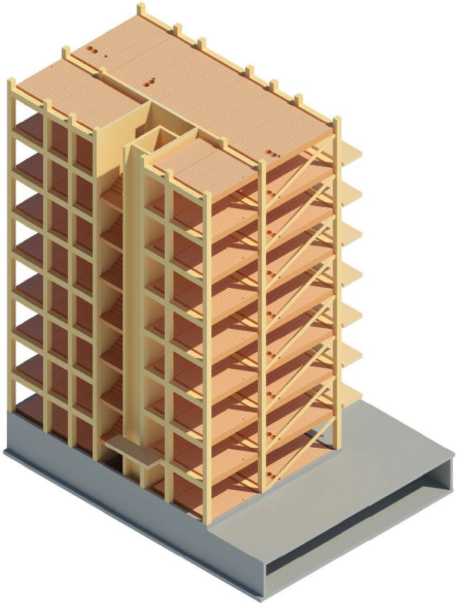
Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Marthe Ruttenborg

Life-cycle assessment of two building alternatives: wood and concrete building

Master's thesis in Industrial Ecology
Supervisor: Helge Brattebø
August 2020



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MASTER THESIS

for

Student Marthe Ruttenborg

Spring 2020

Life-cycle assessment of two building alternatives: wood and concrete building

Livsløpsvurdering av to byggalternativ: bygning i tre og i betong

Background and objective

Future climate change mitigation targets will require large energy savings and greenhouse gas (GHG) emission reductions in the building sector. One of the strategies as a response to these policies is the development of zero emission buildings (ZEB) and zero emission neighborhood (ZEN) concepts; for instance, by urban development where the interplay of activities and subsystems at the neighborhood level give close to zero emissions. In Norway, the ZEN Research Centre studies the energy and emission performance on building and neighbourhood scale, and investigates the combination of specific measures in the building/energy/mobility system as well as local solutions on the neighbourhood scale.

Concrete and wood are common building structural materials, and a better understanding on how they influence life-cycle assessment (LCA) results is needed in order to understand how materials can be used in the most environmentally friendly way. Two comparable residential building designs are chosen in order to compare the material embodied GHG emission performance. Sensitivity analysis is of particular interest in order to better understand (1) what are the decisive parameters for high/low contributions to greenhouse gas (GHG) emissions, and (2) what is the room of action in order to minimize material embodied GHG emissions. Contextual parameters will be included to improve the understanding of total emissions of the different construction materials and how different variables and assumptions affect the results. A systematic approach for including uncertainty for all inventory inputs will be conducted to investigate the variation and range in results, and where focus should be concentrated regarding reliable inventory inputs.

The overall objective of this thesis is to contribute to the understanding of the environmental impacts of wood and concrete as building materials, with an appropriate structure of inventory datasets and a modelling framework for the evaluation of the two buildings and related influence of material choice.

The work is linked to IndEcol’s participation in the FME-ZEN research center. Håvard Bergsdal, Senior Research Scientist at SINTEF Community will act as co-supervisor and provide links to an ongoing case study project in collaboration with Norcem and Moelven.

The following tasks are to be considered:

1. Carry out a literature study relevant to the topic of the thesis work.
2. Develop an outline and modular structure for the two buildings.
3. Develop an LCA model in Arda for the two buildings.
4. Run the LCA model and present results in order to document the embodied GHG emission performance of the buildings analyzed, under different sets of input assumptions.

5. Conduct a sensitivity and uncertainty analysis to find out (1) the decisive parameters and level of uncertainty regarding the building’s embodied GHG emission level, and (2) the room for action to cut GHG emissions.
6. Discuss strengths and weaknesses of your work, and suggestions for follow-up research.

Preface

The objective of this MSc project is to contribute to the understanding of the environmental impact of using different construction materials, wood and concrete. A life cycle assessment (LCA) model was used on two functionally identical case objects, where one is based on wood materials and the other is based on concrete materials. Uncertainty and sensitivity analysis was performed to further investigate the reliability of the results and the room for action for mitigating the environmental impact. Løvseth+Partner have performed the detailed design of both case objects where Moelven and Norcem are partners. The wood building is part of the research project Woodsol. The masters thesis work was linked to Indecol's and Sintef's participation in the FEM-ZEN Research Center and was carried out during the spring semester and summer of 2020 at the Norwegian University of Science and Technology.

To my supervisor Professor Helge Brattebø and co-supervisor Håvard Bergsdal, researcher at SINTEF Community, I would like to express my gratitude for valuable follow-up sessions and discussions during the masters thesis work period. They have both been providing excellent material and help, whenever that was needed. Håvard provided access to the inventory used in the project work and valuable discussions and information about the case objects. I would also like to thank family and friends for all the support and encouragement they have given me during this period.

Trondheim, Monday 24^{th} August, 2020

Marthe Ruttenborg

Marthe Ruttenborg

The picture on the front page is a detailed design sketch of the wood building made by Løvseth+Parner.

Abstract

The building sector is a considerable contributor to climate change being responsible for 39% of energy related CO_2 emissions and 36% of global final energy use in 2018 (Global Alliance for Buildings and Construction, International Energy Agency and the United Nations Environment Programme, 2019). Reducing the life cycle environmental impact of buildings today will have a long term effect because of the long lifetime of buildings (Sandberg et al., 2017).

Life cycle assessment (LCA) has become a well-established tool for calculating the emissions over the life time of a product or process, and have been an important tool for assessing the environmental footprint of buildings. The total impact is calculated based on all the life cycle stages, considering all emissions in all stages.

This work's objective is to assess and evaluate the environmental impact of wood and concrete when used as construction materials in two apartment buildings, which building elements have the largest contribution to climate change and the influence of material choice in such buildings.

Two different calculation methods have been used to investigate the environmental impact of the two buildings; a) LCA calculation using Arda and generic data from Ecoinvent v3.2 and b) impact calculation based on product and material specific environmental product declarations (EPDs).

For the wood building the total emissions calculated using the generic data was 48 % higher then the calculation using specific product EPDs even though the emission distribution between the materials in the building was similar for the two methods.The EPD method also resulted in the lowest emission result for the concrete building, but the difference between the methods is significantly reduced to 14 %. As for the wood building the emission distribution between the materials was similar both methods.

The emission distribution between the building parts is also similar for the two buildings. Slabs, internal walls, and stairs and balconies are the largest contributors in both buildings with both methods.

There are several uncertainties associated with the model used in this study. Parameters which have been assumed to have high uncertainties or are large contributors to the environmental impact have been included in a sensitivity analysis. The calculated results from this analysis have been discussed and further work within the field of LCAs on buildings and construction materials have been suggested.

Sammendrag

Byggesektoren er en betydelig bidragsyter til klimaforandringer ved at de er ansvarlige for 39 % av energirelaterte CO_2 utslippene og 36 % av det globale energiforbruket i 2018(Global Alliance for Buildings and Construction, International Energy Agency and the United Nations Environment Programme, 2019). En reduksjon i bygningers miljøpåvirkning gjennom livsløpet vil ha en langsiktig effekt på grunn av den lange levetiden til bygninger (Sandberg et al., 2017).

Livsløpsvurdering (LCA) har blitt et veletablert verktøy for å beregne utslippene over levetiden til et produkt eller en prosess, og har vært et viktig verktøy for å evaluere miljøavtrykket til bygninger. Den totale virkningen beregnes basert på alle livssyklusstadier, med tanke på alle utslipp i alle stadier.

Formålet med denne studien er å vurdere og evaluere miljøbelastningen av tre og betong når de brukes som byggematerialer i to leilighetsbygg, hvilke bygningselementer som har størst bidrag til klimaendringer og påvirkning av materialvalg i slike bygninger.

To forskjellige beregningsmetoder er brukt for å undersøke miljøpåvirkningen av de to bygningene; a) LCA-beregning ved bruk av Arda og generiske data fra Ecoinvent v3.2 og b) konsekvensberegning basert på produkt- og materialspesifikke miljødeklarasjoner (EPD).

For trebygningen var de totale utslippene beregnet ved å bruke generiske data 48 % høyere enn beregningen ved bruk av produkt spesifikke EPD-er, selv om utslippsfordelingen mellom materialene i bygningen var lik for de to metodene. EPD-metoden resulterte også i det laveste utslippsresultat for betongbygningen, men forskjellen mellom metodene er betydelig redusert til 14 %. I likhet med trebygningen, var utslippsfordelingen mellom materialene tilsvarende for begge metodene.

Utslippsfordelingen mellom bygningsdelene er også lik for de to bygningene. Gulv, innvendige vegger og trapper og balkonger er de største bidragsyterne i begge bygningene med begge metodene.

Det er flere usikkerheter knyttet til modellen som ble brukt i denne studien. Parametere som antas å ha høye usikkerheter eller som er store bidragsytere til miljøpåvirkningen, er inkludert i en sensitivitetsanalyse. De beregnede resultatene fra denne analysen har blitt diskutert og videre arbeid innen LCA-felt med bygninger og byggematerialer er foreslått.

Contents

1 Introduction

1.1 Background

The climate around the world are changing and this is mainly related to the anthropogenic emission of greenhouse gases (GHGs) to the atmosphere (FN-sambandet, 2018). Some observed changes are warming of the atmosphere and ocean, diminishing amounts of ice and snow, rise in sea level and a increase in the concentration of GHGs in the atmosphere (IPCC, 2013). According to IPCC (2014) the anthropogenic greenhouse gas emissions have increased by 10 $GtCO_2$ eq. in ten years from 2000 to 2010, and the increase are directly coming from buildings (3%), transport (11%), industry (30%) and energy supply (47%). Global mean temperature could exceed four degrees by the end of this century if the global GHG emissions continue to rise (IPCC, 2013).

To combat the increasing threat of climate change the Paris Agreement was made during the twenty-first annual United Nations conference on climate change in Paris 2015. The central aim of the Paris Agreement is to make ambitious efforts to keep the global temperature rise this century well below 2° Celsius above pre-industrial levels and to make further efforts to limit the temperature rise to 1,5° Celsius. Every country that signed the agreement made individual Nationally Determined Contribution (NDCs), which outlines every nations own climate change mitigation targets.(UNFCCC, 2018) Norway has committed to reducing the national emissions with at least 40% by 2030 compared to 1990. In 2017 the Norwegian parliament adopted a Climate Change Act which establishes by law Norway's emission reduction target for 2030 and 2050, under this law the Government have to submit annual information on progress and status on achieving the statutory climate targets(Norwegian Ministry of Climate and Environment, 2018).

Buildings are responsible for 28% energy related CO_2 emissions, 39% if the construction industry is included and 36% of global final energy use. The emissions from the building sector have risen to 9.7 $GtCO_2$ in 2018 which is a 7% increase from 2010, while the building construction emissions - related to manufacturing of building materials - amounts for a further 11 $GtCO_2$ (Global Alliance for Buildings and Construction, International Energy Agency and the United Nations Environment Programme, 2019). Mitigation options in the building sector are mainly related to switching from carbon intensive energy sources to renewables and reducing building energy use, by product- and system efficiency measures together with behaviour- and lifestyle changes.(IPCC, 2014)

However, all activities occurring during a buildings lifetime where materials and energy resources are being used, cause environmental impacts. This entails production of building materials, activities in the building process, energy use in use phase and maintenance activities over the lifetime, and finally the demolition and waste management (Fuglseth et al., 2018). The construction industry is responsible for 40–50% of the global output of greenhouse gases (GHGs) with the consumption of 40% of materials entering the global economy (Geng et al., 2017).

Buildings and building components have long lifetimes which necessitates the adaptation of state-of-the-art performance standards in order to avoid considerable lock-in risk associated with long lasting technology solutions both in new construction and when refurbishing old buildings. The environmental performance during the lifetime of buildings is a result of the choises made at the time when the building was built.(IPCC 2014; Sandberg et al. 2017)

In 2009, the Research centre on Zero Emission Buildings (ZEB) was founded in Norway. The research program had a vision of eliminating GHG emissions caused by buildings and their main goals was to develop knowledge, competitive products and solutions for new and existing buildings(Research center on Zero Emission Buildings, 2017). The research center produced publications and developed a ZEB-definition during the project from 2009 to 2017. Several projects around Norway are now using the ZEB concept.

The Research centre on Zero Emission Neighbourhoods (ZEN) was founded in 2017 developing further on the work conducted in the ZEB project and expanding the goal to include whole neighbourhoods to contribute to a low carbon society. Currently the research centre has eight running pilot projects around Norway.(Research centre on Zero Emission Neighbourhoods, 2017)

The urgency of utilizing state-of-the-art performance standard in the building industry has been addressed by the European Parliament with the Energy Performance of Buildings Directive (EPBD). Their vision is to decarbonice the building stock by 2050 and that all new buildings within the European Union shall be nearly Zero Energy Buildings (nZEB) by the end of 2020.(European Commmision, 2010)

1.2 Problem definition

The objective of this assignment is to contribute to the understanding of the environmental impacts of using different main construction materials, wood and concrete. An LCA is conducted with focus on climate change impacts, in particular Global Warming Potential (GWP100). To do this a systematic approach regarding elements and life cycle phases to include is suggested. Then an LCA is performed based on two case objects within the ongoing FME-ZEN research project. Both case object will be compared to comparable studies and the distribution of emissions between the materials in the buildings will be compared. A comparison of the total emissions between the two buildings will not be done.

The following research questions are to be answered:

1. Which elements in the case buildings are the most important contributors to climate change?
2. What are the impact of changing the material choices?
3. What are the associated uncertainties to the LCA results?

1.3 Structure

In Chapter 2 a literature study on relevant research performed relevant to this assignment is presented. Chapter 3 describes and defines the LCA method used in this research, the case objects and includes the associated sensitivity analysis. Chapter 4 presents the results from the conducted LCA simulations and sensitivity analysis, followed by a discussion in chapter 5. In Chapter 6 the results are concluded, and further work is suggested.

2 Litterateur Study

This part looks into the different available literature regarding LCA on building level in Chapter 2.1 and uncertainty analysis in LCA studies in Chapter 2.2. Four different LCAs that compare wood and concrete buildings is reviewed in Chapter 2.1.2.

2.1 LCA of buildings

The building sector has used life cycle assessment methods since 1990 (Buyle, Braet and Audenaert 2013; Ortiz, Castells and Sonnemann 2009; Rønning et al. 2019) and the number of published articles on building LCA have been growing rapidly for the last two decades which is likely to reflect that LCA have been accepted as a approach to analyze the environmental performance of buildings (Geng et al., 2017).

Geng et al. (2017) conducted a review of literature related to building LCA that were publisher from 2000 to 2014 and found that the Norwegian University of Science and Technology was the leading university in terms of this research. The aim of the study was to discover the characteristics of global building LCA literature from 2000 to 2014 and found that, accounting for the largest shares of the 2025 publications found, 521 of the journal articles were associated with energy while 388 was associated with materials.

Operation and building material manufacturing stages have been found to be responsible for a large portion of the environmental impacts. (Geng et al., 2017)
Energy related emissions are responsible for environmental impacts globally and have a great impact on buildings as its part of all building life cycle stages, from manufacturing of materials and their transport, operation and end-of-life treatment (Geng et al., 2017).

LCA studies performed on buildings have shown that emissions from the use phase is the predominant contributor to the total environmental impact of a building. However, regulations, technological developments and energy efficiency measures have reduced the operational energy use of buildings shifting more of the total impact over to the product phase of the buildings life cycle (Buyle, Braet and Audenaert 2013; Malmqvist et al. 2018b). Reducing embodied energy in materials have become more important in able to minimize the buildings environmental impact.

Wooden buildings have been constructed for centuries, but the use of wood as a structural material in larger multi-story buildings have not been a common practice for a long time (Robertson, Lam and Cole 2012; Østnor, Faanes and Lædre 2018). Using wood as the main structural material require more resources during design phase of the building, but can reduce time and create a cleaner working environment during construction. Using laminated timber as a structural material require new construction guidelines regarding fire and acoustic regulations (Østnor, Faanes and Lædre, 2018).

2.1.1 Importance of the Functional Unit

A functional unit (FU) is a reference unit that quantifies the performance of a product system in a life cycle study and are used for facilitating comparisons between different studies or design alternatives (Chau, Leung and Ng, 2015).

Chau, Leung and Ng (2015) conducted a study where it explored different functional units used for building systems and materials and found eight different typically used units and another five units used as functional unit for a whole building.

Norman, MacLean and Kennedy (2006) and Lausselet et al. (2019) found that changing the functional unit to be crucial and to potentially lead to different conclusions for the study when comparing scenarios.

