the lowest global warming potential compared to steel and concrete, with and without material usage. Steel has the lowest ozone depletion potential compared to CLT and concrete. Finally, concrete has the lowest eutrophication potential compared to CLT and steel. There are no results in the research study that indicate which environmental impacts should be regarded as more important when comparing structural construction materials. Most of the policies and sustainable goals, such as the Paris agreement, uses global warming potential or carbon emissions as functional unit, suggesting a higher weighing of global warming potential. The United Nations depicts anthropogenic climate change as one of the major challenges of our time. Green and Karsh (2012), believes that reducing carbon and other GHGs emissions is the best way to mitigate anthropogenic climate change.  The research study does not investigate how the environment is affected depending on the emissions from the environmental impacts.

In the research study, the authors highlight that any choice of structural construction material should not solely rest upon this research study, there are other aspects which will impact the overall sustainability of each of the observed construction materials. Aspects such as moisture and fire hazards are directly linked with CLT and there needs to be other evaluating criteria apart from the presented results in the actual thesis for a just comparison between the structural construction materials.

Another demarcation and comment on the presented results are the need for functional comparison between structural construction materials. In theory, the only viable comparison should be of construction elements of different construction materials which provide the exact same functional effects, such as acoustics, strength, and fire performance etcetera. This is a demarcation of the actual research, whereas the material comparison mainly serves as a platform for material properties and its effect in LCA tools.

However, with the above-mentioned demarcation, the research study shows that the overall environmental performance of CLT is better than steel and concrete. Werner et al. (2005) as well as Fleming, Smith and Ramage (2014) also suggest that especially carbon emissions can be reduced by using wood as a construction material instead of steel and concrete. The research study does not investigate how the reduced GWP will affect the global issue of climate change. Werner, et al. (2005) as well as Fleming, Smith and Ramage (2014) believes that structural construction materials environmental impact on a global scale is most likely insignificant.

## 18.6 Life cycle assessment and environmental product declaration

The increased focus on sustainability among companies as Freidberg (2015) proposes, have resulted in more LCAs being produced. A possible effect of the results of LCAs is that the consumers put pressure on the manufacturers towards producing more sustainable products. The interest in sustainable products may lead to higher production costs and hence higher costs for purchasing the products. Whether the LCAs are being produced in the company's own interest regarding marketing and being regarded as a sustainable company or it is because the customers require it, it is beneficial for the industry. If a company can be transparent considering their environmental impacts related to products and manufacturing processes, it indicates that they have nothing to hide about their production processes.

Conducting an LCA can enlighten the company in terms of being aware of the *hotspots* from a products *cradle-to-grave* and possibly reducing them. A company that aims to optimize their production processes and achieve low emissions within every life cycle phase may get more sustainable values in the EPD and possibly a more attractive product for the industry. For the construction sector, the selection of construction material is important and often based on the presented results from performed LCAs in an EPD. Since, the data from EPDs are used as input values in sustainable building certifications LCA tools the information presented is relevant. LCAs and ultimately EPDs for construction material can be a deal breaker regarding material choice when choosing between different manufacturers. Consequently, low environmental impact values on EPDs can increase manufacturers' competitiveness and possibly increase their market shares.

LCAs should be based on the best information available and only measure what is important to measure, according to Freidberg (2015). Since, the best information available may differ for different products, the quality of LCAs also differ. Consequently, the available information for each product individually effects the overall quality of EPDs for construction material. It may be advantageous to have knowledge about and be experienced with LCAs to understand what is important to measure.

The LCA method is this characterized by uncertainty and relies on which information the assessor finds important to include. In fact, there are some guidelines available in for instance ISO standards about what to include and not. However, these guidelines are not by any means complete methods and therefore includes elements of interpretation, according to Freidberg (2015). This inconsistency in LCA calculations may result in unfair evaluations and companies losing market shares based on the way they assess their products. A consistent method with no room for own interpretation would be the ideal solution. The fact that no such method exists is proposed to be due to the various products that can be assessed and their individual properties. A product segment's specific method may be an alternative to reduce the inconsistency. Future issues regarding sustainable building certifications may arise when standardized methods for EPDs and LCAs are available, whilst the complexity of system boundaries within sustainable building certifications differ. As EPDs and LCAs are developed there should be a framework that prohibits any beneficial exclusion of the environmental performance of materials and buildings to assert a true depiction of the construction materials' or building's sustainable performance.

Life cycle phase *A4 Transport* is included in the LCA tool for the higher grades, silver and gold, in Miljöbyggnad 3.0. The transportation distance is estimated between factory-gate to construction site. When including transport in the LCA tool it can have a significant effect on the chosen construction material's environmental performance. However, if the transport's environmental impact is a high or low value is not assessed. The important aspect is to find information, which is the transportation distance required as well as the transportation mode and use it in the LCA tool. Regarding silver, generic environmental impact data is provided whereas for the grade gold specific data for the actual project must be used. DGNB on the other does not assess *A4 transport*. In the empirical part of the research study, it is clearly shown that *A4 Transport* have a great impact on the environmental performance for CLT.

As shown in the empirical part of the research study covering life cycle phase *A4 Transport,* CLT is heavily affected by the great transportation distance from Austria to Northern Europe. Mode of transport also contributes to the high GWP for life cycle phase *A4 Transport,* where road transport is the most usual mode of transport. Shifting from road to rail transport will reduce the GWP for CLT, however aspects such as supply flexibility and shipment precision could be worsened. As CLT uses a high ratio of prefabrication, off-site management and logistics increases in importance, which ultimately increases the risk of time-related factors regarding CLT and rail transport. As a new manufacturing facility of CLT will be built in Sweden during 2019, the overall GWP for life cycle phase *A4 Transport* will be reduced for CLT. The decreased GWP for CLT within the life cycle phase boundary A1-A4 will improve CLT's performance in Miljöbyggnad 3.0, even when applying for higher grades.

As the empirical part of the research study shows, there a several *hotspots* in the LCA. The *hotspots* differ depending on how CLT is assessed through an LCA and which life cycle phases that are included.  Certain life cycle phases contribute to environmental impacts more than others. For instance, life cycle phase *A4*

*Transport* may be considered a hotspot in Miljöbyggnad 3.0 when assessing CLT for life cycle phases A1-A4. Since, life cycle phase *A4 Transport* have a GWP value that is more than three times higher than A1-A3 for road transport. An unelaborate LCA could depict the worst or most beneficial life cycle stages for any construction material, thus resulting in an unfair representation of the environmental impacts for the construction material. The misrepresentation of construction material's *hotspots* could induce that more extensive LCAs would give a more just representation of the construction material in question.

By not including all life cycle phases in an LCA, there is a potential risk that *tradeoffs* are present in the product's life cycle and not visualized. Weber and Matthews (2008) stake the importance of adapting a critical mind-set when trying to identify different *hotspots,* since they usually enable *tradeoffs.* Plevin (2009) suggest the importance of identifying the *hotspots* and *tradeoffs* for new products in an early stage, to be able to take measures against it. The aim of attaining high grades in sustainable building certifications may be an incitement for manufacturers to make elaborate decisions regarding *tradeoffs*.

Hafner (2014) and Kutnar and Hill (2017) mentions the importance of sustainable forestry to prevent and avoid deforestation. Any type of negative impact on the environment, should be presented in the EPDs, thus resulting in a worse environmental impact value for the construction material. When designing an LCA tool it might not be necessary to include all life cycle phases that are present in standard EN 15804. To identify the worst life cycle phases regarding environmental impacts, general *hotspots* for different construction materials should be identified. However, there are potential *tradeoff*-risks related to only assess certain number of life cycle phases. As a result of *tradeoff*-actions, the distribution of environmental impacts for a product will ultimately result in a new set of *hotspots.* Consequently, an extensive LCA tool in terms of included life cycle phases is to prefer. The number of environmental impact categories should also be considered, since the same potential risk regarding continuation of *tradeoff*-actions exists.