2.1.2 LCA studies comparing wood and concrete structures

A study performed by Skullestad, Bohne and Lohne (2016a) used LCA methodology to compare the climate change impact of reinforced concrete structures to corresponding timber structures in a Nordic market for building heights of 3, 7, 12 and 21 storeys. The goal of the study was to investigate the potential for reducing greenhouse gas emissions from the construction industry by building multistory buildings and high-rise buildings using wood. The reinforced concrete structures are used as benchmark structures for the timber structures, which are modeled to the same load conditions. This study used three different calculation approaches, but found that the timber structures cause lower climate change impact than the reinforced concrete structures for all structures, in all approaches and scenarios. The functional unit of the study was kg CO_2-eq per building, with system boundaries to be the product stage (A1–A3). The environmental impact of the 7 storey building was 174522 – 220415 kg CO_2-eq between the best and the worst scenario for the wooden building, and 471487 – 1010788 kg CO_2-eq for the concrete building. Three different calculation methods was used in the study and the results mentioned are from method 1 which follows standards used for EPDs.

Hofmeister et al. (2015) conducted a study on material emissions from a concept building built with traditional building material solutions of steel and concrete with no innovative design solution or material choices to reduce emissions, and compared it with emissions from an alternative wooden load bearing structure. The concept building was based on a theoretical office concept study by Dokka et al. (2013). The wooden structure is dimensioned to the same load, fire and sound conditions as the concrete and steel structure. Modules included in the study are the product phase (A1–A3), end-of-life stages (C3–C4) and recycling and energy recovery (D). The results in this study also show that the wooden structure have the lowest GHG emissions for all approaches and scenarios. The functional unit of the study is 1 m^2 of total 1980 m^2 heated floor area (BRA) over the estimated service life time of 60 years (kg CO_2-eq/m^2/year). The results for the wood building was 1,8–2,1 kg CO_2-eq/m^2/year, while the impact from concrete and steel structure is calculated to be 3,2–3,5 kg CO_2-eq/m^2/year.

A study conducted by Malmqvist et al. (2018a) performed an LCA on five different structural solutions, all based on the same architectural drawings and meeting the same basic requirements. The study looked at three different concrete solutions, 1) cast-in-place concrete slabs, and external and internal walls, 2) cast-in-place concrete slabs, load-bearing internal walls and external lightweight compartment walls with steel and wood joists and supporting steel pillars integrated in the facade, and 3) prefabricated concrete hollow core slabs with Granab flooring system to meet the sound requirements. Other then the concrete solutions the study looked at two different wood solutions, a) prefabricated volume elements in wood b) external walls and slabs in solid glued laminated timber elements with Granab flooring system to meet the sound requirements. Figure 1 show illustrations of all five structural solutions. The study included the product stage (A1–A3), construction process stage (A4–A5), use stages including maintenance, repair, replacement and energy consumption in operation (B1–B4 and B6), and end-of-life stages (C1–C4). The structures were designed to have the same operational energy use of 41 kWh/m^2 $\cdot$ A$_{temp}$, the areas of the building heated to a temperature above 10 °C, so the operational energy use over the lifetime of the buildings was the same for all structures. Generally, the results show that the wood solutions have an overall better emission performance then the concrete solutions, where the product stage is the crucial factor. The product stage (A1–A3) results for the concrete solutions are 279, 234 and 218 kg CO_2-eq/m^2 $\cdot$ A$_{temp}$, and the wood solutions have impacts of 176 and 167 kg CO_2-eq/m^2 $\cdot$ A$_{temp}$.

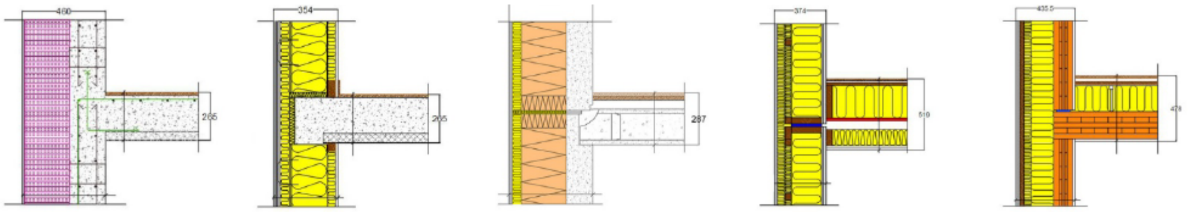


Figure 1: Illustration of the the five structural solutions investigated by Malmqvist et al. (2018a)

Rønning et al. (2019) conducted an LCA study of two comparable office building structures, for buildings with 4, 8 and 16 floors, built with the two construction materials wood and concrete. The study was performed on behalf of Betongelementforeningen, a contractor association for concrete element manufacturers and assembly contractors, in 2019. Both structures was dimensioned to meet the same fire, acoustic and load conditions by an independent company and analysed using EPDs as background data for the material inputs.

Concrete manufacturers were directly involved in the study, first by giving their specific EPDs to meet the products specified by the independent company, then by optimizing their products to minimize the associated greenhouse gas emissions. No wood product company was directly involved other then using their public EPDs for the background data.(Rønning et al., 2019)

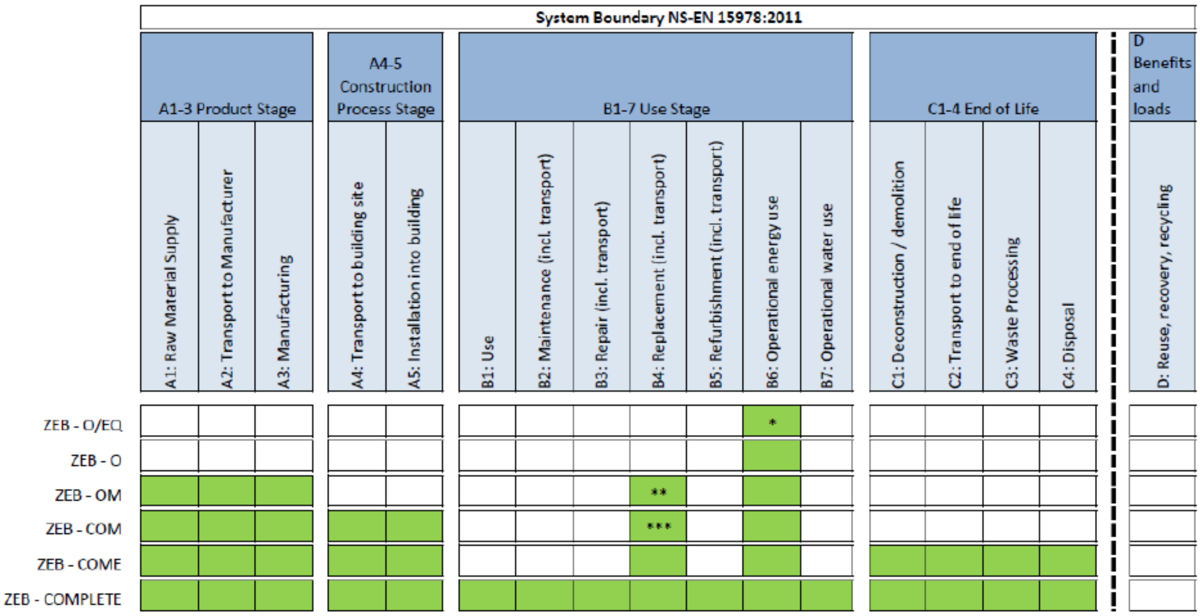
Three different scenarios for the concrete solution was created - typical concrete structure, environmentally optimized and best concrete products - while only one scenario was made for the wooden solution. A number of EPDs for the products glued laminated timber and cross laminated timber from different wood product producers were investigated and the producer with the lowest emissions from the product stage was used as background data for the wooden solution.(Rønning et al., 2019)

The total emissions from the concrete building with 8 floors are between 65 and 85 kg CO2-eq/m2 and about 70 kg CO2-eq/m2 for the wood building. A comparison between all the scenarios and solutions show that the wood structure have the lowest emissions for the building with 4 floors, while the best concrete products solution have the lowest emissions for the building with 16 floors. The difference between the best concrete products and wood solution is minimal for the 8 floors high building.(Rønning et al., 2019)

2.1.3 Zero Emission Buildings and Neighbourhoods

From 2009 to 2017 a national research center, Zero Emission Buildings (ZEB), conducted research on buildings with the goal of eliminate the greenhouse gas emissions caused by buildings. This research lead to a Norwegian definition of ZEBs and associated calculation methodologies (Research center on Zero Emission Buildings, 2017). Fufa et al. (2016) define a ZEB based on different ambition levels, where the associated greenhouse gas equivalent emissions during the lifetime of a building is balanced with the emission reduction associated with onsite energy production instead of grid power.

The different ambition levels dictate which building life cycle stages that must be included to reach the different levels. Figure 2 show the different ZEB ambition levels and which life cycle stages that are included according to the standard NS-EN 15978.



System Boundary NS-EN 15978:2011

	A1-3 Product Stage			A4-5 Construction Process Stage		B1-7 Use Stage							C1-4 End of Life				D Benefits and loads
	A1: Raw Material Supply	A2: Transport to Manufacturer	A3: Manufacturing	A4: Transport to building site	A5: Installation into building	B1: Use	B2: Maintenance (incl. transport)	B3: Repair (incl. transport)	B4: Replacement (incl. transport)	B5: Refurbishment (incl. transport)	B6: Operational energy use	B7: Operational water use	C1: Deconstruction / demolition	C2: Transport to end of life	C3: Waste Processing	C4: Disposal	D: Reuse, recovery, recycling
ZEB - O/EQ											🟩 *						
ZEB - O											🟩						
ZEB - OM	🟩	🟩	🟩						🟩 **		🟩						
ZEB - COM	🟩	🟩	🟩	🟩	🟩				🟩 ***		🟩						
ZEB - COME	🟩	🟩	🟩	🟩	🟩				🟩		🟩		🟩	🟩	🟩	🟩	
ZEB - COMPLETE	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	

* Does not include operational energy of electrical equipment

** Does not include transport to building site (A4), installation into building (A5) or end of life treatment of the replaced materials

*** Does not include end of life treatment of the replaced materials

NB: Biogenic carbon should only be included at a ZEB-COME or ZEB-COMPLETE level

Figure 2: Rendering of the ZEB ambition levels according to the standard NS-EN 15978:2011 (Fufa et al., 2016)

The M in the ambition levels stand for the emissions from building construction materials and components. Fixed inventory, sanitary installations, telecommunication and automation as well as any outdoor installations are not included in the material stage for the three ambition levels ZEB-OM, ZEB-COM and ZEB-COME.(Fufa et al., 2016)

A Zero Emission Neighbourhood (ZEN) research center was established in 2017 and continued the research from ZEB, widening the system boundaries to include whole neighbourhoods with the goal of developing solutions for future buildings and neighbourhoods with no greenhouse gas emissions and thereby contribute to a low carbon society (Research centre on Zero Emission Neighbourhoods, 2017).

Buildings have a large environmental impact during its lifetime from the production of materials used to the waste treatment at the buildings end-of-life stage. Kristjansdottir et al. (2018) did a comparative emission analysis of low-energy and zero-emission buildings and found that the embodied emissions accounted for about 60 – 70% of the total embodied and delivered energy emissions.

Kristjansdottir et al. (2018) conducted a study to see if a pilot residential ZEB could reach the goal of balancing the life cycle emissions of the building with onsite renewable energy production, where the energy production accounted for negative emissions as it replaced grid power. The study found that embodied emissions in materials greatly impacted the balance and that the pilot was not able to reach a balance of zero emission over its life cycle.

2.2 Uncertainty Analysis in LCA studies

In LCA, there is three types of uncertainty; parameter, scenario and model. Parameter uncertainty is the most frequently used method for quantifying uncertainty in published journal articles within the LCA field (Baek, Tahara and Park 2018; Bamber et al. 2020).

OpenLCA is a LCA software with uncertainty analysis capability using Monte Carlo (MC) Simulation where uncertainties in relation to data variability, data quality and characterization factors can be included in the analysis(Bamber et al., 2020). Another software with uncertainty analysis capability is Simapro, which use pedigree matrix approach and MC to quantify parameter uncertainty(Simapro Help Center, 2020). The Pedigree matrix approach are used to quantify parameter uncertainties in the Ecoinvent database(Ciroth et al., 2016).

Bamber et al. (2020) found that the importance of quantifying and communicating uncertainties associated with the result of scientific studies are generally recognised, but that reporting of uncertainties are not yet a common practice within the LCA community. More then 2600 published journal articles from 2014 to 2018 was reviewed and less then 20% reported any kind of uncertainties. There was also no evidence of any increase of reporting uncertainties over time.

Wiik et al. (2018) have found that changing the LCA inventory from generic data, from such sources as the Ecoinvent database, to EPDs can lead to a 20% reduction of environmental impact for the modelled system. EPDs was developed as a tool to stimulate the demand for greener products and materials through easy access, understandable format, and credible information that they provide (Borghi 2013).

3 Methodology

This chapter describes the methods used to perform the uncertainty and sensitivity analysis's. For this study the uncertainty analysis is performed using the Pedigree matrix approach and Monte Carlo simulation.

The objective of this paper is to investigate the environmental impact of two buildings built with different main building materials – concrete and wood. Two emission calculations is performed using a) EPDs and b) generic data from Ecoinvent. Parameter uncertainty is calculated based on the emission calculation with EPDs while sensitivity analysis is conducted on both emission calculations to investigate how it can affect the overall environmental impact of the buildings.

Not all types of uncertainty are included. Since not all types of uncertainty are included, the results can not be assumed to be correct for the overall system, but are considered good enough to answer the research questions of the paper.

The uncertainty calculation is conducted using the Pedigree Matrix approach together with Monte Carlo Simulation in Excel. The Pedigree Matrix approach assigns uncertainty to all parameters as a log transformed variance while the Monte Carlo simulation utilize this variance to simulate the uncertainty distribution of the parameters and the overall systems uncertainty. Both methods are explained further in Chapter 3.7.

3.1 Life Cycle Assessment (LCA)

LCA is a method used to address the potential environmental impacts of a service or product throughout it's life cycle. The assessment can include all life phases from raw material extraction and material processing, manufacturing, distribution, use, maintenance and repairs, to end-of-life treatment, recycling and final disposal. Which phases that are included depends on the aim and intended use of the LCA. Often, LCA is used to find improvement opportunities in the life cycle, asses design solutions and marketing. The International Standard ISO 14040:2006 (Standard Norge, 2006a) describes the principles and framework of LCA including the four different steps of an LCA, illustrated in Figure 3. A short description of the different steps are given under the figure.

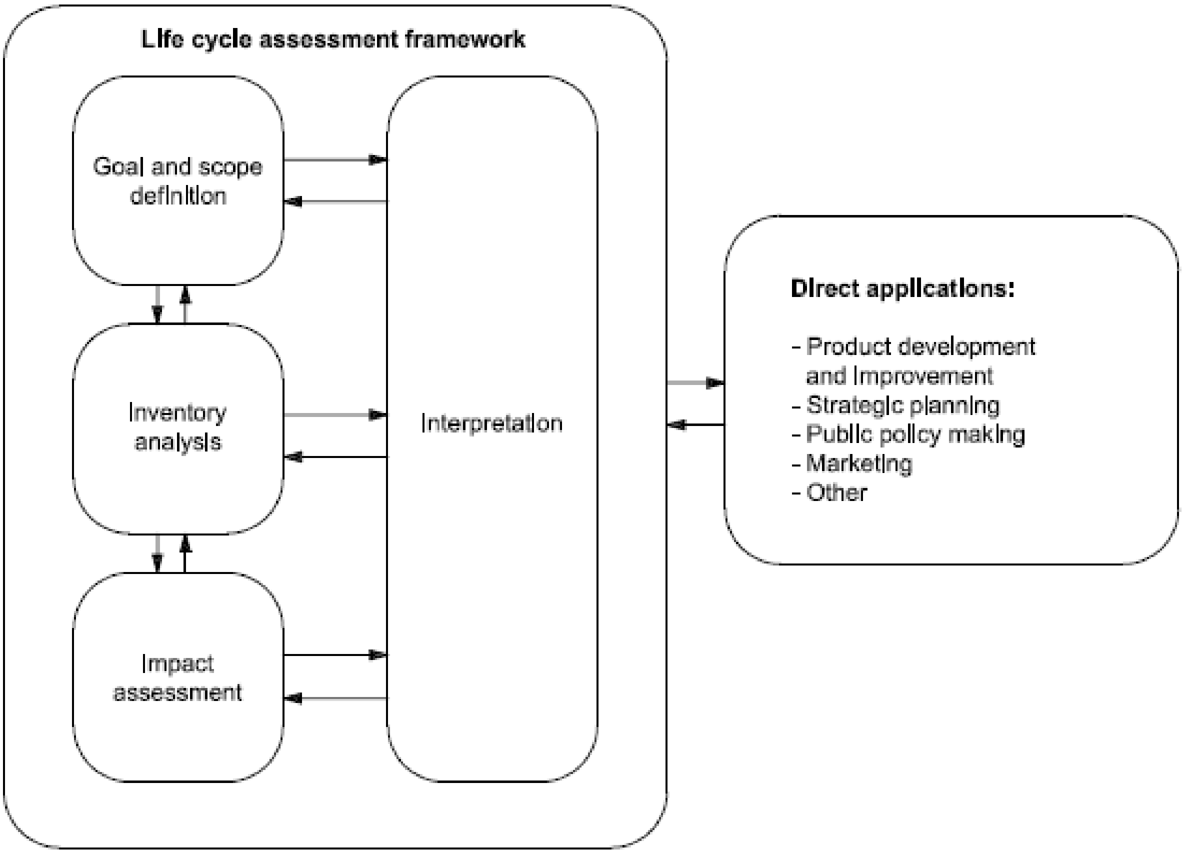


Figure 3: Stages of an LCA(Standard Norge, 2006a).

Goal and Scope Definition

The first step of an LCA is the goal and scope definition. In this step the goal of the study is defined, which entails describing the objective, audience, and actors, while the scope definition details the methodological choice's of the study and assumptions. Detailing, depth and breadth of the study should be sufficiently well defined in the scope definition to ensure compatibility and so that it is sufficient to address the stated goal.

The aim and intended use of the LCA greatly influence the depth of the study, such as which life cycle phases are included and the resolution, which is why it is important to state this early in the process. As Figure 3 illustrates, LCA is a iterative process, and various aspects of the scope definition may require modification to meet the original goal of the study as further research is conducted and increasing amounts of data and information is collected.

Life Cycle Inventory (LCI) Analysis

The second step of an LCA is the inventory (LCI) analysis. The goal here is to quantify relevant material and energy inputs and outputs of a product system to meet the goals of the study, which require data collection and calculation procedures. Required data can be collected from different sources depending on what kind of data is needed.

Life Cycle Impact Assessment (LCIA)

This stage classify and characterise the stressors into respective impact categories and impact units. Stressors is a more general therm then emissions and includes emissions, waste products, land use and resource extraction. After the stressors are classified, thy are aggregated using characterization factors and compared to form a single category indicator. The different environmental impact categories is climate change, ozone depletion, ecotoxicity, human toxicity, photochemical ozone formation a, acidification, eutrophication, resource depletion and land use. Climate change are widely assumed using global warming potential (GWP) expressed in therms of kg carbon dioxide equivalents (CO_2-eq).

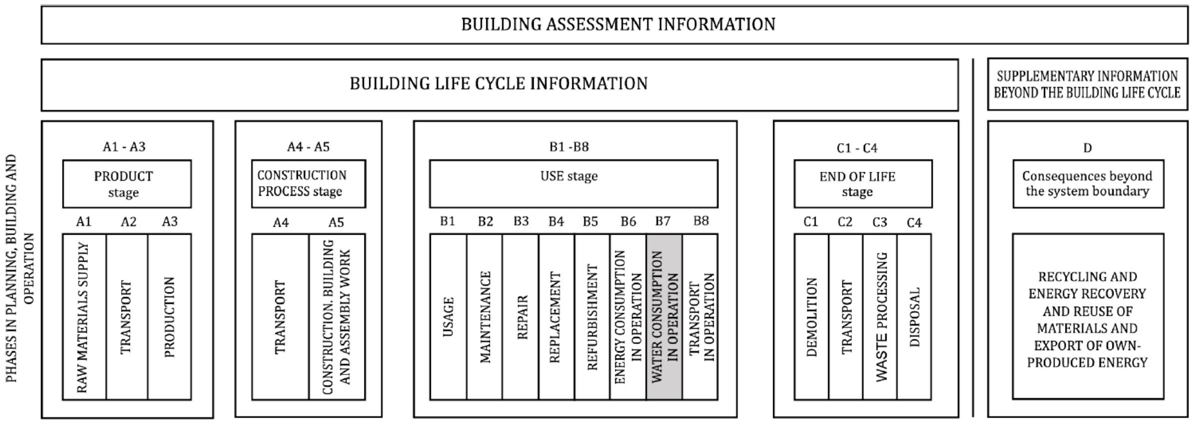
Interpretation

Finally the life cycle interpretation of results. The significant contributions from emissions and processes are identified and presented in accordance with the goal and scope of the study. Sensitivity analysis is performed to establish confidence in the results by seeing how the conclusions change with respect to any model assumptions. At the end, uncertainties in the study is analysed to strengthen the results.

3.2 NS 3720 - Method for Greenhouse Gas Calculation in Buildings

In 2018 a new Norwegian standard for GHG calculation in buildings was published. The standard describes a calculation methodology for GHG emissions connected to the lifetime of a building or building part with the purpose of making the results comparable across different tools and models (Standard Norge, 2018a). Figure 4 show the different stages and modules the building assessment is divided into.

Classification and coding of building elements that are to be included in the GHG calculations have to be in accordance with the subdivision in (Standard Norge; Standard Norge, 2018a; 2019a). Figure 5 show a cut out of the table of building elements for a building on a 2-digit level which is the minimum required resolution for conducting an LCA on of a building (Standard Norge, 2019a). Appendix A show the table of building elements with a resolution down to a 3-digit level that is not required but should be used if possible.

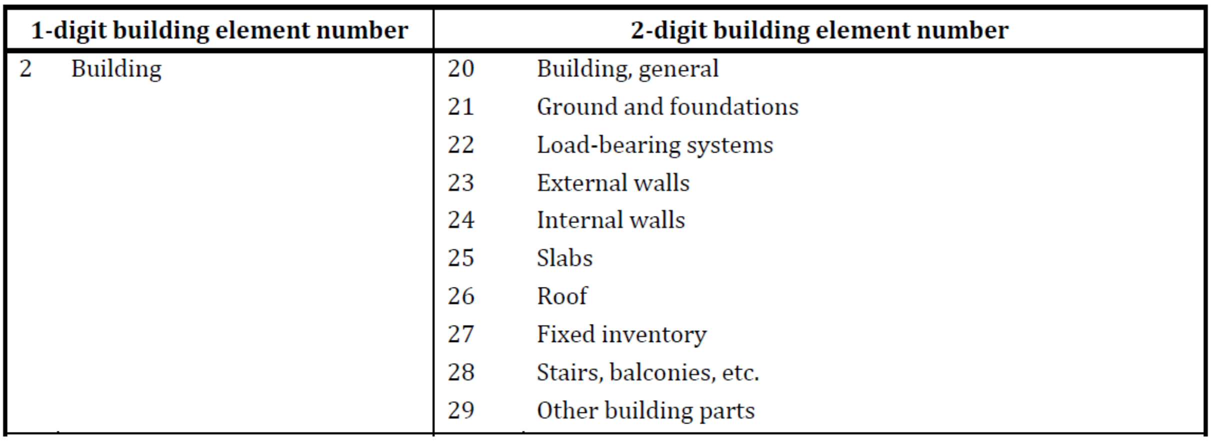


Key

A1–C4	modules into which the life cycle can be divided
D	covers additional information over and above the building's life cycle
B8	new module compared to NS-EN 15978
B7	not covered by this standard, with the exception of the energy use that is required for the distribution and heating of water for consumption that is included in module B6.

Figure 4: Display of information modules for the different stages in a building assessment (Standard Norge, 2018a)

This standard defines rules for both complete greenhouse gas calculations and for various partial calculations. It stipulates that an basic overall greenhouse gas calculation for a building without location must include emissions from the building site, materials and energy in operation. (Standard Norge, 2018a)



1-digit building element number		2-digit building element number	
2	Building	20	Building, general
		21	Ground and foundations
		22	Load-bearing systems
		23	External walls
		24	Internal walls
		25	Slabs
		26	Roof
		27	Fixed inventory
		28	Stairs, balconies, etc.
		29	Other building parts

Figure 5: A cut out of the table of building elements for a building on a 2-digit level (Standard Norge, 2019a).

The standard distinguishes between two levels of data quality, level 1 and level 2. Level 1 is when specific data for the tangible product has been used, such as EPDs where a third party has verified the declaration. Level 2 is all LCA data that does not meet the requirements of level 1, such as when generic data, average data and representative data (proxy data) have been used. (Standard Norge, 2018a)

Biogenic carbon

Biogenic carbon is the carbon dioxide that the threes take up during growth and store in the wood. Some or all of the stored biogenic carbon can be released as carbon dioxide during burning or decay of the wood.(Rønning and Tellnes, 2018)

The standard stipulates that the biogenic carbon should be included in the module where the binding takes place or where the emission of carbon takes place. This would result in a typically negative effect in the production phase and a equivalent emission in the waste treatment phase. It is, however, in many LCA studies a common practice to simplify the calculation by accounting the contribution from biogenic carbon as having no effect on climate change, even though several studies show that biogenic carbon has an real climate effect even though its only temporary storage(Rønning and Tellnes, 2018).

Carbonation

Carbonation of concrete is a chemical reaction where carbon dioxide in the atmosphere react with calcium oxide (CaO) in the concrete and becomes calcium carbonate ($CaCO_3$) (Rønning and Tellnes, 2018). This reaction process progressively continues during the service lifetime of the built concrete structure with increasing depth. Several factors affect the tempo and amount of carbon taken up by the concrete; temperature, CO_2 concentration, relative humidity, type and area of exposed concrete, and surface treatment (Collins, 2010). Standard Norge (2018a) stipulates that the absorption of carbon must be included in the calculations and calculated according to the NS-EN 16757 for the modules B1, C3 and C4, as well as module D.

3.3 LCA tool - Arda

The reliability of the life cycle analysis depend on the background processes used in the life cycle inventory. The data for the background processes can mainly be collected in two ways, either by using environmental product declarations (EPDs) that exists for specific products or available databases that can be linked to the foreground processes. EPDs has a standardized format that follows the international standard ISO 14025 and presents the environmental performance of the product in a transparent and comparable way (Standard Norge, 2010). Some of the available databases are Ecoinvent, BUWAL, ESU and Idemat.

The LCA tool used in this study, Arda, is a Matlab based program made by the Industrial Ecology research group at NTNU. Arda calculate the environmental impact using the background database Ecoinvent v.3.2, allows the user to upload their own foreground system and connects it with the background database. The software supports the use of ReCiPe impact methodology. (Majeau-Bettez and Strømman, 2016)

3.4 Environmental Product Declarations

There are several databases for EPDs online. For this study, the EPD-Norge online database was the main database used to collect needed EPDs. EPD-Norge is a program operator for type III EPDs according to ISO 14025. The program has established a system for verification, registration and publication of EPDs as well as maintenance of the register for EPDs and PCR (Product Category Rules).(The Norwegian EPD Federation, 2019)

A total of 233 EPDs has been used in this study where 198 was from the EPD-Norge database and 35 was from other EPD databases. The EPD databases and number of EPDs from each database is presented in Table 1.

Table 1: EPD databases and number of EPDs utilized.

EPD database	**Number of EPDs**
EPD Australasia	7
EPD Danmark	12
EPD-Norge	198
The International EPD System	14

A average value is calculated from all EPDs for a material or product that have the same functional unit. A average is used because of differences in the environmental impact of the materials or products and because the specific materials and products that will be used in the buildings is unknown. The EPD-Norge Database consists of many EPDs from industries and companies outside of Norway and it is found that many of these materials and products have a larger environmental impact then the Norwegian materials and products. The buildings are assumed built in Norway and as far as possible EPDs from Norwegian industries and companies has been used.

3.5 System Description

A modular approach have been used to model the case objects in this study. Two dimensions of the system boundaries have been used, where the first dimension characterize the physical boundaries, while the second dimension characterize the system boundaries of the building life cycle.

The bench-marking of the life cycle performance of buildings should rely on a consistent methodology for life cycle assessment. Therefor, the methodology used in this study is based on the framework of the Norwegian standard NS3720. The physical boundaries are limited to the building, excluding fixed inventory and other building parts that are not included in other categories according to NS3451. Heating, Ventilation and Air Conditioning (HVAC), electrical power, telecommunication and automation, other installations and outdoors have not been included in this study and will not be referred hereafter.

The system boundaries are in this study limited to the product stage (A1 – A3) of the materials used in the buildings. The choice is considered appropriate when considering material choices for a given structural system. The case objects are considered context independent in this study. Transport from supplier to construction site, construction phase and the demolition phase are affected by conditions that can vary greatly from project to project. It is acknowledged that conceptual parameters have a impact on the total emissions of a building and that such parameters should be included when performing a complete LCA of a building.

This study is mainly looking at the structural system of the buildings, where the materials have the same lifetime as the building itself. Repairs and replacements are not included as it is assumed not to be necessary for the building materials investigated.

Carbonation of concrete and biogenic carbon in wood have also not been included in this study. Inclusion of these parameters would lead to a lower impact from all of the wood materials assuming sustainable forestry.

3.6 Case objects

The case objects are two residential buildings that are functionally identical, dimensioned to the same fire, acoustic and load conditions. Both buildings have eight floors, gross floor area (GFA) of 2516.1 m^2 and indoor height of 2.95m. The building are calculated with having a parking garage in the basement which accounts for 460.1 m^2 of the total GFA. The calculations comprises of two main alternative construction materials; concrete construction and glued laminated timber. Both buildings have a assumed service lifetime of 60 years and none of the included building elements are assume replaced within the lifetime of the building.

The floor structure in the wood building is twice the thickness of the floor structure in the concrete building, making the wooden building taller. The difference makes a large impact on the amount of cladding on the buildings, which is why this building part is important to include even though its built up with the same materials. The amount of materials used is larger for the wood structure.

Each floor in both buildings have three different apartments accessible form a shared hallway with access to stairs and elevator. The floor plan of each floor are identical accept for one apartment in the first floor which is smaller because of a shared entrance to the building. The stairs and elevator are also accessible from the parking garage in the basement. Floor plans for the wood building are given in Appendix B. Windows, doors and floor finishing in both buildings was identical and not included in this report. Steel reinforcing in the cast-in-place concrete floors in both buildings are also not included.

Access to inventory data sets for both buildings was given from Sintef and originated from detailed design made by Løvset+Partner in the program Revit. The inventory included all elements made in Revit which lead to a double counting of some of the floor elements in both buildings. All adjustments and assumptions made for both buildings is explained in the detailed description in Chapter 3.6.1 and Chapter 3.6.2. All information about the concrete building came from the inventory, while more information could be found for the wooden building which is a part of the research project Woodsol where published articles are available.

Wall framing was not included in the inventory for either of the buildings. Detailed drawings from the wood building show that it has a wooden framing for the external walls and a metal framing system for the internal walls, see Figure 6. Because of similarities in the inventories, the same build-up of the wall structure was assumed for both buildings. Wood framing in the external walls have been estimated and included for both buildings, while the metal framing have not been included.

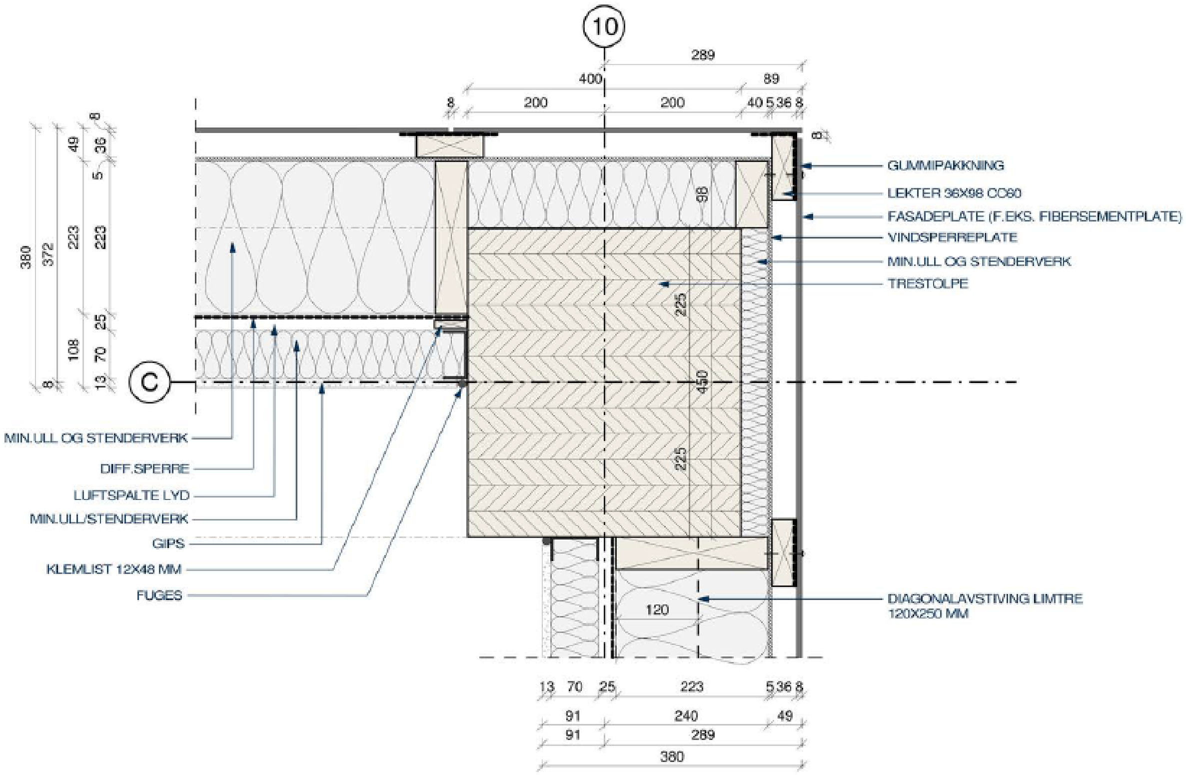


Figure 6: Illustration showing the wall build up for external walls(Løvseth, 2019).