## 18.7 Circular economy, waste and end of life

According to the empirical part of the research study, reusing construction materials especially CLT, limits the GWP the most. To promote the limitation of GWP, a circular model is beneficial to incorporate reusability for construction materials. As Nussholz and Milios (2017) implies, traditional linear models of resource consumption are unsustainable.  A circular model that support *a cradle-to-cradle* approach have the potential to increase environmental sustainability in the construction sector. Conscious, well-founded decisions regarding construction material choice is paramount to address anthropogenic climate change. Stahel (2008) recommend increased usage time for construction materials to decrease the annual average environmental impacts from buildings. A potential barrier for manufacturers to increase the lifespan of their construction products can be correlated to economic profits. Since, replacement of construction material generates income for manufacturers they may be resilient towards producing construction products of too high quality and long lifespans. However, to decrease the environmental impacts from the construction sector regarding construction material, a joint effort is required from manufacturers, developers and suppliers.

How to handle the arising question of whether carbon sequestration should be included or not in the choice of EOL scenario for CLT can be neglected to some extent. As the empirical part of the research study indicates the most beneficial EOL scenarios for the environment are as follows (from least harmful to most harmful) for both including and excluding carbon sequestration in all certification and EOL scenarios:

1. Reuse
2. Recycling
3. Incineration

The above hierarchy is in line with the EU Waste Directive 2008/98/EC Of the European Parliament and of the Council, 19.11.2008, excluding pre-emptive waste reduction as the best option. To further specify, the choice regarding inclusion or exclusion of carbon sequestration for CLT will have no impact on the EOL scenario performance comparisons within the construction material. Carbon sequestration will however play a major role when comparing the environmental performance of CLT to other construction materials.

Carbon sequestration in this research can be implemented in bio-based construction materials such as CLT. The possible inclusion of carbon sequestration will improve CLT's environmental performance and GWP compared to steel and concrete. There is no included carbon negative EOL scenarios for concrete or steel. Even without carbon sequestration, CLT is the structural construction material with the lowest GWP compared to steel and concrete.

As the Swedish Environmental Protection Agency (2018b) states, the most important aspect of reducing waste is the preemptive waste reduction. Before any other action of reducing waste is considered preemptive waste reduction should according to the waste hierarchy be prioritized. As Kralj and Markic (2008) highlights, preemptive waste reduction actions in the construction sector should be considered in the design phase. By choosing materials that easily can be dismantled, reusability increases. In addition, reusability provides the greatest environmental benefits, according to the empirical part of the research study. The challenge for LCA, rests upon the ability of quantifying certain aspects of dismantling and creating a standardized approach for the construction industry to adapt to.

The greatest challenge concerning LCA and its application in the construction sector is to standardize methods to enable just comparisons and evaluations between projects. Regarding economic incitements on reused or recycled construction materials, there must be a documented gain in LCAs for the viability of economic incitements on reused or recycled construction materials.

Once the circular aspect of using materials is adopted, it is crucial to further specify how to reuse materials properly. According to Roth (2005) *recirculation* is a term that implies a direct reuse of a certain material or product. However, any material's ability to be reused is highly dependent on material type and application within a certain building. An example of this is steel, which has a high material value and if properly handled has a high recycle value. It is important to include aspects such as *upgrading* and *cascading* when evaluating a construction material's ability to be reused. It is not environmentally sustainable to recycle a construction material if the energy needed to rework the used material to its original state is higher than producing the material anew.

# 18.8 Environmental building certifications

### Evaluation of construction material in Miljöbyggnad 3.0 and DGNB

It is considered a positive development for the construction sector that sustainable building certifications are increasingly focused on building materials. Operational energy is indeed important from a sustainable perspective, but the sustainable aspects of construction material has been neglected for a long time, according to Hafner (2014). The choice of construction material has a significant impact on the environment and the environmental impact differs between different construction materials, as shown in the empirical study. As a result, construction materials should be considered in sustainable building certifications.

Construction materials are evaluated in both Miljöbyggnad 3.0 and DGNB, in different ways. The most significant difference between the two assessments is the amount of data that is required to be provided in the LCA tools. DGNB has a by far more extensive LCA tool, which also include more life cycle phases, as seen in section 14.1. According to R1 SGBC, the reason for the LCA tool to be simple is that the users should get acquainted with doing LCA calculations. This is a valid argument since introducing a new method for the construction sector in a simple and instructional matter will potentially increase the understanding of the method. R1 SGBC suggests that SGBC can modify the LCA tool in later versions of the third generation of Miljöbyggnad. Gradual changes in the LCA tool towards a more complete assessment of the construction material from *cradle-to-grave* is a natural development. A complex and difficult LCA tool could result in fear of doing something wrong and not having the time or patience to understand it. A simple assessment on the other hand, could result in more users and therefore a greater understanding of sustainable construction materials and their environmental impacts.

R1 SGBC emphasize the beneficial aspects of using a simple LCA tool within the sustainable building certification. Miljöbyggnad 3.0 focuses on environmental sustainability and an LCA tool that have standardized methods for life cycle calculations. R1 SGBC suggests that there is no point of including excessive LCA phases, which may lead to confusion and varying calculation methods. R2 DK-GBC points out that any limitation of the system boundary for LCAs will exclude important environmental impacts and lead to a beneficial representation of the studied construction material’s environmental impact. A more extensive and thorough LCA tool and sustainable building certification will result in increased accuracy regarding the environmental performance of construction materials and buildings.

To address the varying complexity of sustainable building certifications, it is important to divide the subject into subcategories. Regarding stakeholder participation and the increased motivation of attaining sustainability within the construction sector. A simpler sustainable building certification will increase capacity building through a participatory approach. Over time, this may enable sustainable criteria to be implemented by a larger ratio of the construction sector effectively. The drawback will initially be a demarcation of material’s and building’s accuracy regarding their overall depicted environmental performance. As R3 C.F. Møller reaffirms, a more complex sustainable building certification will depict the environmental performance of the building or material with higher accuracy. However according to R3 C.F. Møller, a balance of complex and simple sustainable building certifications in construction sector is desirable. Since, using sustainable building certification is not mandatory, any type of initiative to increase the sustainability will initially have positive effects.

R1 SGBC mention a significant reason for not including all life cycle phases in standard EN 15804 in the LCA tool is that there are no consistent methods for calculating all life cycle phases. R1 SGBC considers it important that the information inserted in the LCA tool is accurate. If the users can base their calculations for environmental impacts on how they interpret a standard and in ways that is most beneficial for them, the results in the LCA tool has no credibility. Consistent methods for calculating the correct environmental impacts is important in regards of having a fair evaluation and grading system.

The varying complexity of the studied sustainable building certifications is potentially related to the different focus on target groups that will use the LCA tools. As R2 DK-GBC implies, any building project below 2 000 000 euro is not economically defensible for the building developer to certify with DGNB. This demarcation will limit the DGNB building certification user group to larger building developers and may exclude smaller building developers and their building projects. On the other hand, larger construction projects compared to smaller, will presumably have a greater environmental impact related to the size and magnitude of the project.

The distinction between Miljöbyggnad 3.0 and DGNB in the research study can to some extent be described as targeting different market segments. The varying complexity of LCA tools requires different experience and knowledge of sustainable building certifications. SGBC and DK-GBC have different strategies regarding complexity. While Miljöbyggnad 3.0 is intended to be easy to understand and user-friendly for many stakeholders in the construction sector, the DGNB LCA tool requires substantial knowledge of the tool before it is used. However, the DGNB LCA tool is not intended to be used without the assistance of DGNB auditors. There are certified DGNB auditors that are experts on the certification system and assists in the certification process, as mentioned in section 8.2. Consequently, there is a motivation for the DGNB LCA tool to be complex and extensive.