The amount of wooden wall framing was calculated based on a framework of studs with a maximum width of 600 mm between them (Byggforsk, 2014), as illustrated in Figure 7, and that the framing is built on the load-bearing beams of the building.

All the inventory for both buildings was given with area (m^2) or volume (m^3) units for all amounts, except for steel amounts for the concrete building. Table 2 list all conversion factors used in this study and references used.

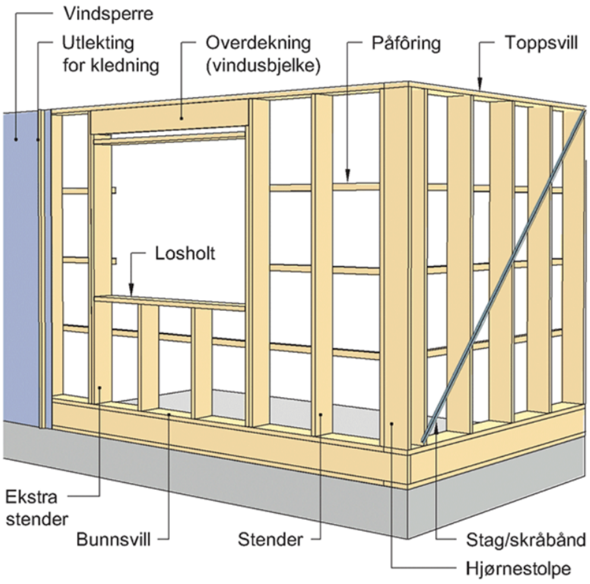


Figure 7: Illustration of a wooden framing structure for external walls(Byggforsk, 2014).

Table 2: Conversion factors used for the inventory of both buildings and the connected reference.

Conversion factors			
Product	**Value**	**Unit**	**Reference**
Vapor barrier	930	kg/m^3	British Plastics Federation (BPF) (n/a)
Chipboard	700	kg/m^3	Skaar and Rønning (2014)
Steel in hollow core concrete	1,5 %	per ton hollow core concrete	Østrem and Skårland (2019), Knutsen and Thomassen (2016), Kermit and Mælen (2019), Olavsen and Henriksen (2019), Rønning and Tellnes (2018)
Plasterboard	720	kg/m^3	Cobb (2017)
Hollow core concrete	400	kg/m^2	Knutsen and Thomassen (2016)
Hollow space in hollow core concrete	40 %		Østrem and Skårland (2019)
Fibre cement	2000	kg/m^3	Steine and Larsen (2017) During and Erlandsson (2017)
Glass wool	20	kg/m^3	Thue (2019)
Gravel	1400	kg/m^3	Grusbutikken (n/a)

The external walls are not load-bearing structures in any of the buildings which increases the design freedom. Internal walls around the stairs, elevator and hallway, marked in blue and red in Figure 8, are stabilizing structures in both buildings and built with their respective construction material; concrete or glued laminated timber. The structural internal GLT wall, marked in red in Figure 8, are longer then the concrete counterpart. All internal walls have been included in the inventory because of small differences between wall structures used in the buildings. Tiles used on the bathroom walls was identical in both buildings and not included in the model inventory. None of the other internal walls in either building are load bearing. Larger floor plan drawings is found in Appendix B.

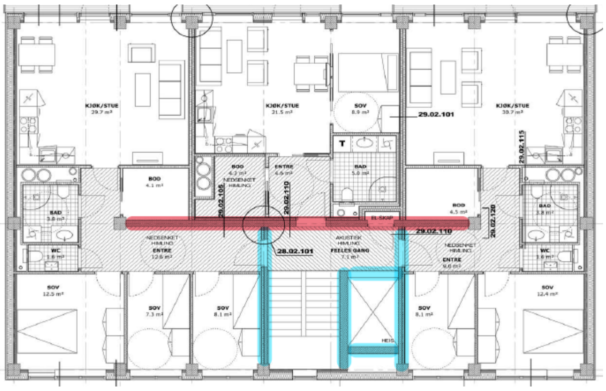


Figure 8: Floor plan of the wooden building with structural stabilizing internal walls marked in blue and red. Edited illustration from Løvseth (2019)

3.6.1 Wooden structure

The Woodsol research project focus on developing fire and acoustic solutions when building multi-story buildings with wood materials(Løvseth, 2019). The building are therefor assumed not optimized for reducing GHG emissions from materials.

The building are built with four different floor structures for different building elements. Table 4 show the different structures thickness's for the different elements and how they are built up.

Table 3: The different building element floor structures in the wooden building

Building element	**Thickness**	**Build up**	
Floor on ground (concrete)	300 mm	300 mm	Cast-in-place concrete
Prefabricated floors *	530 mm	63 mm	Kerto LVL panel
		404 mm	GLT joists
		63 mm	Kerto LVL panel
Balconies	320 mm	60 mm	Wood decking
		260 mm	GLT panel
Stair landings between floors	320 mm	60 mm	Kerto LVL panel
		260 mm	GLT joists
** The hollow sections of the prefabricated floor is filled with gravel*			

The prefabricated wooden floor structure consists of two laminated veneer lumber panels separated by laminated wooden framing where the hollow space in the structure are filled with gravel. Framing of the floor structures had to be calculated based on a maximum width of 600 mm between the joists, as illustrated in Figure 9.

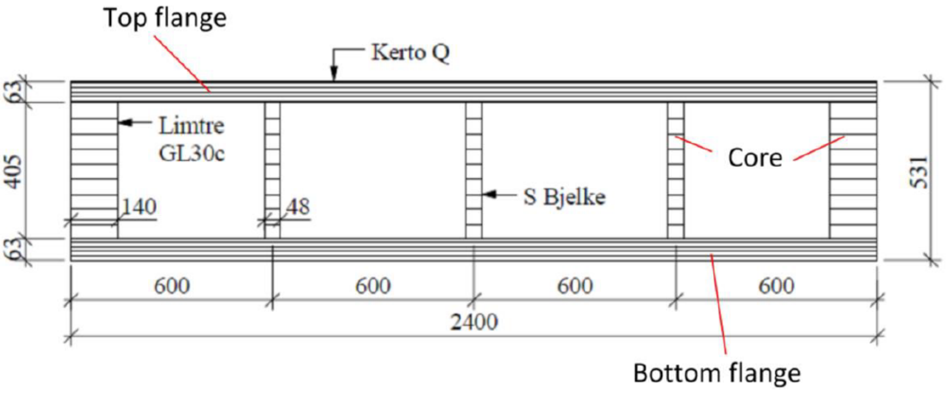
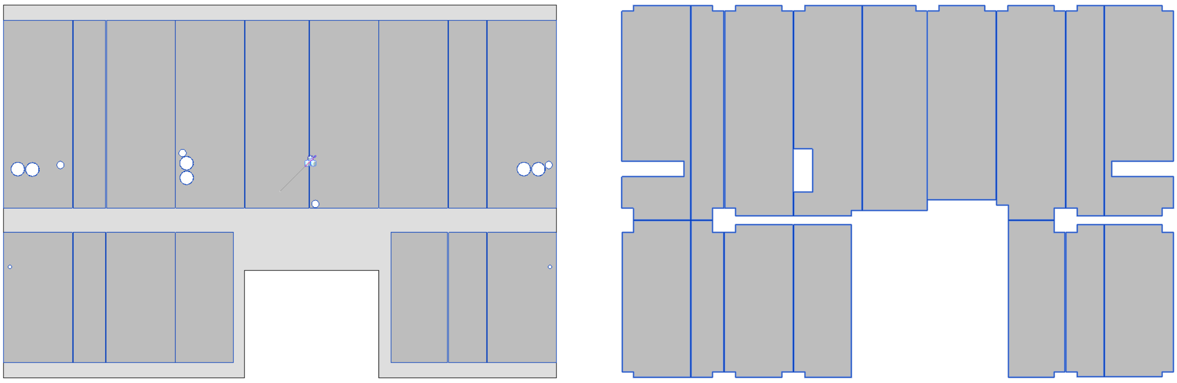


Figure 9: The build up of the floor construction. (Stamatopoulos and Malo, 2018)

Figure 10 show three different area drawings for the slabs. The area value used for the top and bottom flange is 230 m^2, while the core framing was calculated based on a floor area of 189 m^2, both areas illustrated in Figure 10a. The area shown in Figure 10b was dismissed as it didn't fit with the floor plan drawings of the building.



(a) Light and dark gray: 230 m^2. Dark gray: 189 m^2.

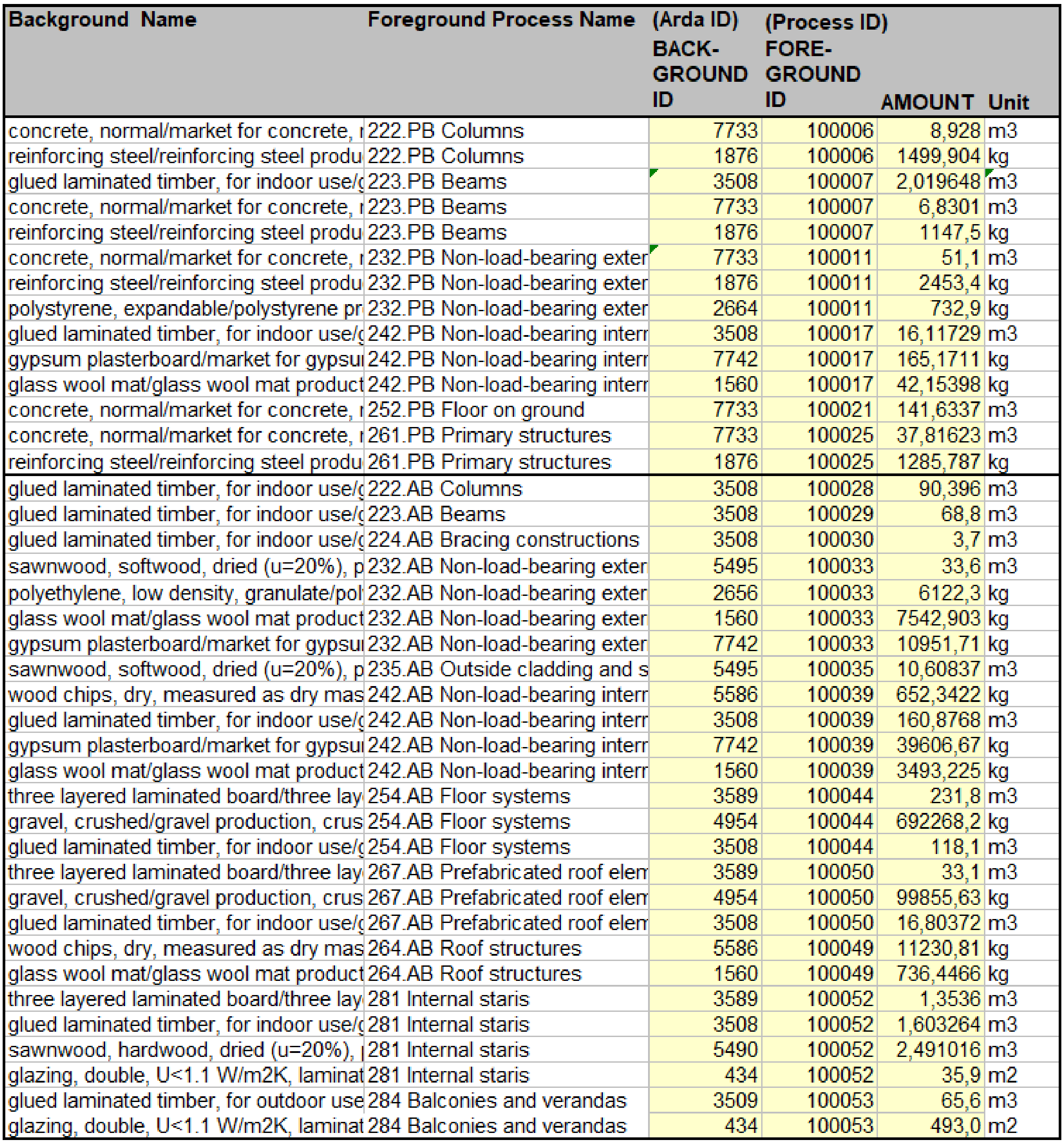
(b) Dark gray: 204 m^2

Figure 10: Show different areas used for calculating the floor area of the wooden building.

The difference in areas are because of the steel connections between the slabs and columns in the building, see Figure 11. No steel elements have been included in the inventory for the wooden building.

Figure 11: Steel connection between the wooden slabs and columns (Løvseth, 2019).

The complete inventory used in the Arda-model is shown in Figure 12 on a 3-digit resolution level according to NS3451 (Standard Norge, 2019a).