Miljöbyggnad bronze is a certification grade that is equivalent to follow the Swedish building regulations, according to Sweden Green Building Council (2018c). Any transcendence, from Miljöbyggnad grade bronze, will result in an improvement from the minimum required level regarding environmental and building performance and thus a potentially higher certification grade. DNGB on the other hand, has no explicit grade that directly represent the Danish building regulations. Any building project below a total production cost of 2 000 000 euro, have a small opportunity to afford sustainable building certification in Denmark. The lacking ability to incorporate smaller projects in sustainable building certifications can influence how sustainable the built environment is overall. There is an ongoing initiative that aims to involve the target group of projects below total costs of 2 000 000 euro and is called *Frivillig Bæredygtighedsklasse*. The initiative is anticipated to involve building developers that wants to build sustainable buildings, with better environmental performance than the standard requirements in the Danish building regulations. It is important to encourage and motivate all sustainable efforts among stakeholders in the built environment. *Frivillig Bæredygtighedsklasse* may serve as encouragement for all building and project developers. R3 C.F. Møller suggests that *Frivillig Bæredygtighedsklasse* may be able to include a larger adopter category, according to E.M. Rogers Diffusion of Innovation Theory, compared to DGNB.

**Grading in the LCA tool of sustainable building certifications**

For Miljöbyggnad 3.0, the purpose of the LCA tool is to increase the amount of available EPDs on the market, as stated by R1 SGBC. The difference between getting the lowest grade bronze or one of the higher grades silver and gold is the origin of the environmental data. For bronze, the environmental impacts are provided in the LCA tool as generic data and for the higher grades, they must originate from EPDs. The difference between obtaining one of the higher grades is the percentage amount of EPDs provided by the user. Consequently, it becomes the users concern to find EPDs if they aim for any of the higher grades. The environmental impact values are not evaluated further, regarding how harmful they are for the environment. Therefore, there is no reward in the LCA tool to choose construction material with low environmental impact. However, the users are rewarded with higher grades if they can find EPDs by themselves instead of using the generic values. The generic values may be average values for environmental impacts within each construction material category, according to R1 SGBC. The environmental impact values obtained from EPDs may therefore be lower than the generic values and consequently seemingly better for the environment.

R1 SGBC suggests that the focus on EPDs in the LCA tool will change in time when the construction material manufacturers consider it natural to produce and present EPDs for their products. Miljöbyggnad 3.0 includes environmental impact values for GWP for life cycle phases A1-A3 and weight of the construction material, as explained in section 14.3. If the combined total value for A1-A4 regarding GWP is reduced with ten percent, compared to silver the grade gold can be achieved in Miljöbyggnad 3.0. There are two possibilities for reducing the combined total value and that is choosing a different EPD with lower GWP values or reduce the amount, weight, of construction material. In addition, the transportation mode can be changed or altered to reduce the GWP. There is no specific requirement of documentation that can prove in what way the GWP value is reduced. The LCA tool can easily be manipulated in this manner and the lack of required documentation of the improvements can be considered a weakness in the LCA tool. According to R1 SGBC, the approach of not including any stringent requirements regarding documentation within the LCA tool, is mainly due to the ambition to make it accessible for the users. In time, the understanding of LCAs within the construction sector will increase and modifications of the LCA tool will be implemented. With more strict demands regarding environmental impacts, the LCA tool can be used as an instrument to restrict environmental impacts generated by buildings.

R3 C.F. Møller and R1 SGBC are in conjunction regarding the importance of incitements from important stakeholders such as municipalities, construction clients and banks for the increased use of sustainable building certifications. R3 C.F. Møller points out that construction clients and municipalities have an important part in formulating demands in construction contracts to assure certification with sustainable building certifications. R1 SGBC mentions the impact that banks can have on the level of environmental sustainability in the built environment. Economical incitements regarding beneficial loans to building developers with criteria regarding environmental sustainability and sustainable building certifications can be a driver for certifying buildings. As the progression and development of LCA tools and other aspects of sustainability increases, its implementation in sustainable building certifications may increase in stringency, which can lead to an assertion of sustainable factors that can be quantified and measured. According to Reichardt et al. (2012), another driver for sustainable building certifications is the demand of acquiring sustainable certified building as a part of companies CSR.

According to Park, Yoon and Kim (2017), sustainable building certifications in general may implement changes in the construction sector towards higher environmental standards. Enforcing strict building regulations will only elevate the minimum accepted standards within the building sector overall. The aim for acquiring a certain sustainable building certification grade may limit the creativity for choosing more sustainable options for certain criteria since the grade does not explicitly require it. The focus should be on making the most sustainable choices as possible, within the project boundaries, and not settle when the limit values within a certain criterion is satisfied. The aim should not be to attain a certain grade within sustainable building certifications, it should be to build as sustainable as possible.

## 18.9 Cross-laminated timber in an architectural perspective

The literature review in the research study highlights the extensive design work that needs to be performed before the project starts when using CLT as a structural construction material. Sutton, Black and Walker (2011) explicitly mentions the thorough design work and its effects on a CLT building project. As a positive effect, thorough design work may improve the overall design and performance of the building. However, the design work needs to be finished before the project starts, due to off-site manufacturing. CLT is in the research study depicted as a versatile construction material in an architectural aspect due to its ability to be used as both non-visual and as exposed finishes. The manufacturers of CLT has already adopted this phenomenon of the architectural versatility of CLT, thus manufacturing both construction grade CLT and appearance grade CLT, according to FPInnovations and Binational Softwood Lumber Council (2013). The versatility of CLT can be deducted from the different presented CLT projects, as shown in chapter 13. CLT can for instance be used for multi-story buildings, sustainable constructions, sustainable urban areas and provide a lightweight alternative regarding structural construction materials.

In accordance with Ballard Bell and Rand (2006), this approach to find construction materials which cover specific needs, is highly correlated with innovations and technology, developing and finding construction materials. Ballard Bell and Rand (2006) also highlight the misconception to consider design without material and thus assuring a pathway towards a non-successful building.

According to R1 SGBC architectural values are hard to measure and quantify, thus resulting in no explicit inclusion of architectural values in Miljöbyggnad 3.0. R1 SGBC distinguishes between aesthetical and functional architectural values, whereas aesthetical architectural values is not included. However, the functional architectural values such as availability, furnishability etcetera are regulated in the Swedish building regulations. R2 DK-GBC re-establishes the difficulty to define and measure architectural values, however some of the functional architectural values, such as indoor climate and availability are embedded in the DGNB system. In addition, architectural values are considered in criterion SOC 3.1 and DGNB Diamond, as seen in section 8.4 Architectural consideration in DGNB. Regarding differences between Sweden and Denmark, the delimitation of functional architectural values in Miljöbyggnad 3.0 compared to DGNB is observed. However, the application for any building project, using any of the two studied building certifications would ultimately, regardless of location (Sweden, Denmark), include some functional architectural values. Whether the functional architectural values are embedded in the building certification, alternatively the building regulations, this would still assure some architectural values for the building.

# Chapter 19 Conclusions

## 19.1 Research questions answered

*Research question 1: What are the differences in life cycle assessment evaluation of construction materials in Miljöbyggnad 3.0 and DGNB?*

The amount of data that is required to be provided in the life cycle assessment tool is by far more extensive in DGNB compared to Miljöbyggnad 3.0. The DGNB life cycle assessment tool is more complex whereas the tool from Miljöbyggnad 3.0 is more accessible. The number of included life cycle phases in the life cycle assessment tool for Miljöbyggnad 3.0 is fewer than in the DGNB tool. Life cycle production stage phases A1-A4 is included in the Miljöbyggnad 3.0 tool. Life cycle phases A1-A3, B2, B4, B6, C3, C4 and D is included in the DGNB tool. There is a different focus on target groups that will use the life cycle assessment tools. DGNB primarily focuses on DGNB auditors and experienced users while Miljöbyggnad 3.0 focus on a variety of potential users. The purpose of the Miljöbyggnad 3.0 life cycle assessment tool is primarily to increase the amount of available environmental product declarations on the market. DGNB on the other hand, aims to assess the construction materials completely and avoid any beneficial representation of a construction material by having an extensive tool. The number of included environmental impacts differ between Miljöbyggnad 3.0 and DGNB. Miljöbyggnad 3.0 only assess global warming potential. Whereas DGNB assess global warming potential, acidification potential, ozone depletion potential, eutrophication potential, photochemical ozone creation potential, abiotic depletion potential- elements and abiotic depletion potential- fossil fuels.

*Research question 2: What are the effects of evaluating a certain way in life cycle assessments regarding cross-laminated timber?*

The included life cycle phases in life cycle assessments will have an impact on the overall environmental performance of cross-laminated timber. The environmental impacts related to the end of life scenarios for CLT follows the waste hierarchy, where reuse is most beneficial for the environment and incineration the worst end of life scenario.

*Effects in the Miljöbyggnad 3.0 life cycle assessment tool*

Miljöbyggnad 3.0 grade bronze, only include life cycle phases A1-A3, which results in a GWP of 60 kg $CO_2$-eq. Comparing the different structural construction materials, CLT, steel and concrete in Miljöbyggnad 3.0 grade bronze, the obtained results will be as follows: for one tonne of CLT, 130 kg $CO_2$-eq for one tonne of steel the GWP is 1735 kg $CO_2$-eq and for two tonnes of concrete, the GWP is 315 kg $CO_2$-eq. In Miljöbyggnad 3.0 the life cycle phase *A4 Transport* is evaluated for certification grade silver and gold. Due to the current long transport distances for cross-laminated timber, life cycle phase *A4 Transport* gives a worse environmental impact for cross-laminated timber, compared to steel and concrete. Life cycle phase *A4 Transport* can be considered a *hotspot* in Miljöbyggnad 3.0. Since, life cycle phase *A4 Transport* have a GWP value that is more than three times higher than life cycle phases *A1-A3* combined, regarding road transport.

*Effects in the DGNB life cycle assessment tool*

The Danish version of DGNB, with different applied EOL scenarios for CLT display differences in environmental impact regarding structural construction materials. DGNB Reuse, result in the GWP for CLT being 3.2 kg $CO_2$-eq, which compared to DGNB recycling (51 kg $CO_2$-eq) and DGNB Incineration (338 kg $CO_2$-eq) is the best EOL scenario for CLT regarding GWP. The structural construction material comparison is highly dependable on chosen EOL scenario for CLT. If CLT is reused, steel is reused, recycled or recovered and concrete is reused in DGNB, the GWP for steel and concrete will compared to CLT be 114 and 43 times higher. If the EOL scenario is changed for CLT to recycling in DGNB, the GWP for steel and concrete will compared to CLT be seven and three times higher. If the EOL scenario is changed for CLT to incineration in DGNB, the GWP for steel and concrete will compared to CLT be 1.1 and 0.4 times higher. Resulting in concrete being a more environmentally sustainable material if CLT is incinerated. Regarding the other six environmental impacts that are assessed in DGNB, there are differences between EOL scenarios and the harmful effects linked to each environmental impact, caused by production of CLT. DGNB Reuse results in the most beneficial emissions linked to global warming potential (with and without carbon sequestration), acidification potential, eutrophication potential, photochemical ozone creation potential and abiotic depletion potential–elements. DGNB Incineration is by far the best EOL scenario regarding ozone depletion potential, whereas DGNB incineration results in negative emission and thus positive environmental effects.

*Research question 3: What are the environmental impacts of cross-laminated timber, taking account of carbon sequestration?*

The inclusion of carbon sequestration improves CLT's environmental performance and GWP compared to steel and concrete. There is no included carbon negative EOL scenarios for concrete or steel. Even without carbon sequestration, CLT is the structural construction material with the lowest GWP compared to steel and concrete.

*Miljöbyggnad 3.0*

If carbon sequestration is accounted for, the GWP for CLT is -671 kg $CO_2$-eq resulting in a positive environmental impact by including carbon sequestration. Comparing the different structural construction materials, CLT, steel and concrete in Miljöbyggnad 3.0 grade bronze. The obtained results will be as follows: for one tonne of CLT, the GWP is -1430 kg $CO_2$-eq with carbon sequestration for one tonne of steel the GWP is 1735 kg $CO_2$-eq and for two tonnes of concrete, the GWP is 315 kg $CO_2$-eq.

*DGNB*

*For the below stated conclusions, material usage for the structural construction materials are included.*

Regarding the other environmental impacts, EOL scenario reuse in DGNB for CLT results in the lowest values for acidification potential, eutrophication potential, photochemical ozone creation potential, abiotic depletion potential-elements and abiotic depletion potential–fossil fuels compared to reused, recovered or recycled steel and reused concrete. Resulting in CLT presenting lower values for five out of six studied environmental impacts compared to steel and concrete. EOL scenario recycling in DGNB for CLT results in the lowest values for acidification potential, photochemical ozone creation potential and abiotic depletion potential-elements compared to reuse, recovered or recycled steel and reused concrete. Resulting in CLT presenting lower values for three out of six studied environmental impacts compared to steel and concrete. EOL scenario incineration in DGNB for CLT results in the lowest values for ozone depletion potential and abiotic depletion potential– fossil fuels compared to reuse, recovered or recycled steel and reused concrete. Resulting in CLT presenting lower values for two out of six studied environmental impacts compared to steel and concrete.

*Research question 4: How can life cycle assessment tools be designed to better attend the environmental impacts from structural construction materials, in terms of included life cycle phases?*

When designing any life cycle assessment tool, the included life cycle phases will have a great effect on the portrayed sustainability for the researched construction material. The environmental impacts that at least should be included are the ones with the most harmful effects for the environment. The life cycle phases with most harmful effects may vary among different construction materials. Therefore, an inclusive life cycle assessment tool regarding included life cycle phases and environmental impacts is preferred to include *hotspots* and limit the risk regarding *tradeoff*-actions. To avoid uncertainties regarding how to conduct life cycle calculations, standardized calculation methods for all life cycle phases should be used.

# Chapter 20 Proposed future research

### Extended comparison of sustainable building certifications

Due to the limitation of the research study related to the number of sustainable building certifications as well as the number of indicators studied, there are more certifications and indicators that can be compared. It is suggested to additionally assess of the grading and weighting of different criteria within the sustainable building certification and what impact construction materials have. Construction material indicators in for instance LEED and BREEAM that are also used in Sweden and Denmark is an option.

### Increase the environmental impact data

Since, the research study is limited to study environmental impacts in rather few environmental product declarations it would be interesting to explore if the results would differ in any way by using other or average environmental impact data for CLT, steel and concrete.

### Limit values for environmental impacts

To decide which limit values that could be used in life cycle assessment tools is desirable for the next generation of life cycle assessment tools in sustainable building certifications. Limit values might be decided by comparable studies of environmental product declarations and possibly other product categories.