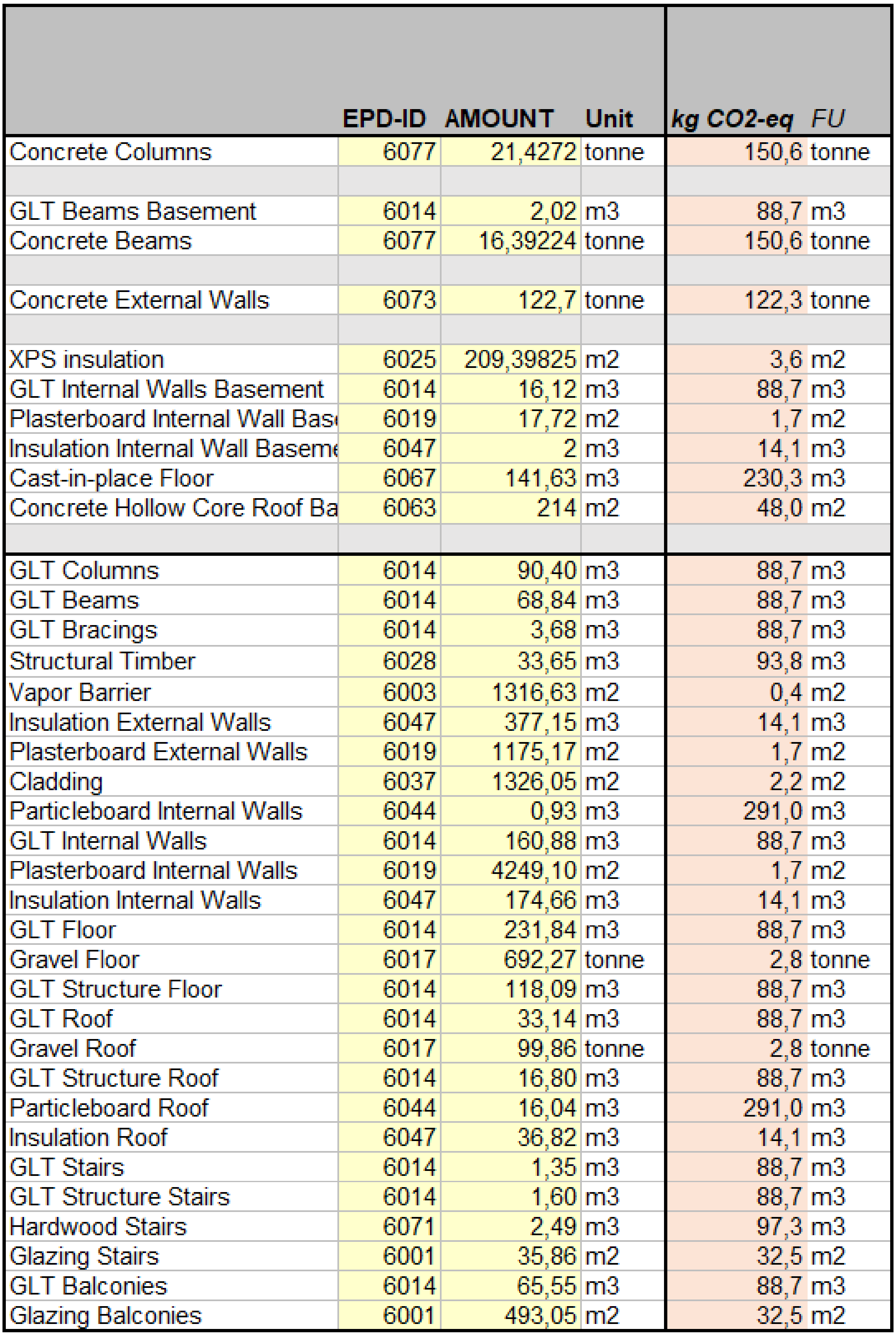


Background Name	Foreground Process Name	(Arda ID) BACK-GROUND ID	(Process ID) FORE-GROUND ID	AMOUNT	Unit
concrete, normal/market for concrete,	222.PB Columns	7733	100006	8,928	m3
reinforcing steel/reinforcing steel produ	222.PB Columns	1876	100006	1499,904	kg
glued laminated timber, for indoor use/	223.PB Beams	3508	100007	2,019648	m3
concrete, normal/market for concrete,	223.PB Beams	7733	100007	6,8301	m3
reinforcing steel/reinforcing steel produ	223.PB Beams	1876	100007	1147,5	kg
concrete, normal/market for concrete,	232.PB Non-load-bearing exter	7733	100011	51,1	m3
reinforcing steel/reinforcing steel produ	232.PB Non-load-bearing exter	1876	100011	2453,4	kg
polystyrene, expandable/polystyrene pr	232.PB Non-load-bearing exter	2664	100011	732,9	kg
glued laminated timber, for indoor use/	242.PB Non-load-bearing inter	3508	100017	16,11729	m3
gypsum plasterboard/market for gypsu	242.PB Non-load-bearing inter	7742	100017	165,1711	kg
glass wool mat/glass wool mat product	242.PB Non-load-bearing inter	1560	100017	42,15398	kg
concrete, normal/market for concrete,	252.PB Floor on ground	7733	100021	141,6337	m3
concrete, normal/market for concrete,	261.PB Primary structures	7733	100025	37,81623	m3
reinforcing steel/reinforcing steel produ	261.PB Primary structures	1876	100025	1285,787	kg
glued laminated timber, for indoor use/	222.AB Columns	3508	100028	90,396	m3
glued laminated timber, for indoor use/	223.AB Beams	3508	100029	68,8	m3
glued laminated timber, for indoor use/	224.AB Bracing constructions	3508	100030	3,7	m3
sawnwood, softwood, dried (u=20%), p	232.AB Non-load-bearing exter	5495	100033	33,6	m3
polyethylene, low density, granulate/pol	232.AB Non-load-bearing exter	2656	100033	6122,3	kg
glass wool mat/glass wool mat product	232.AB Non-load-bearing exter	1560	100033	7542,903	kg
gypsum plasterboard/market for gypsu	232.AB Non-load-bearing exter	7742	100033	10951,71	kg
sawnwood, softwood, dried (u=20%), p	235.AB Outside cladding and s	5495	100035	10,60837	m3
wood chips, dry, measured as dry mas	242.AB Non-load-bearing inter	5586	100039	652,3422	kg
glued laminated timber, for indoor use/	242.AB Non-load-bearing inter	3508	100039	160,8768	m3
gypsum plasterboard/market for gypsu	242.AB Non-load-bearing inter	7742	100039	39606,67	kg
glass wool mat/glass wool mat product	242.AB Non-load-bearing inter	1560	100039	3493,225	kg
three layered laminated board/three lay	254.AB Floor systems	3589	100044	231,8	m3
gravel, crushed/gravel production, crus	254.AB Floor systems	4954	100044	692268,2	kg
glued laminated timber, for indoor use/	254.AB Floor systems	3508	100044	118,1	m3
three layered laminated board/three lay	267.AB Prefabricated roof ele	3589	100050	33,1	m3
gravel, crushed/gravel production, crus	267.AB Prefabricated roof ele	4954	100050	99855,63	kg
glued laminated timber, for indoor use/	267.AB Prefabricated roof ele	3508	100050	16,80372	m3
wood chips, dry, measured as dry mas	264.AB Roof structures	5586	100049	11230,81	kg
glass wool mat/glass wool mat product	264.AB Roof structures	1560	100049	736,4466	kg
three layered laminated board/three lay	281 Internal staris	3589	100052	1,3536	m3
glued laminated timber, for indoor use/	281 Internal staris	3508	100052	1,603264	m3
sawnwood, hardwood, dried (u=20%),	281 Internal staris	5490	100052	2,491016	m3
glazing, double, U<1.1 W/m2K, laminat	281 Internal staris	434	100052	35,9	m2
glued laminated timber, for outdoor use	284 Balconies and verandas	3509	100053	65,6	m3
glazing, double, U<1.1 W/m2K, laminat	284 Balconies and verandas	434	100053	493,0	m2

Figure 12: Material inventory used in the Arda-model for the wooden building.

The complete inventory used in the EPD-model is shown in Figure 13. The Figure also show the average environmental impact in kg CO_2-eq calculated based on the gathered EPDs. The difference from the Arda-Inventory is that reinforcement is included in the concrete products in the EPD-Inventory.

The two inventories is shown side by side in Appendix C.



	EPD-ID	AMOUNT	Unit	kg CO2-eq	FU
Concrete Columns	6077	21,4272	tonne	150,6	tonne
GLT Beams Basement	6014	2,02	m3	88,7	m3
Concrete Beams	6077	16,39224	tonne	150,6	tonne
Concrete External Walls	6073	122,7	tonne	122,3	tonne
XPS insulation	6025	209,39825	m2	3,6	m2
GLT Internal Walls Basement	6014	16,12	m3	88,7	m3
Plasterboard Internal Wall Bas	6019	17,72	m2	1,7	m2
Insulation Internal Wall Baseme	6047	2	m3	14,1	m3
Cast-in-place Floor	6067	141,63	m3	230,3	m3
Concrete Hollow Core Roof Ba	6063	214	m2	48,0	m2
GLT Columns	6014	90,40	m3	88,7	m3
GLT Beams	6014	68,84	m3	88,7	m3
GLT Bracings	6014	3,68	m3	88,7	m3
Structural Timber	6028	33,65	m3	93,8	m3
Vapor Barrier	6003	1316,63	m2	0,4	m2
Insulation External Walls	6047	377,15	m3	14,1	m3
Plasterboard External Walls	6019	1175,17	m2	1,7	m2
Cladding	6037	1326,05	m2	2,2	m2
Particleboard Internal Walls	6044	0,93	m3	291,0	m3
GLT Internal Walls	6014	160,88	m3	88,7	m3
Plasterboard Internal Walls	6019	4249,10	m2	1,7	m2
Insulation Internal Walls	6047	174,66	m3	14,1	m3
GLT Floor	6014	231,84	m3	88,7	m3
Gravel Floor	6017	692,27	tonne	2,8	tonne
GLT Structure Floor	6014	118,09	m3	88,7	m3
GLT Roof	6014	33,14	m3	88,7	m3
Gravel Roof	6017	99,86	tonne	2,8	tonne
GLT Structure Roof	6014	16,80	m3	88,7	m3
Particleboard Roof	6044	16,04	m3	291,0	m3
Insulation Roof	6047	36,82	m3	14,1	m3
GLT Stairs	6014	1,35	m3	88,7	m3
GLT Structure Stairs	6014	1,60	m3	88,7	m3
Hardwood Stairs	6071	2,49	m3	97,3	m3
Glazing Stairs	6001	35,86	m2	32,5	m2
GLT Balconies	6014	65,55	m3	88,7	m3
Glazing Balconies	6001	493,05	m2	32,5	m2

Figure 13: Material inventory used in the EPD-model for the wooden building.

3.6.2 Concrete building

The Building uses four different concrete floor structures for different parts of the building. Table 4 show the different structure thickness's for the different elements and how they are built up.

Table 4: The different building element floor structures in the concrete building.

Building element	**Thickness**	**Build up**
Floor on ground	300 mm	Cast-in-place concrete
Prefabricated floors	265 mm	Hollow core concrete slabs
Balconies	220 mm	Hollow core concrete slabs
Stair landings	200 mm	Hollow core concrete slabs

The slabs in the building are hollow core slabs, as illustrated in Figure 14, which reduces the concrete amount used in the floor structures (Østrem and Skårland, 2019). The given concrete amounts did not account for the hollow sections or reinforcing bars, and had to be calculated based on the conversion factors listed in table 2.

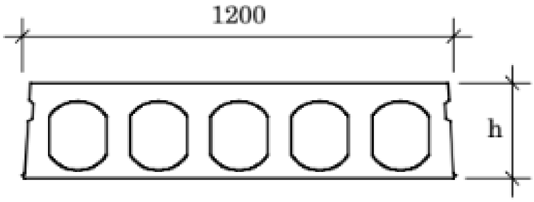
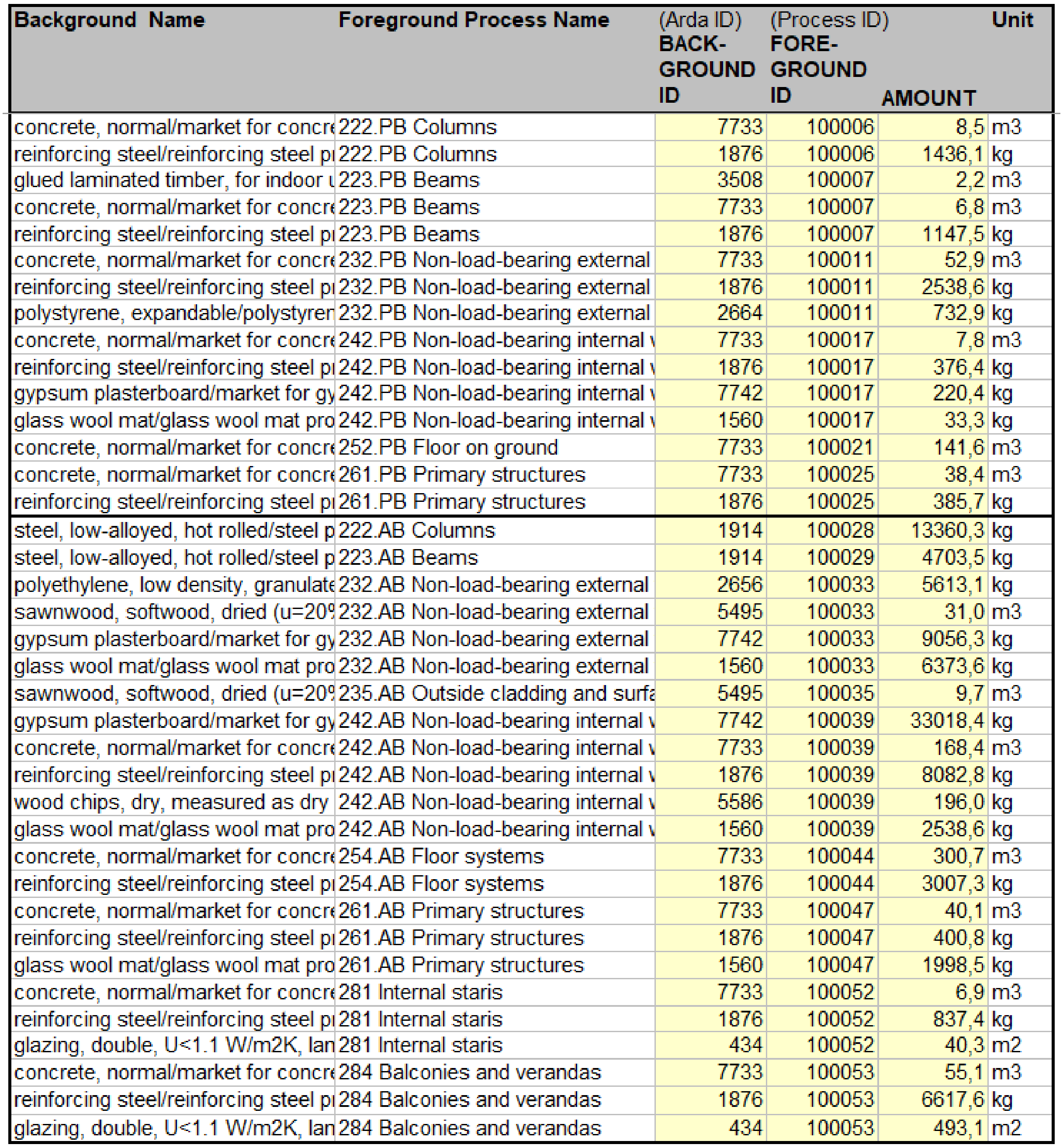


Figure 14: Rendering of a standard concrete floor element. Source: Vinje, Wilberg and Alexander (2010)

All concrete areas and volumes for the slabs in the AB part of the building was doubled in the given inventory and had to be corrected in the model inventory. No other steel components other then columns, beams and reinforcing bars in the hollow core slabs have been included in the model inventory.

The complete inventory used in the model is shown in Figure 15 on a 3-digit resolution level according to NS3451 (Standard Norge, 2019a).