### Life cycle assessment design

To design an inclusive and accurate life cycle assessment tool for sustainable building certifications is proposed. Emphasis could be on which life cycles that must be included for a fair assessment and if limit values should exist. Furthermore, standardized methods should be defined for the included life cycle calculations.

### End of life scenarios

To further assess which end of life scenarios that are possible for CLT, steel and concrete is proposed. How the construction material is actually taken care of and how to guarantee that the chosen end of life scenario is realized in the future.

### Cross- laminated timber

Compare the potential of cross-laminated timber as a structural construction material as well as the current and future use of cross-laminated in Sweden and Denmark. Assess important areas such as fire safety, moisture safety, acoustic properties, load-bearing properties etcetera.

### Carbon sequestration

The avoided radiative forcing, which is enabled due to carbon sequestration needs to be quantified. If any research could indicate the effect of avoided radiative forcing and quantify its effect, implementations in sustainable building certifications would raise the environmental benefits of wood-products. Research regarding carbon pools of harvested wood products could potentially shed light on important features regarding sustainable forestry and reduce the carbon stocks of atmospheric carbon.

# References

Achenbach, H., Wenker, J. L. & Rüter, S. (2018). Life cycle assessment of product- and construction stage of prefabricated timber houses: a sector representative approach for Germany according to EN 15804, EN 15978 and EN 16485. *European Journal of Wood and Wood products*, 76(2), pp. 711-729.

Acton Ostry Architects and the University of British Columbia. (2016). Brock Commons Student Residence, Canada. https://www.dlubal.com/en-US/news-and-events/news/current-news/2016/2016-08-11-student-residence-brock-commons-canada. [2018-11-20]

Altenstedt, J. & Pleijel, K. (1998). *POCP for individual VOC under European conditions.* (B-1305). Göteborg: IVL Swedish Environmental Research Institute. https://www.ivl.se/download/18.343dc99d14e8bb0f58b7368/1445515409320/B1305.pdf

Alvehus, J. (2013). Skriva uppsats med kvalitativ metod: En handbok. Stockholm: Liber.

Ballard Bell, V. & Rand, P. (2006). *Materials for architectural design*. Laurence King Publishing Ltd, London

Bauformstahl. (2013). Bauformstahl e.V. Ökobaudat. *Environmental Product Declaration:Baustähle: Offene Walzprofile und Grobbleche, Baustahl. 4.1.03.* Düsseldorf, Germany. https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=890a8e3c-f0ad-4a7e-9d42-553a1d875bc9&stock=OBD_2017_I&lang=de.

Bhochhibhoya, S., Zanetti, M., Pierobon, F., Gatto, P., Maskey, R. K. & Cavalli, R. (2017). The Global Warming Potential of Building Materials: An Application of Life Cycle Analysis in Nepal. *Mountain Research and Development*, 37(1), pp. 47-55.

Big Red Dog. (2017). 5 Reasons Wood Would be Good for Your Next project. https://bigreddog.com/5-reasons-wood-would-be-good-for-your-next-project/. [2018-11-26]

Blengini, G. A. & Carlo, T. D. (2010). The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. *Energy and buildings*, 42 (6), pp. 869-880.

Boston University School of Public Health. (2018). Diffusion of Innovation Theory.http://sphweb.bumc.bu.edu/otlt/MPH-Modules/SB/BehavioralChangeTheories/BehavioralChangeTheories4.html [2018-11-06]

Boverket. (2014). Atemp. https://www.boverket.se/sv/byggande/bygg-och-renovera-energieffektivt/Atemp/ [2018-10-15]

Boverket. (2017). Byggande: Bygg- och fastighetssektorns uppkomna mängder av avfall. https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/miljoindikatorer---aktuell-status/avfall/. [2019-01-04]

Boverket. (2018). Klimatdeklaration av byggnader (Rapport 2018:1). Karlskrona: Boverket. https://www.boverket.se/globalassets/publikationer/dokument/2018/klimatdeklaration-av-byggnader.pdf

Brandão, M., Levasseur, A., Kirschbaum, M. U., Weidema, B. P., Cowie, A. L., Jorgensen, S. V., Hauschild, M.Z., Pennington, D.W. & Chomkhamsri, K. (2013). Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. *International Journal of Life Cycle Assessment*, 18(1), pp. 230-240.

Brandner, R. (2013). Production and Technology of Cross Laminated Timber (CLT): A state-of-the-art Report. Focus Solid Timber Solutions- *European Conference on Cross Laminated Timber (CLT).* Graz, Austria 21-22 May 2013. ResearchGate.

Broniatowski, D. A. & Tucker, C. (2017). Assessing causal claims about complex engineered systems with quantitative data: internal, external, and construct validity. *Systems Engineering*, 20 (6), pp. 483-496.

Building Research Establishment. (2013). Product Category Rules for Type III environmental product declaration of construction products to EN 15804:2012. http://www.bre.co.uk/filelibrary/Materials/BRE_EN_15804_PCR.PN514.pdf [2019-01-04]

Canadian Consulting Engineer. (2016). Quick time finish for Brock Commons at UBC. https://www.canadianconsultingengineer.com/engineering/quick-time-finish-brock-commons-ubc/1003403405/. [2018-11-20]

Canadian Wood Council. (2004). Energy and the environment in residential construction. Ottawa, Canada: Canadian Wood Council. http://cwc.ca/wp-content/uploads/publications-Energy-and-the-Environment.pdf [2019-01-09]

Cellura, M., Guarino, F., Longo, S. & Tumminia, G. (2018). Climate change and the building sector: Modelling and energy implications to an office building in southern Europe. *Energy for sustainable development,* 45, pp.46-65

Chen, P-C. & H-W. Ma. (2015). Using an industrial waste account to facilitate national level industrial symbioses by uncovering the waste exchange potential. *Journal of Industrial Ecology,* 19(6), pp. 950–962.

Cherubini, F., Bright, R.M., & Strømman, A. (2012). Site-specific global warming potentials of biogenic $CO_2$ for bioenergy: Contributions from carbon fluxes and albedo dynamics. *Environmental Research Letters,* 7.

Cole, R. J. & Jose Valdebenito, M. (2013). The importation of building environmental certification systems: international usages of BREEAM and LEED. *Building Research & Information,* 41(6), pp. 662–676.

Continuing Education Center. (2018). Building Materials Matter: Life-cycle view supports informed choices, contributes to sustainable design. https://continuingeducation.bnpmedia.com/courses/think-wood/building-materials-matter/1/. [2018-11-12]

Crawford, R.H. (2011). *Life Cycle Assessment in the Built Environment.* New York: Spon Press.

Darby, H.J., Elmualim, A.A. & Kelly, F. (2012). A case study to investigate the life cycle carbon emissions and carbon storage capacity of a cross laminated timber, multi-storey residential building. *Technologies for sustainable built environments Engineering Doctorate Conference 3rd July 2012,* Reading, UK.

Department for Environment, Food and Rural Affairs (DEFRA). (2011). Department for Environment Food and Rural Affairs. Guidance on applying the Waste Hierarchy. London, Crown

DePoy,E. & Gitlin,N.L. (1999).Forskning-en introduktion. Lund: Studentlitteratur.

DGNB System. (2018). Criteria set: New construction building. Version 1 English edition. Deutsche Gesellschaft für Nachhaltiges Bauen (German Sustainable Building Council), Stuttgart, Germany.

Diener, D. L. (2017). Scrap happens, but does it have to? On the potential of increasing machine component reuse. Göteborg: Chalmers University of Technology, 2017 (Doktorsavhandlingar vid Chalmers tekniska högskola. Ny serie: 4299). http://ludwig.lub.lu.se/login?url=http://search.ebscohost.com.ludwig.lub.lu.se/login.aspx?direct=true&db=cat01310a&AN=lovisa.005023973&site=eds-live&scope=site. [2019-01-11]

Di Maio, F., Hu, M., Lin, X. & Roekel, E.V. (2012). Fates of end-of-life concrete and their economic implications. Proceedings of the 27th international conference on solid waste technology and management. Philadelphia, Widener University School of Engineering, U.S.A. March 11-14, 2012.