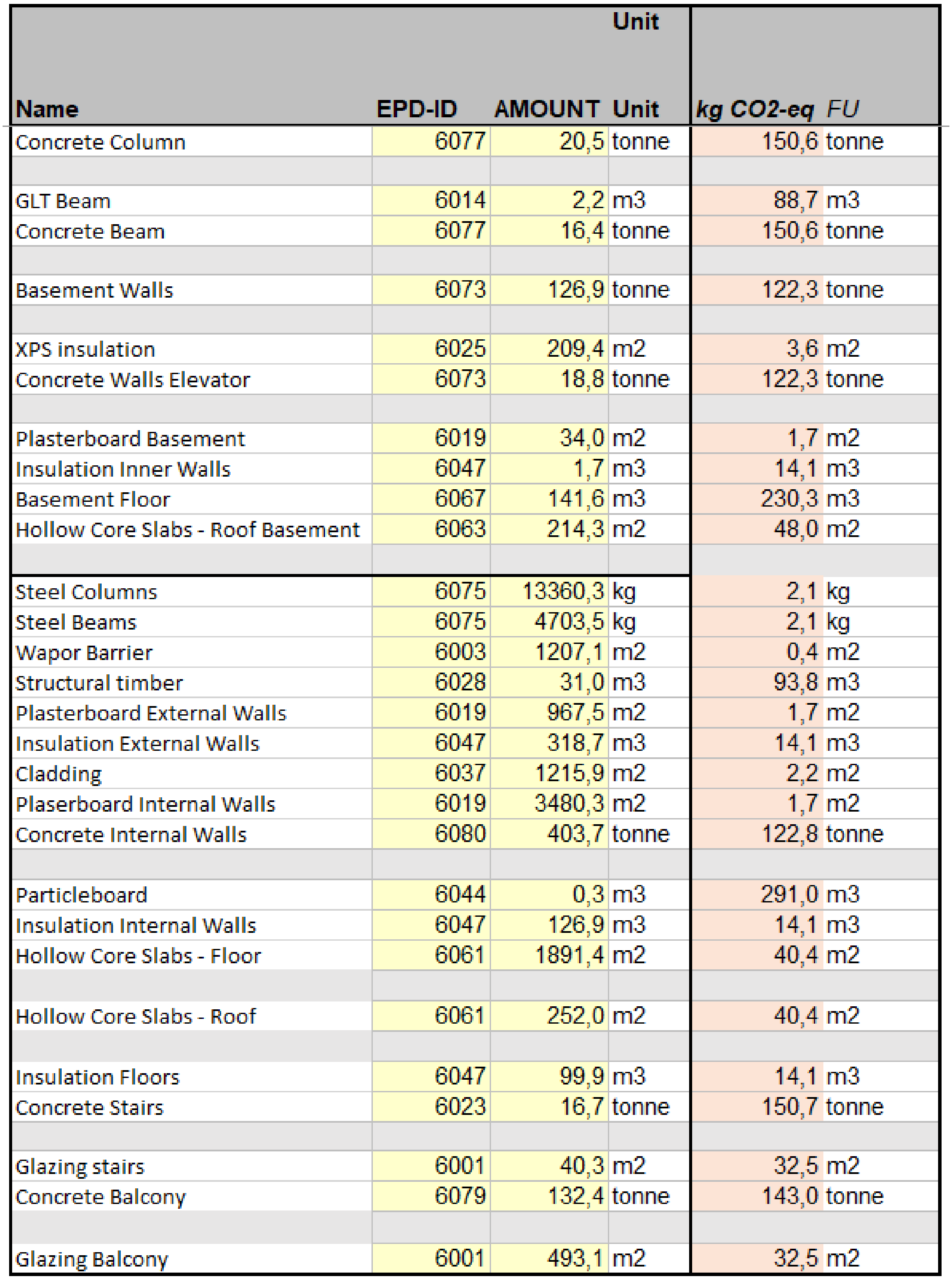


Background Name	Foreground Process Name	(Arda ID) BACK-GROUND ID	(Process ID) FORE-GROUND ID	AMOUNT	Unit
concrete, normal/market for concre	222.PB Columns	7733	100006	8,5	m3
reinforcing steel/reinforcing steel pı	222.PB Columns	1876	100006	1436,1	kg
glued laminated timber, for indoor ı	223.PB Beams	3508	100007	2,2	m3
concrete, normal/market for concre	223.PB Beams	7733	100007	6,8	m3
reinforcing steel/reinforcing steel pı	223.PB Beams	1876	100007	1147,5	kg
concrete, normal/market for concre	232.PB Non-load-bearing external	7733	100011	52,9	m3
reinforcing steel/reinforcing steel pı	232.PB Non-load-bearing external	1876	100011	2538,6	kg
polystyrene, expandable/polystyrer	232.PB Non-load-bearing external	2664	100011	732,9	kg
concrete, normal/market for concre	242.PB Non-load-bearing internal ı	7733	100017	7,8	m3
reinforcing steel/reinforcing steel pı	242.PB Non-load-bearing internal ı	1876	100017	376,4	kg
gypsum plasterboard/market for gy	242.PB Non-load-bearing internal ı	7742	100017	220,4	kg
glass wool mat/glass wool mat pro	242.PB Non-load-bearing internal ı	1560	100017	33,3	kg
concrete, normal/market for concre	252.PB Floor on ground	7733	100021	141,6	m3
concrete, normal/market for concre	261.PB Primary structures	7733	100025	38,4	m3
reinforcing steel/reinforcing steel pı	261.PB Primary structures	1876	100025	385,7	kg
steel, low-alloyed, hot rolled/steel p	222.AB Columns	1914	100028	13360,3	kg
steel, low-alloyed, hot rolled/steel p	223.AB Beams	1914	100029	4703,5	kg
polyethylene, low density, granulate	232.AB Non-load-bearing external	2656	100033	5613,1	kg
sawnwood, softwood, dried (u=20%	232.AB Non-load-bearing external	5495	100033	31,0	m3
gypsum plasterboard/market for gy	232.AB Non-load-bearing external	7742	100033	9056,3	kg
glass wool mat/glass wool mat pro	232.AB Non-load-bearing external	1560	100033	6373,6	kg
sawnwood, softwood, dried (u=20%	235.AB Outside cladding and surfa	5495	100035	9,7	m3
gypsum plasterboard/market for gy	242.AB Non-load-bearing internal ı	7742	100039	33018,4	kg
concrete, normal/market for concre	242.AB Non-load-bearing internal ı	7733	100039	168,4	m3
reinforcing steel/reinforcing steel pı	242.AB Non-load-bearing internal ı	1876	100039	8082,8	kg
wood chips, dry, measured as dry	242.AB Non-load-bearing internal ı	5586	100039	196,0	kg
glass wool mat/glass wool mat pro	242.AB Non-load-bearing internal ı	1560	100039	2538,6	kg
concrete, normal/market for concre	254.AB Floor systems	7733	100044	300,7	m3
reinforcing steel/reinforcing steel pı	254.AB Floor systems	1876	100044	3007,3	kg
concrete, normal/market for concre	261.AB Primary structures	7733	100047	40,1	m3
reinforcing steel/reinforcing steel pı	261.AB Primary structures	1876	100047	400,8	kg
glass wool mat/glass wool mat pro	261.AB Primary structures	1560	100047	1998,5	kg
concrete, normal/market for concre	281 Internal staris	7733	100052	6,9	m3
reinforcing steel/reinforcing steel pı	281 Internal staris	1876	100052	837,4	kg
glazing, double, U<1.1 W/m2K, lan	281 Internal staris	434	100052	40,3	m2
concrete, normal/market for concre	284 Balconies and verandas	7733	100053	55,1	m3
reinforcing steel/reinforcing steel pı	284 Balconies and verandas	1876	100053	6617,6	kg
glazing, double, U<1.1 W/m2K, lan	284 Balconies and verandas	434	100053	493,1	m2

Figure 15: Material inventory used in the Arda model for the concrete building.

The complete inventory used in the EPD-model is shown in Figure 16. The Figure also show the average environmental impact in kg CO_2-eq calculated based on the gathered EPDs. The difference from the Arda-Inventory is that reinforcement is included in the concrete products in the EPD-Inventory.

The two inventories is shown side by side in Appendix C.



			Unit		
Name	**EPD-ID**	**AMOUNT**	**Unit**	***kg CO2-eq***	*FU*
Concrete Column	6077	20,5	tonne	150,6	tonne
GLT Beam	6014	2,2	m3	88,7	m3
Concrete Beam	6077	16,4	tonne	150,6	tonne
Basement Walls	6073	126,9	tonne	122,3	tonne
XPS insulation	6025	209,4	m2	3,6	m2
Concrete Walls Elevator	6073	18,8	tonne	122,3	tonne
Plasterboard Basement	6019	34,0	m2	1,7	m2
Insulation Inner Walls	6047	1,7	m3	14,1	m3
Basement Floor	6067	141,6	m3	230,3	m3
Hollow Core Slabs - Roof Basement	6063	214,3	m2	48,0	m2
Steel Columns	6075	13360,3	kg	2,1	kg
Steel Beams	6075	4703,5	kg	2,1	kg
Wapor Barrier	6003	1207,1	m2	0,4	m2
Structural timber	6028	31,0	m3	93,8	m3
Plasterboard External Walls	6019	967,5	m2	1,7	m2
Insulation External Walls	6047	318,7	m3	14,1	m3
Cladding	6037	1215,9	m2	2,2	m2
Plaserboard Internal Walls	6019	3480,3	m2	1,7	m2
Concrete Internal Walls	6080	403,7	tonne	122,8	tonne
Particleboard	6044	0,3	m3	291,0	m3
Insulation Internal Walls	6047	126,9	m3	14,1	m3
Hollow Core Slabs - Floor	6061	1891,4	m2	40,4	m2
Hollow Core Slabs - Roof	6061	252,0	m2	40,4	m2
Insulation Floors	6047	99,9	m3	14,1	m3
Concrete Stairs	6023	16,7	tonne	150,7	tonne
Glazing stairs	6001	40,3	m2	32,5	m2
Concrete Balcony	6079	132,4	tonne	143,0	tonne
Glazing Balcony	6001	493,1	m2	32,5	m2

Figure 16: Material inventory used in the EPD model for the concrete building.

3.6.3 Flowchart

Figure 17 show the flows of building elements starting from a 3-digit resolution on the left, as described in NS3451, ending up in the functional unit “a building” on the right. Inputs to the 3-digit resolution is the inventory earlier described in this chapter.

Stairs, balconies are not connected to either PB or AB, but are directly input to the building. The material inputs to the stairs have not been divided between the floors of the building which is why it is not set as a input to either PB or AB.

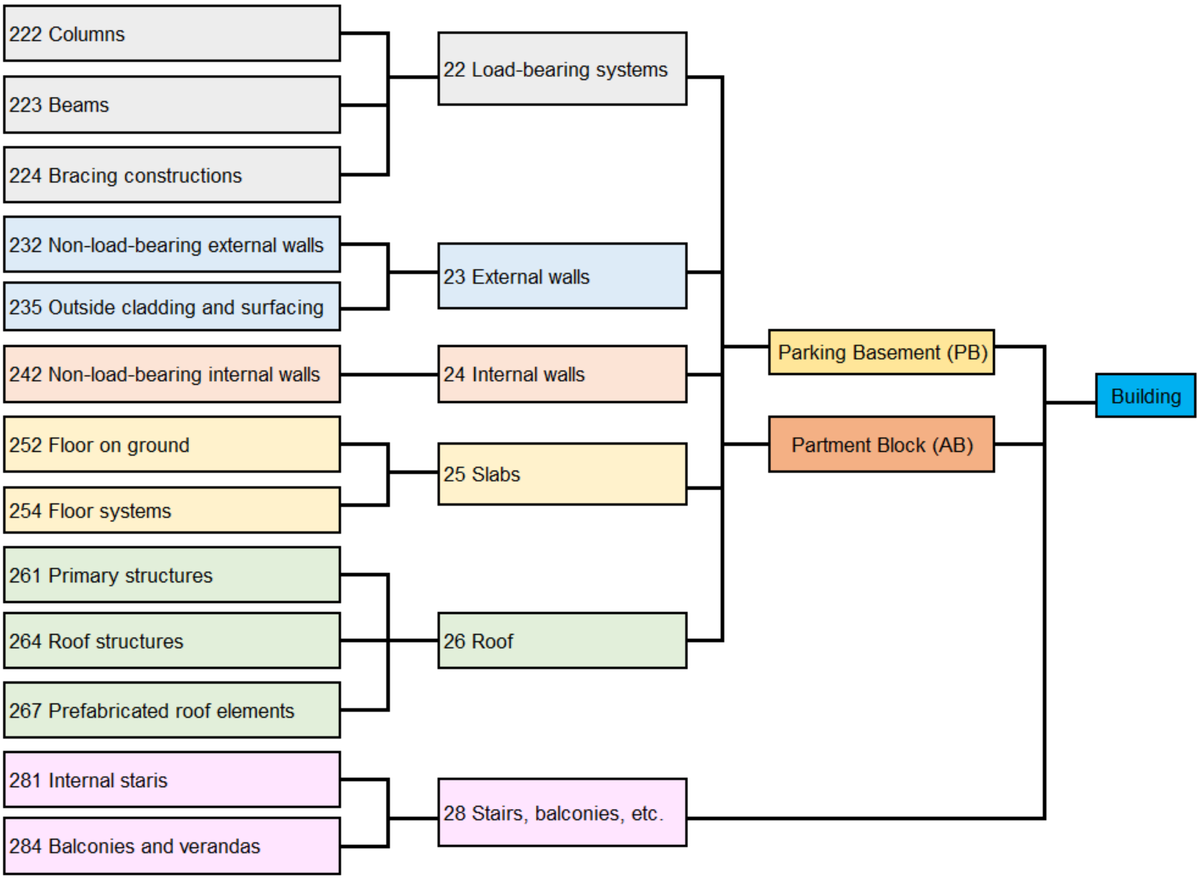


Figure 17: Flow chart sketch of LCA resolution on a building level.

3.7 Uncertainty and sensitivity analysis

3.7.1 Pedigree Matrix Approach

The parameter uncertainty is calculated utilizing the Pedigree matrix approach. The rows of the matrix are composed of different relevant aspects while the columns express different degrees of data quality or uncertainty. Each column is assigned a indicator score from one to five, where one is the highest quality and lowest uncertainty. Each cell of the matrix express a qualitative description and a assigned quantitative value, expressed as log transformed variance, σ^2. Figure 18 show the pedigree matrix and its components. This study uses the same Pedigree Matrix as the Ecoinvent database(Weidema et al., 2013).

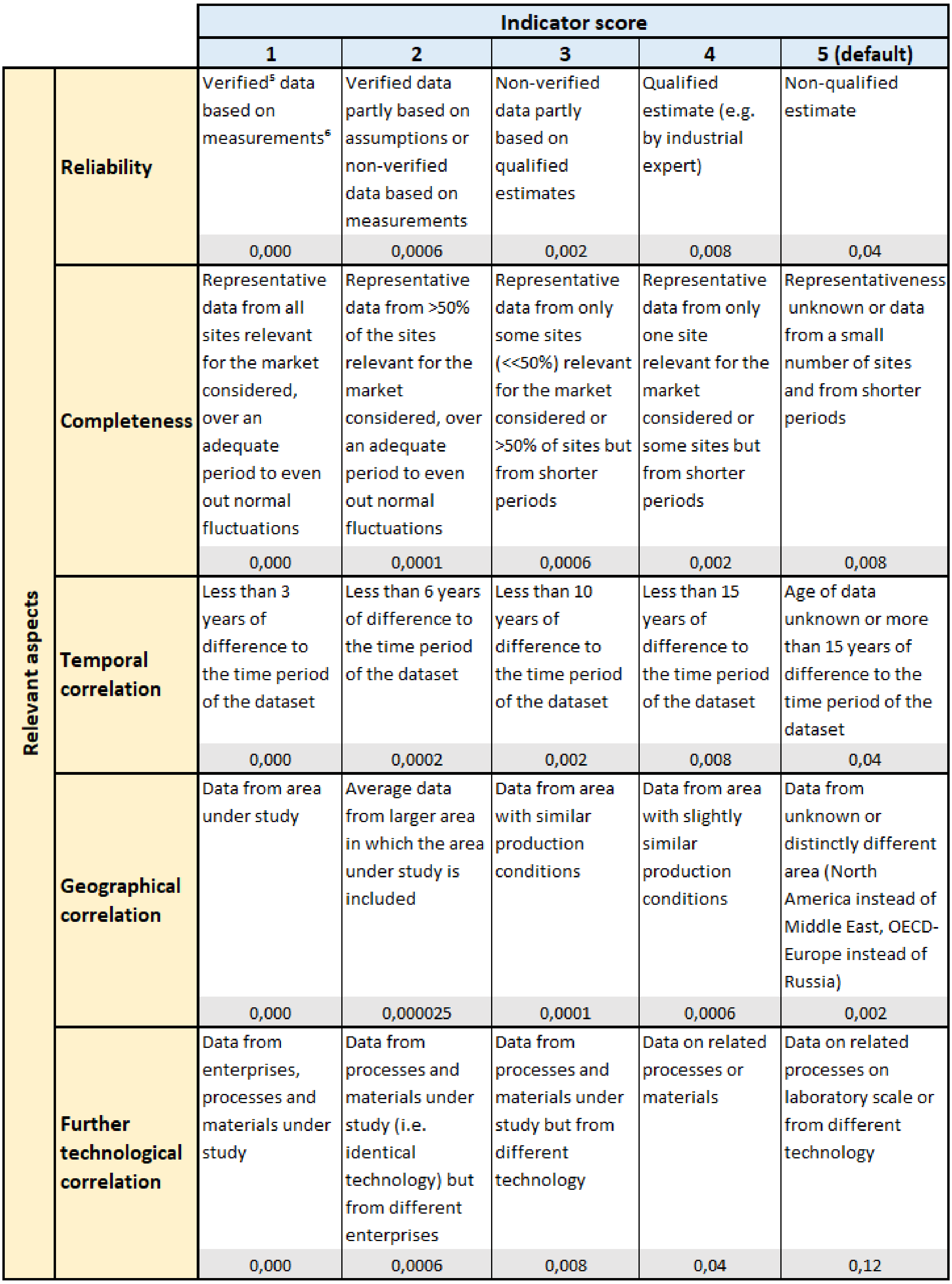
A indicator score are assigned to each of the relevant aspects for a given parameter and the uncertainty are calculated as the sum of the assigned variance, Equation 1.

$$\sigma^2 = \sum_{i=1}^{n} \sigma_n^2 \tag{1}$$

The calculation method utilized are based on log transformed values. The connection between variance and log transformed variance is given in Equation 2

$$\left(\sigma^2\right)^* = \exp\left(\sqrt{\sigma^2}\right)^2 \tag{2}$$

where $(\sigma^2)^*$ is the variance and σ^2 is the log transformed variance.