Ding, G.K.C. (2008). Sustainable construction- The role of environmental assessment tools. *Journal of Environmental Management,* 86(3), pp. 451-464.

Directive 2008/98/EC Of the European Parliament and Of the Council,19.11.2008 on waste and repealing certain Directives. *Official journal of the European Union.*

Ellen MacArthur Foundation. (2015). Delivering the circular economy: A toolkit for policymakers. Isle of Wight,UK.https://www.ellenmacarthurfoundation.org/assets/downloads/publications/EllenMacArthurFoundation_PolicymakerToolkit.pdf [2018-12-03]

EPD-Norge. (2016a). Environmental Product Declaration: Kompaktvegg: Opplandske Betongindustri AS, NEPD-1232-382-NO. https://www.epd-norge.no/getfile.php/136953-1482230600/EPDer/Byggevarer/Betongvarer/NEPD-1232-382_Kompaktvegg.pdf.

EPD-Norge. (2016b). Environmental Product Declaration: Forsterket stålprofil AS, NEPD-00178N. https://www.epd-norge.no/bygningsplater/norgips-forsterket-stalprofil-article1284-318.html.

European Environment Agency. (2018). Industry. https://www.eea.europa.eu/soer-2015/europe/industry#tab-based-on-indicators [2018-10-15]

Finkbeiner, M. (2014). Product environmental footprint – breakthrough or breakdown for policy implementation of life cycle assessment? *The International Journal of Life Cycle Assessment,* 19, pp.266-271

Fleming, P., Smith, S. & Ramage, M. (2014). Measuring-up in timber: A critical perspecive on mid-and high-rise timber building design. *Architectural Research Quarterly,* 18 (1), pp. 20-30.

Forest Products Association of Canada. (2009). Tackle Climate Change, use Wood (Canadian edition). http://cwc.ca/wp-content/uploads/sustainability-Tackle-Climate-Change-Use-Wood.pdf [2018-11-08]

Forestry Innovation Investment. (2019). Naturally:wood. *Brock Commons Tallwood House.* https://www.naturallywood.com/resources/brock-commons-tallwood-house-0.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schultz, M. & Van Dorland, R. (2007). Changes in Atmospheric Constituents and in Radiative Forcing. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom: Cambridge University Press.

FPlnnovations & Binational Softwood Lumber Council. (2013). CLT Handbook: Cross-Laminated Timber. Pointe-Claire, Canada: FPInnovations

Freidberg, S. (2015). It's Complicated: Corporate Sustainability and the Uneasiness of Life Cycle Assessment. *Science as Culture*, 24 (2), pp.157-182.

Gomm, R., Hammersley, M. & Foster, P. (2000). Case Study Method. London: SAGE Publications Ltd

Green, M. C. & Karsh, J. E. (2012). The Case for Tall Wood Buildings- How Mass Timber Offers a Safe,Economical, and Environmentally Friendly Alternative for Tall Building Structures. http://cwc.ca/wp-content/uploads/publications-Tall-Wood.pdf [2019-01-09]

Green Building Council Denmark. (2017a). Guide til DGNB for bygninger – Certificering af

bæredygtigere bygninger.

Green Building Council Denmark. (2017b). DGNB Diamant. http://www.dk-gbc.dk/dgnb/certificering/dgnb-diamant/ [2018-12-20]

Green Building Council Denmark. (2018). Statistik over certificeringer. http://www.dk-gbc.dk/dgnb/certificering/statistik-over-certificeringer/ [2019-01-10]

Green Building Council Denmark. (2019a). DGNB i Danmark. http://www.dk-gbc.dk/dgnb/introduktion-til-dgnb/dgnb-i-danmark-historisk-rids/. [2019-01-11]

Green Building Council Denmark. (2019b). Helhedstankegangen i DGNB. http://www.dk-gbc.dk/dgnb/introduktion-til-dgnb/helhedstankegangen-i-dgnb/. [2019-01-11]

Green Building Council Denmark. (2019c). Hvad kan certifieres?. http://www.dk-gbc.dk/dgnb/certificering/hvad-kan-certificeres/. [2019-01-11]

Green Building Council Denmark. (2019d). Processen skridt for skridt. http://www.dk-gbc.dk/dgnb/certificering/processen-skridt-for-skridt/. [2019-01-11]

Green Building Council Denmark. (2019e). Sølv, guld og platin. http://www.dk-gbc.dk/dgnb/certificering/soelv-guld-og-platin/. [2019-01-11]

Hafner, A. (2014). Contribution of timber buildings on sustainability issues. *World Sustainable Building Conference*. Barcelona, Spain. 28-30 October 2014.

Institut Bauen und Umwelt. (2013a). Informations Zentrum Beton GmbH. Ökobaudat Environmnetal Product Declaration: Beton der Druckfestigkeitsklasse C 20/25. 1.4.01. Erkrath, Germany *https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=0c468e84-542a-46ff-9865-d3aad68b8a5e&stock=OBD_2017_I&lang=de*. [2019-01-11]

Institut Bauen und Umwelt. (2013b). Informations Zentrum Beton GmbH. Ökobaudat *Environmnetal Product Declaration: Beton der Druckfestigkeitsklasse C 25/30.* 1.4.01. Erkrath, Germany *https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=3a854482-aafc-4887-ae9e-14aa1b5e938d&stock=OBD_2017_I&lang=de*. [2019-01-11]

Institut Bauen und Umwelt. (2013c). Informations Zentrum Beton GmbH. Ökobaudat *Environmnetal Product Declaration: Beton der Druckfestigkeitsklasse C 30/37.* 1.4.01. Erkrath, Germany *https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=3c782eb3-0e19-4a71-96ee-ccf7bc13901d&stock=OBD_2017_I&lang=de*. [2019-01-11]

Institut Bauen und Umwelt. (2013d). Informations Zentrum Beton GmbH. Ökobaudat. *Environmnetal Product Declaration: Beton der Druckfestigkeitsklasse C 35/45.* 1.4.01. Erkrath, Germany *https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=dfd1979e-e3d5-44bb-aafd-b07bc4560257&stock=OBD_2017_I&lang=de*. [2019-01-11]

Institut Bauen und Umwelt. (2013e). Informations Zentrum Beton GmbH. Ökobaudat. *Environmnetal Product Declaration: Beton der Druckfestigkeitsklasse C 45/55.* 1.4.01. Erkrath, Germany *https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=a939e79d-0991-49d1-a06a-cee6887934a3&stock=OBD_2017_I&lang=de*. [2019-01-11]

Institut Bauen und Umwelt. (2013f). Informations Zentrum Beton GmbH. Ökobaudat. Environmnetal Product Declaration: Beton der Druckfestigkeitsklasse C 50/60. 1.4.01.Erkrath, Germany *https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=9* *fee07b9-a623-4e02-afc1-59637b0e1b7d&stock=OBD_2017_I&lang=de*. [2019-01-11]

International Energy Agency. (2018). Buildings. https://www.iea.org/buildings/

International Living Future Institute. (2016). Living Building Challenge V.3.1: A Visionary Path to a RegenerativeFuture.https://living-future.org/wp-content/uploads/2016/11/LivingBuilding-Challenge-3.1-Standard.pdf [2019-01-04].

International Organization for Standardization. (2006). Environmental management- Life cycle assessment- Requirements and guidelines, ISO 14044:2006(E). Switzerland: ISO.

Jauk, G. (2017a). Triumph of CLT continues. Massive increase of 14% to 700 000 $m^3$/yr. https://www.timber-online.net/holzprodukte/2017/11/siegeszug-von-bsp-setzt-sich-fort.html [2019-01-09]

Jauk, G. (2017b). Stora Enso to build CLT factory in Sweden Site with 100,000 $m^3$/yr will go into operation in 2019. https://www.timber-online.net/holzprodukte/2017/07/stora-enso-baut-bsp-werk-in-schweden.html. [2018-12-13]

Jonsson, P & Mattsson, S. (2016). Logistik: Läran om effektiva materialflöden. Kapitel 3, Materialflödet, 3. uppl. Lund: Studentlitteratur AB.

Kim, T.H. & Chae, C.U. (2016). Environmental Impact Analysis of Acidification and Eutrophication Due to Emissions from the Production of Concrete. *Sustainability,* 8(6).

Kralj, D. & Markic, M. (2008). Building Materials Reuse and Recycle. *WSEAS Transactions on Environment and Development,* 4(5), pp.409-418

Kungliga Tekniska Högskolan. (2014). Något om hur GWP-värden bestäms. Hämtat från https://www.kth.se/itm/inst/energiteknik/forskning/ett/projekt/koldmedier-med-lag-gwp/low-gwp-news/nagot-om-hur-gwp-varden-bestams-1.474589 [2019-01-09]

Kutnar, A. & Hill,C. (2017). Life Cycle Assessment – Opportunities for Forest Products Sector. *BioProducts Business,* 2(6), pp. 52-64.

Kvale, S. (1996). InterViews; An introduction to Qualitative Research Interviewing, Thousand Oaks: Sage

Lane, J.-E. (2018). Global warming: preventing irreversibility. *Brazilian Journal of Political Economy / Revista de Economia Política,* 38(4), pp. 740–748.

Lehtila, A. & Pingoud, K. (2002). Fossil carbon emissions associated with flows of wood products. *Mitigation and Adaption Strategies for Global Change,* 7(1), pp. 63-83

Levasseur, A., Lesage, P., Margni, M., Deschenes, L. & Samson, R. (2010). Considering Time in LCA: Dynamic LCA and Its Application to Global Warming Impact Assessments. *Environmental.Science & Technology,* 44 (8) pp. 3169-3174.

Life Cycle Association of New Zealand. (2010). Impact Category. Eutrophication Potential. http://www.lcanz.org.nz/sites/default/files/imce/eutrophication_lcanz.pdf. [2018-11-05]

Liu, Y., Guo, H., Sun, C., & Chang, W.S. (2016). Assessing Cross Laminated Timber (CLT) as an Alternative Material for Mid-Rise Residential Buildings in Cold Regions in China—A Life Cycle Assessment Approach. *Sustainability,* 8(10).

Monno, V. & Conte, E. (2015). Sustainability in the Built Environment: Integrating Scales of Action and Evaluation. *European Journal of Sustainable Development,* 4(2), pp. 51-60.

Mundaca, L., Ürge-Vorsatz, D. & Wilson, C. (2018). Demand-side approaches for limiting global warming to 1.5°C. *Energy efficiency,* pp. 1-20

National Aeronautics and Space Administration (NASA). (2019). What is Ozone? https://www.nasa.gov/pdf/752034main_Ozone_Hole_Poster.pdf. [2019-01-04]

Ness, D.A. & Xing, K. (2017). Toward a Resource-Efficient Built Environment: A Literature Review and Conceptual Model. *Journal of Industrial Ecology,* 21 (3), pp. 572-592.

Nussholz, J. & Milios, L. (2017). Applying circular economy principles to building materials: Front-running companies' business model innovation in the value chain for buildings. Paper presented at SustEcon Conference, Berlin, Germany.

Park, J., Yoon, J. & Kim, K-H. (2017). Critical Review of the Material Criteria of Building Sustainability Assessment Tools. Sustainability, 9(2), pp.186

Peñaloza, D., Erlandsson, M. & Falk, A. (2016). Exploring the climate impact effects of increased use of bio-based materials in buildings. *CONSTRUCTION AND BUILDING MATERIALS,* 125, pp. 219-226.

Pikon, K. (2012). Abiotic depletion in energy and waste management systems. *Energy policy journal.* 15(4).

Pivo, G. & J.D. Fischer. (2010). Income, Value and Returns in Socially Responsible Office Properties. *Journal of Real Estate Research*, 32(3), pp. 243-270.

Plevin, R. J. (2009) Modeling corn ethanol and climate, Journal of Industrial Ecology, 13(4), pp. 495-507

Region Skåne. (2017). Strategi för den hållbara gods- och logistik regionen Skåne www.skane.se/infrastruktur

Reichardt, A., Fuerst, F., Rottke, N.B & Zietz, J. (2012). Sustainable Building Certification and the Rent Premium: A Panel Data Approach. *Journal of Real Estate Research*, 34(1), pp. 99–126.

Reid Middleton. (2017). Timber Construction Using CLT. http://www.reidmiddleton.com/reidourblog/timber-construction-using-clt/. [2018-11-26]

Roth, L. (2005). Reuse of construction materials: environmental performance and assessment methodology. Linköping: Dept. of Mechanical Engineering. Univ., 2005 (Linköping : Unitr.) (Linköping studies in science and technology. Dissertation: 928)

Royal Society of Chemistry (2008). Construction: The concrete conundrum. Chemistry world. *http://www.rsc.org/images/Construction_tcm18-114530.pdf*. [2018-12-15]

Sakai, K. (2009). Recycling Concrete -The present state and future perspective. *The TCG (Technical Chamber of Greece) - JSCE Joint Seminar*. 20th November 2009. Athens, Greece.

Shepherd, D. (2016). Environmental product declarations – transparency reporting for sustainability. *2016 IEEE-IAS/PCA Cement Industry Technical Conference Cement Industry Technical Conference, 2016 IEEE-IAS/PCA.*:1-5 May, 2016.

Slättö & C.F. Møller. (2017). Kv. Najaden 1 - Markanvisning Råbylund.

Stahel,W. (2008).Global Climate Change in the Wider Context of Sustainability. The Geneva Papers on Risk and Insurance. Issues and Practice, 33(3), pp. 507–529.

Stauder, C. (2013). CROSS-LAMINATED TIMBER: An analysis of the Austrian industry and ideas for fostering its development in America. Salzburg: Austrian Marshall Plan Foundation.https://static1.squarespace.com/static/559921a3e4b02c1d7480f8f4/t/585c32fa6a4963601460c3f0/1482437399758/Stauder.pdf [2019-01-09]

Stora Enso. (2017). *Environmental Product Declaration: CLT by Stora Enso.* Stora Enso, Division Wood Products. Helsinki, Finland. https://www.storaenso.com/-/media/Documents/Download-center/Certificates/Wood-products-approvals-and-certificates/EPD---CLT-by-Stora-Enso-2017.ashx.

Sutton, A., Black, D. & Walker, P. (2011). CROSS-LAMINATED TIMBER: An introduction to low-impact building materials. Bracknell, United Kingdom: BRE

Svenning, C. (2003). Metodboken. 5th ed. Eslöv: Lorentz Förlag.