		Indicator score				
		1	2	3	4	5 (default)
Relevant aspects	**Reliability**	Verified[5] data based on measurements[6]	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
		0,000	0,0006	0,002	0,008	0,04
	Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (<<50%) relevant for the market considered or >50% of sites but from shorter periods	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Representativeness unknown or data from a small number of sites and from shorter periods
		0,000	0,0001	0,0006	0,002	0,008
	Temporal correlation	Less than 3 years of difference to the time period of the dataset	Less than 6 years of difference to the time period of the dataset	Less than 10 years of difference to the time period of the dataset	Less than 15 years of difference to the time period of the dataset	Age of data unknown or more than 15 years of difference to the time period of the dataset
		0,000	0,0002	0,002	0,008	0,04
	Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)
		0,000	0,000025	0,0001	0,0006	0,002
	Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study (i.e. identical technology) but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials	Data on related processes on laboratory scale or from different technology
		0,000	0,0006	0,008	0,04	0,12

Figure 18: Pedigree matrix with the quantitative description and qualitative value expressed as log-transformed variance.(Weidema et al., 2013)

Ecoinvent utilize different distributions to calculate uncertainty, but lognormal is the most commonly used and is therefor the chosen distribution method utilized in this paper.(Muller et al., 2014)

All EPDs used in this study was assigned indicator scores according to the qualitative Pedigree Matrix.

3.7.2 Monte Carlo Simulation (MCS)

MCS is a method for random sampling used for uncertainty analysis. Input parameters must be specified as uncertainty distributions to perform MCS and these uncertainty distributions restrict the random variability of the input parameters. The MCS method randomly selects values from all the parameter uncertainty distributions and run the calculation hundreds and thousands of times. A higher number of iterations increase the reliability of the distribution.

In this study, the lognormal distribution is used for all input parameters. The MCS use the logtransformed value of the input parameter as well as the logtransformed strandard deviation. The Simulación 4.0 add on to Excel is used to perform the MSC in this study.(Ricardo, 2003)

The MCS calculates the mean, variance, standard deviation and relative error, and gives the minimum and maximum values calculated.

The EPDs used for the inventories have been set as inputs in the MCS with the logtransformed standard deviation calculated from the variance given from the Pedigree matrix. No uncertainty have been assigned to the inventory data even though the parameters have been used in the MCS.

No other uncertainties has been included other then the EPD uncertainties. Inventory parameters have been used to calculate the total emissions without assigning individual uncertainties to these.

3.7.3 Sensitivity Analysis

The inputs to the model are associated with uncertainties. The effect on changes in specific parameters have on the results are found by doing a sensitivity analysis. Chosen parameters are either associated with large uncertainties or have a large contribution to the environmental impact. The sensitivity ratio (SR), in Equation 3, measures the effect on changes in the parameters, where an SR of 2 implies that when its value is increased by 10 %, the final result is increased by 20 %.

$$SR = \frac{\frac{\Delta R}{R_0}}{\frac{\Delta P}{P_0}} \tag{3}$$

- $\Delta \mathrm{R}/\mathrm{R}_0$ is the relative change in results
- $\Delta \mathrm{P}/\mathrm{P}_0$ is the relative change in parameter value

Bamber et al. (2020) found that over time, the rate of reporting any kind of uncertainty in LCA studies does not seem to be increasing, and since 2014 it has been included in less then 20% of studies.

Polystyrene and glass wool are both insulation materials and have been added together for the sensitivity analysis. Also all concrete and reinforced steel, and GLT products have also been added together for the sensitivity analysis, named reinforced concrete and glued laminated timber.

Table 5: Parameters investigated in the sensitivity analysis and the associated variations.

Parameter	**Variation**
Reinforced Concrete	+ 25 %
Plasterboard	+ 25 %
Glazing	+ 25 %
Insulation	+ 25 %
Glued laminated timber	+ 25 %

4 Results

This chapter presents the results from the LCA calculations. Results for the wood building is presented in Chapter 4.1 while Chapter 4.2 presents the results for the concrete building. Both chapters presents the associated uncertainty and sensitivity results.

4.1 Wood Building

Figure 19 show the total emissions from the wood building for both the Ecoinvent and the EPD calculation. The total emissions for the EPD calculation include the calculated relative error of 2,04 %. The parking basement and apartment block of the building is also shown as individual columns showing the environmental impact from each of the different building parts according to NS3451.

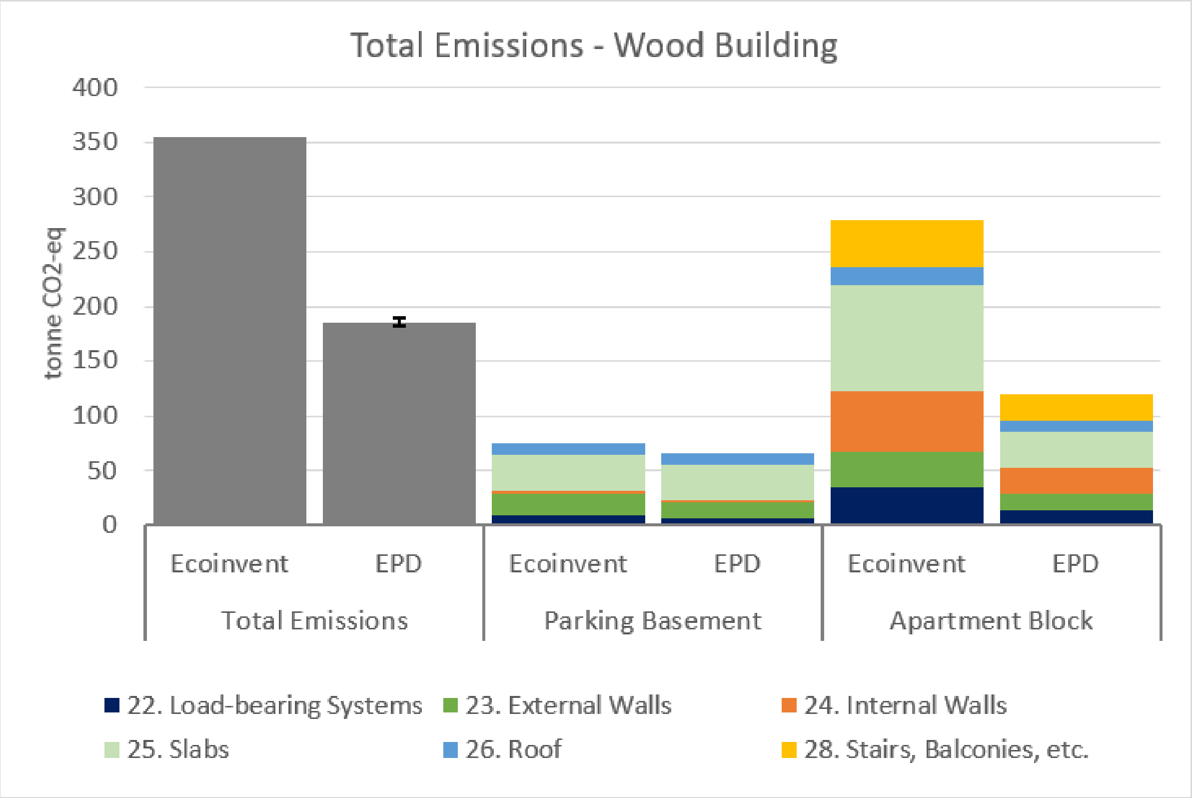


Figure 19: Total emissions from wood building with uncertainty in results for the EPD calculation.

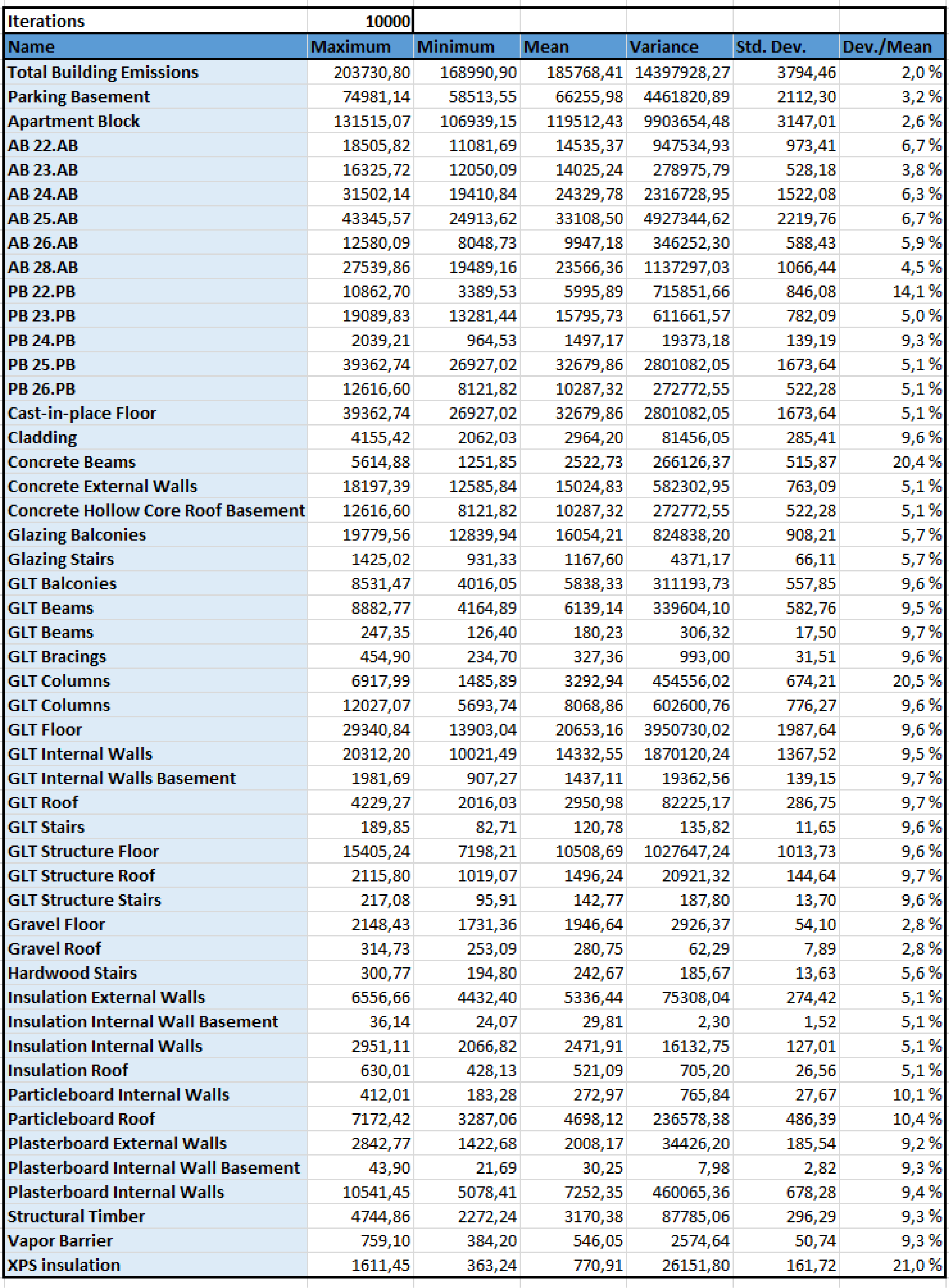
The figure show a significant difference between the calculated emissions between the two calculation methods. Performing the emission calculation with EPD leads to a reduction in emissions by 48 %. The EPD calculation is 12 % lower for the parking basement, while its 57 % lower for the apartment block part of the building.

Table 6 show the impact distribution between the materials in the wood building. GLT are the main building material and accounts for more then 40% of the emissions in both cases. The reinforced concrete used in the parking basement accounts for almost 1/5 of the buildings emissions.

Table 6: Impact distribution between the materials in the wood building

Material	**% of total emissions Arda**	**% of total emissions EPD**
Glued laminated timber	54,0 %	40,6 %
Reinforced Concrete	19,5 %	17,6 %
Glazing	7,6 %	9,3 %
Plasterboard	6,2 %	5,0 %
Insulation materials	4,4 %	4,9 %
Vapor Barrier	3,6 %	0,3 %
Gravel	2,4 %	10,8 %
Structural timber and cladding	1,3 %	3,3 %
Particleboard	0,3 %	2,7 %
Hardwood stairs	0,0 %	0,1 %
Total emissions	**354 242,3 kg CO_2-eq**	**185 768,4 kg CO_2-eq**

The results from the uncertainty calculation is given in Figure 20. Several of the input parameters have larger uncertainties such as the XPS insulation and the GLT columns and Concrete Beams, but the overall uncertainty of the system given all input parameters have a small uncertainty of 2,0 %.



Iterations	10000					
Name	**Maximum**	**Minimum**	**Mean**	**Variance**	**Std. Dev.**	**Dev./Mean**
Total Building Emissions	203730,80	168990,90	185768,41	14397928,27	3794,46	2,0 %
Parking Basement	74981,14	58513,55	66255,98	4461820,89	2112,30	3,2 %
Apartment Block	131515,07	106939,15	119512,43	9903654,48	3147,01	2,6 %
AB 22.AB	18505,82	11081,69	14535,37	947534,93	973,41	6,7 %
AB 23.AB	16325,72	12050,09	14025,24	278975,79	528,18	3,8 %
AB 24.AB	31502,14	19410,84	24329,78	2316728,95	1522,08	6,3 %
AB 25.AB	43345,57	24913,62	33108,50	4927344,62	2219,76	6,7 %
AB 26.AB	12580,09	8048,73	9947,18	346252,30	588,43	5,9 %
AB 28.AB	27539,86	19489,16	23566,36	1137297,03	1066,44	4,5 %
PB 22.PB	10862,70	3389,53	5995,89	715851,66	846,08	14,1 %
PB 23.PB	19089,83	13281,44	15795,73	611661,57	782,09	5,0 %
PB 24.PB	2039,21	964,53	1497,17	19373,18	139,19	9,3 %
PB 25.PB	39362,74	26927,02	32679,86	2801082,05	1673,64	5,1 %
PB 26.PB	12616,60	8121,82	10287,32	272772,55	522,28	5,1 %
Cast-in-place Floor	39362,74	26927,02	32679,86	2801082,05	1673,64	5,1 %
Cladding	4155,42	2062,03	2964,20	81456,05	285,41	9,6 %
Concrete Beams	5614,88	1251,85	2522,73	266126,37	515,87	20,4 %
Concrete External Walls	18197,39	12585,84	15024,83	582302,95	763,09	5,1 %
Concrete Hollow Core Roof Basement	12616,60	8121,82	10287,32	272772,55	522,28	5,1 %
Glazing Balconies	19779,56	12839,94	16054,21	824838,20	908,21	5,7 %
Glazing Stairs	1425,02	931,33	1167,60	4371,17	66,11	5,7 %
GLT Balconies	8531,47	4016,05	5838,33	311193,73	557,85	9,6 %
GLT Beams	8882,77	4164,89	6139,14	339604,10	582,76	9,5 %
GLT Beams	247,35	126,40	180,23	306,32	17,50	9,7 %
GLT Bracings	454,90	234,70	327,36	993,00	31,51	9,6 %
GLT Columns	6917,99	1485,89	3292,94	454556,02	674,21	20,5 %
GLT Columns	12027,07	5693,74	8068,86	602600,76	776,27	9,6 %
GLT Floor	29340,84	13903,04	20653,16	3950730,02	1987,64	9,6 %
GLT Internal Walls	20312,20	10021,49	14332,55	1870120,24	1367,52	9,5 %
GLT Internal Walls Basement	1981,69	907,27	1437,11	19362,56	139,15	9,7 %
GLT Roof	4229,27	2016,03	2950,98	82225,17	286,75	9,7 %
GLT Stairs	189,85	82,71	120,78	135,82	11,65	9,6 %
GLT Structure Floor	15405,24	7198,21	10508,69	1027647,24	1013,73	9,6 %
GLT Structure Roof	2115,80	1019,07	1496,24	20921,32	144,64	9,7 %
GLT Structure Stairs	217,08	95,91	142,77	187,80	13,70	9,6 %
Gravel Floor	2148,43	1731,36	1946,64	2926,37	54,10	2,8 %
Gravel Roof	314,73	253,09	280,75	62,29	7,89	2,8 %
Hardwood Stairs	300,77	194,80	242,67	185,67	13,63	5,6 %
Insulation External Walls	6556,66	4432,40	5336,44	75308,04	274,42	5,1 %
Insulation Internal Wall Basement	36,14	24,07	29,81	2,30	1,52	5,1 %
Insulation Internal Walls	2951,11	2066,82	2471,91	16132,75	127,01	5,1 %
Insulation Roof	630,01	428,13	521,09	705,20	26,56	5,1 %
Particleboard Internal Walls	412,01	183,28	272,97	765,84	27,67	10,1 %
Particleboard Roof	7172,42	3287,06	4698,12	236578,38	486,39	10,4 %
Plasterboard External Walls	2842,77	1422,68	2008,17	34426,20	185,54	9,2 %
Plasterboard Internal Wall Basement	43,90	21,69	30,25	7,98	2,82	9,3 %
Plasterboard Internal Walls	10541,45	5078,41	7252,35	460065,36	678,28	9,4 %
Structural Timber	4744,86	2272,24	3170,38	87785,06	296,29	9,3 %
Vapor Barrier	759,10	384,20	546,05	2574,64	50,74	9,3 %
XPS insulation	1611,45	363,24	770,91	26151,80	161,72	21,0 %

Figure 20: Result from the uncertainty calculation for the wood building.