Sweden Green Building Council. (2017a). Miljöbyggnad 3.0 Metodik. https://www.sgbc.se/app/uploads/2018/07/Milj%C3%B6byggnad-3.0-Metodik-vers-170915.pdf [2018-10-15]

Sweden Green Building Council. (2017b). Miljöbyggnad 3.0 Bedömningskriterier för nyproduktion. https://www.sgbc.se/app/uploads/2018/07/Miljöbyggnad-3.0-Nyproduktion-vers-170915.pdf [2018-10-15]

Sweden Green Building Council. (2018a). Certifiera med Miljöbyggnad. https://www.sgbc.se/certifiering/miljobyggnad/certifiera-med-miljobyggnad/ [2018-10-15]

Sweden Green Building Council. (2018b). Certifieringsprocessen för Miljöbyggnad. https://www.sgbc.se/certifiering/miljobyggnad/certifieringsstod-for-miljobyggnad/certifieringsprocessen-for-miljobyggnad/ [2018-10-15]

Sweden Green Building Council. (2018c). Vad är miljöbyggnad? https://www.sgbc.se/certifiering/miljobyggnad/vad-ar-miljobyggnad/ [2018-10-15]

Sweden Green Building Council. (2019a). Certifieringar för den svenska marknaden. https://www.sgbc.se/certifiering/ [2019-01-10]

Sweden Green Building Council. (2019b). Vad är ett Green Building Council? https://www.sgbc.se/om-oss/vad-ar-ett-green-building-council/ [2019-01-10]

Sweden Green Building Council. (2019c). Manualer och verktyg för certifiering i Miljöbyggnad. https://www.sgbc.se/certifiering/miljobyggnad/certifieringsstod-for-miljobyggnad/manualer-och-verktyg-for-certifiering-i-miljobyggnad/ [2019-01-10]

Swedish Environmental Protection Agency. (2018a). Fördjupad analys av svensk klimatstatistik 2018 (Rapport 6848). Stockholm: Naturvårdsverket. https://www.naturvardsverket.se/Documents/publikationer6400/978-91-620-6848-6.pdf?pid=23767. [2018-12-05]

Swedish Environmental Protection Agency. (2018b). Lagar och regler om avfall. https://www.naturvardsverket.se/Stod-i-miljoarbetet/Vagledningar/Avfall/Lagar-och-regler-om-avfall/. [2018-12-05]

The Intergovernmental Panel on Climate Change (IPCC). (2013). Climate change 2013 The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel

The Intergovernmental Panel on Climate Change (IPCC). (2018). Mitigation pathways compatible with 1.5°C in the context of sustainable development. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. https://www.ipcc.ch/site/assets/uploads/sites/2/2018/11/SR15_Chapter2_Low_Res.pdf [2019-01-10]

Trost, J. (2005). Kvalitativa intervjuer. 3rd ed. Lund: Studentlitteratur.

Turk, S., Quintana, S. & Zhang, X. (2018). Life-cycle analysis as an indicator for impact assessment in sustainable building certification system: the case of Swedish building market. *Energy Procedia*, 153, pp. 414-419.

United Nations. (2019). Climate Change. http://www.un.org/en/sections/issues-depth/climate-change/. [2019-01-11]

United Nations. (2018b). Climate Change. http://www.un.org/en/sections/issues-depth/climate-change/. [2018-12-06]

United Nations. (1998). Kyoto protocol to the United Nations framework convention on climate change. https://unfccc.int/resource/docs/convkp/kpeng.pdf.

United Nations. (2009). United Nations Framework Convention on Climate Change. Report of the Conference of the Parties on its fifteenth session held in Copenhagen from 7 to 19 December 2009)

United Nations. (2015). Adoption of the Paris agreement. *In Conference of the Parties (COP), UN Framework Convention on Climate Change (FCCC),* Paris: France. 12 December, 2015.

United Nations. (2018a). Goal 13: Take urgent action to combat climate change and its impacts. https://www.un.org/sustainabledevelopment/climate-change-2/ [2018-11-08]

United Nations Environment Programme. (2013). Metal Recycling: Opportunities, Limits, Infrastructure, A Report of the Working Group on the

Global Metal Flows to the International Resource Panel. Reuter, M. A., Hudson, C., van Schaik, A., Heiskanen, K., Meskers, C., & Hagelüken, C.

United States Environmental Protection Agency (EPA). (2018). Greenhouse Gas Emissions. https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions [2018-12-06]

Vieira, D.R., Calmon, L.J. & Coelho, F.Z. (2016). Life cycle assessment (LCA) applied to the manufacturing of common and ecological concrete: A review. *Construction and Building Materials*. 124, pp 656-666

Watt Boolsen, M. (2007). Kvalitativa analyser. Malmö: Gleerups Utbildning.

Waugh Thistleton Architects. (2019a). Waugh Thistleton Architects. *Murray Grove: The original Timber Tower***.** http://waughthistleton.com/murray-grove/. [2019-01-11]

Waugh Thistleton Architects. (2019b). Waugh Thistleton Architects. Dalston Works: The World’s largest CLT Building. *http://waughthistleton.com/dalston-works/*. [2019-01-11]

Weber, C. L. & Matthews, H. S. (2008). Food-miles and the relative climate impacts of food choices in the United States, Environmental Science & Technology, 42(10), pp. 3508 – 3513.

Werner, F., Taverna, R., Hofer, P. & Richter, K. (2005). Carbon pool and substitution effects of an increased use of wood in buildings in Switzerland: first estimates. *ANNALS OF FOREST SCIENCE*, 62 (8), pp. 889-902.

World Green Building Council. (2019). About us. https://www.worldgbc.org/our-mission

Yu, A.T.W., Poon, C.S., Wong, A., Yip, R. & Jaillon, L. (2013). Impact of Construction Waste Disposal Charging Scheme on work practices at construction sites in Hong Kong, *Waste Management*, 33(1), pp.138-146

# Appendix 1: Interview questions for respondents at Sweden Green Building Council and Green Building Council Denmark

## Sustainable building certifications

1. What is the most important element in a sustainable building certification?
2. What is the main purpose of the existence of sustainable building certifications?
3. What is your opinion about the amount of available sustainable building certifications?
4. 4. In what way are the three aspects of sustainable development (economic, social and environmental) acknowledged in the sustainable building certification?
5. Do you make sure that architectural values are considered in the sustainable building certification?

## LCA tool in sustainable building certifications

6. What considerations were the most important when designing the LCA tool?
7. What are the pros and cons about the level of complexity in your LCA tool?
8. What is your opinion about having reference values, with different grades, for the environmental impacts in the LCA tool?
9. How was the procedure to decide which LCA phases that should be included in the material indicator and why did you decide as you did?
10. General comments about challenges in designing LCA tools.
11. How do you make sure the data from the EPDs is accurate?

## Construction material

12. What are the benefits for a client to choose your sustainable building certification, regarding material choice?
13. What are the benefits for the environment by choosing your sustainable building certification, regarding material choice?
14. CLT is a wood-based product that can be used as a constructional material. The used wood for CLT, sequestrates (stores) CO2 during the growth/regrowth of forests. How can and should carbon sequestration be incorporated in the LCA tool?
15. General comments about material choice in sustainable building certifications

# Appendix 2: Interview questions for respondent at C.F. Møller

## Sustainable building certifications

1. Which sustainable building certifications are you familiar with?
2. What influence does an architect in Denmark have, to use and make decisions concerning sustainable building certifications?
3. What is your opinion about the amount of available sustainable building certifications?
4. Have you ever had to modify your designs to fit a certain sustainable building certification?
5. Do you think the strive to achieve certain grades in sustainable building certifications could limit any aspect of sustainability for a building?

## Construction materials

6. What limitations and challenges surround the construction materials CLT, steel and concrete in an architectural perspective?
7. What impact does sustainable building certifications have on material choice for buildings?
8. Do you think effects like sequestration of $CO_2$ in wood-based products should be taken account of in green building certifications? If the answer is yes, in what way can sequestration be incorporated in an LCA tool?

## General question

9. Do you have any other opinions about sustainable building certifications, CLT and architectural values in general?