4.2 Concrete Building

Figure 21 show the total emissions from the concrete building for both the Ecoinvent and the EPD calculation. The total emissions for the EPD calculation include the calculated relative error of 2,01 %.

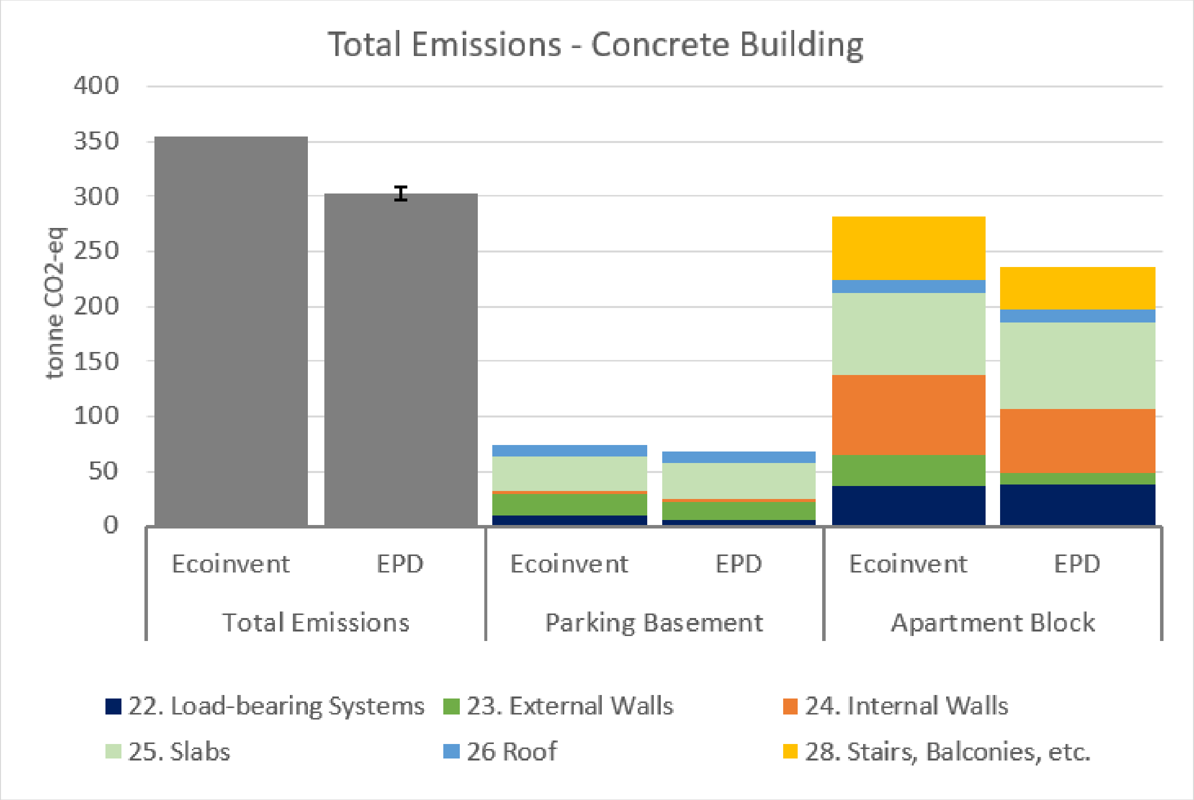


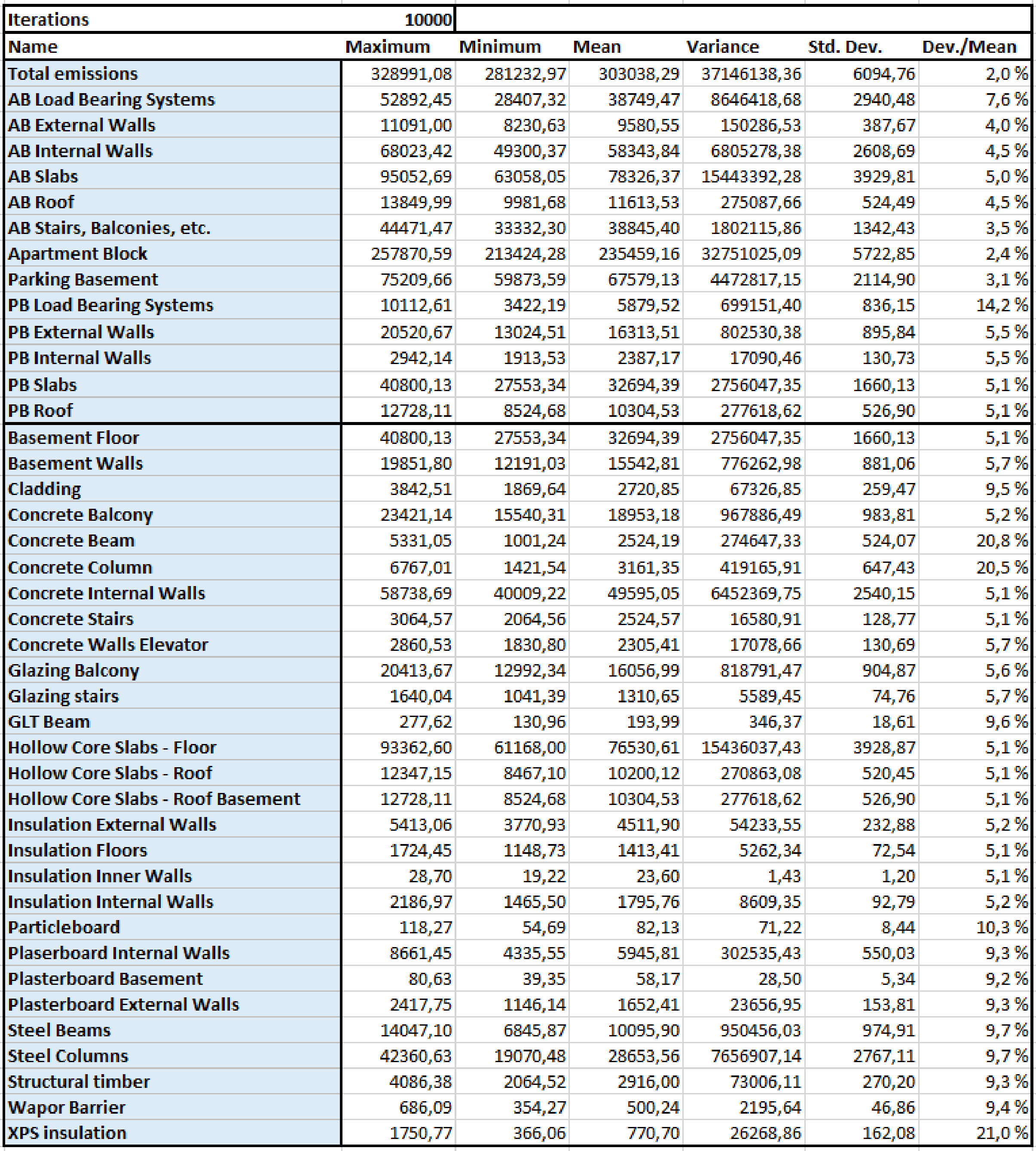
Figure 21: Total emissions from concrete building with uncertainty in results for the EPD calculation.

There is a clear difference between the Arda calculation and the EPD calculation. For the total emissions the EPD calculation is 14 % lower then the arda calculation. The difference is smaller for the parking basement where the EPD calculation is 8 % lower then the arda calculation, while the difference is 16 % for the apartment block part of the building.

Table 7: Impact distribution between the materials in the concrete building

Material	**% of total emissions Arda**	**% of total emissions EPD**
Reinforced Concrete	67,6 %	74,2 %
Structural Steel	10,2 %	12,8 %
Glazing	7,6 %	5,7 %
Plasterboard	5,1 %	2,5 %
Insulation materials	4,8 %	2,6 %
Vapor Barrier	3,3 %	0,2 %
Structural timber and cladding	1,2 %	1,9 %
Glued laminated timber	0,1 %	0,1 %
Particleboard	0,0 %	0,0 %
Total emissions	**354 644,5 kg CO_2-eq**	**302 290,4 kg CO_2-eq**

The results from the uncertainty calculation is given in Figure 22. Several of the input parameters have larger uncertainties such as the XPS insulation and the GLT columns and Concrete Beams, but the overall uncertainty of the system given all input parameters have a small uncertainty of 2,0 %.



Iterations	10000					
Name	**Maximum**	**Minimum**	**Mean**	**Variance**	**Std. Dev.**	**Dev./Mean**
Total emissions	328991,08	281232,97	303038,29	37146138,36	6094,76	2,0 %
AB Load Bearing Systems	52892,45	28407,32	38749,47	8646418,68	2940,48	7,6 %
AB External Walls	11091,00	8230,63	9580,55	150286,53	387,67	4,0 %
AB Internal Walls	68023,42	49300,37	58343,84	6805278,38	2608,69	4,5 %
AB Slabs	95052,69	63058,05	78326,37	15443392,28	3929,81	5,0 %
AB Roof	13849,99	9981,68	11613,53	275087,66	524,49	4,5 %
AB Stairs, Balconies, etc.	44471,47	33332,30	38845,40	1802115,86	1342,43	3,5 %
Apartment Block	257870,59	213424,28	235459,16	32751025,09	5722,85	2,4 %
Parking Basement	75209,66	59873,59	67579,13	4472817,15	2114,90	3,1 %
PB Load Bearing Systems	10112,61	3422,19	5879,52	699151,40	836,15	14,2 %
PB External Walls	20520,67	13024,51	16313,51	802530,38	895,84	5,5 %
PB Internal Walls	2942,14	1913,53	2387,17	17090,46	130,73	5,5 %
PB Slabs	40800,13	27553,34	32694,39	2756047,35	1660,13	5,1 %
PB Roof	12728,11	8524,68	10304,53	277618,62	526,90	5,1 %
Basement Floor	40800,13	27553,34	32694,39	2756047,35	1660,13	5,1 %
Basement Walls	19851,80	12191,03	15542,81	776262,98	881,06	5,7 %
Cladding	3842,51	1869,64	2720,85	67326,85	259,47	9,5 %
Concrete Balcony	23421,14	15540,31	18953,18	967886,49	983,81	5,2 %
Concrete Beam	5331,05	1001,24	2524,19	274647,33	524,07	20,8 %
Concrete Column	6767,01	1421,54	3161,35	419165,91	647,43	20,5 %
Concrete Internal Walls	58738,69	40009,22	49595,05	6452369,75	2540,15	5,1 %
Concrete Stairs	3064,57	2064,56	2524,57	16580,91	128,77	5,1 %
Concrete Walls Elevator	2860,53	1830,80	2305,41	17078,66	130,69	5,7 %
Glazing Balcony	20413,67	12992,34	16056,99	818791,47	904,87	5,6 %
Glazing stairs	1640,04	1041,39	1310,65	5589,45	74,76	5,7 %
GLT Beam	277,62	130,96	193,99	346,37	18,61	9,6 %
Hollow Core Slabs - Floor	93362,60	61168,00	76530,61	15436037,43	3928,87	5,1 %
Hollow Core Slabs - Roof	12347,15	8467,10	10200,12	270863,08	520,45	5,1 %
Hollow Core Slabs - Roof Basement	12728,11	8524,68	10304,53	277618,62	526,90	5,1 %
Insulation External Walls	5413,06	3770,93	4511,90	54233,55	232,88	5,2 %
Insulation Floors	1724,45	1148,73	1413,41	5262,34	72,54	5,1 %
Insulation Inner Walls	28,70	19,22	23,60	1,43	1,20	5,1 %
Insulation Internal Walls	2186,97	1465,50	1795,76	8609,35	92,79	5,2 %
Particleboard	118,27	54,69	82,13	71,22	8,44	10,3 %
Plaserboard Internal Walls	8661,45	4335,55	5945,81	302535,43	550,03	9,3 %
Plasterboard Basement	80,63	39,35	58,17	28,50	5,34	9,2 %
Plasterboard External Walls	2417,75	1146,14	1652,41	23656,95	153,81	9,3 %
Steel Beams	14047,10	6845,87	10095,90	950456,03	974,91	9,7 %
Steel Columns	42360,63	19070,48	28653,56	7656907,14	2767,11	9,7 %
Structural timber	4086,38	2064,52	2916,00	73006,11	270,20	9,3 %
Wapor Barrier	686,09	354,27	500,24	2195,64	46,86	9,4 %
XPS insulation	1750,77	366,06	770,70	26268,86	162,08	21,0 %

Figure 22: Result from the uncertainty calculation for the concrete building.

4.3 Sensitivity analysis

Parameters that have the greatest sensitivity ratio, and thus have the largest influence on the total emissions are represented in table 8 and 9 which show the results from the sensitivity analysis.

4.3.1 Wooden building

Table 8: Parameters investigated in the sensitivity analysis and the associated variations, sensitivity ratio and relative change in result.

Parameter	**Variation**	Sensitivity ratio	Change in total emission result from base case
Reinforced Concrete	+ 25 %	0,048	4,5 %
Plasterboard	+ 25 %	0,014	1,4 %
Glazing	+ 25 %	0,018	1,7 %
Insulation	+ 25 %	0,012	1,1 %
Glued laminated timber	+ 25 %	0,134	11,8 %

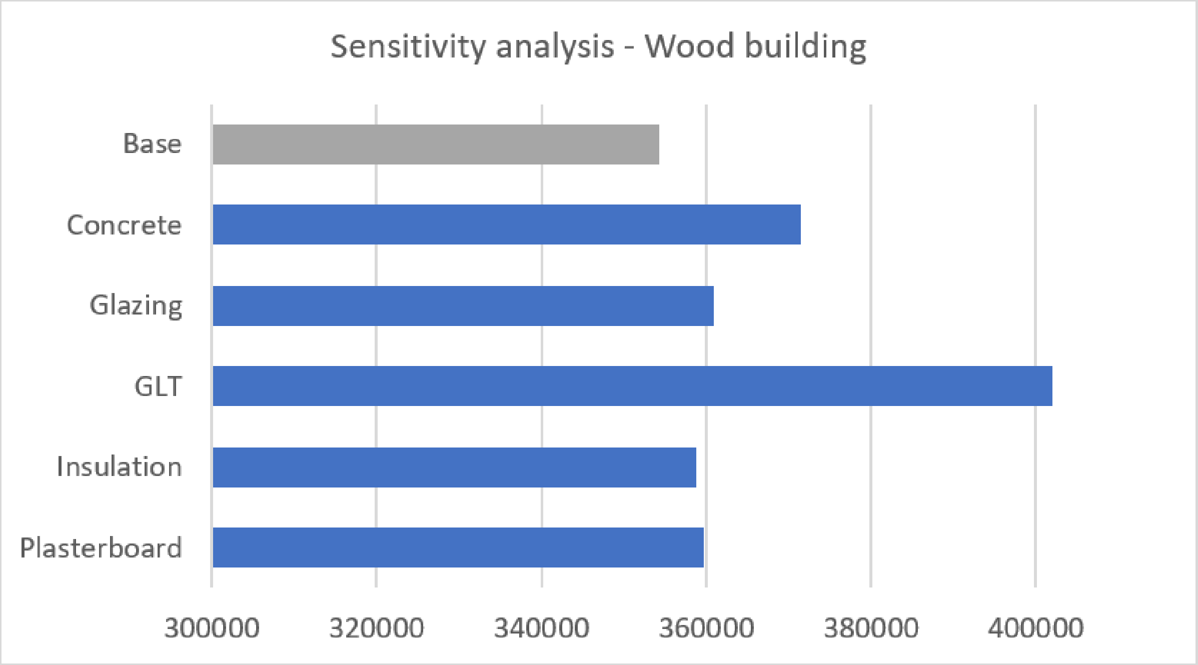


Figure 23: Emission results from sensitivity analysis – Wood building.

4.3.2 Concrete building

The reinforced concrete is the material in the concrete building with the largest sensitivity to

Table 9: Parameters investigated in the sensitivity analysis and the associated variations, sensitivity ratio and relative change in result.

Parameter	**Variation**	Sensitivity ratio	Change in total emission result from base case
Reinforced Concrete	+ 25 %	0,17	14,4 %
Plasterboard	+ 25 %	0,013	1,3 %
Glazing	+ 25 %	0,019	1,9 %
Insulation	+ 25 %	0,012	1,2 %
Glued laminated timber	+ 25 %	0,000	0,0 %

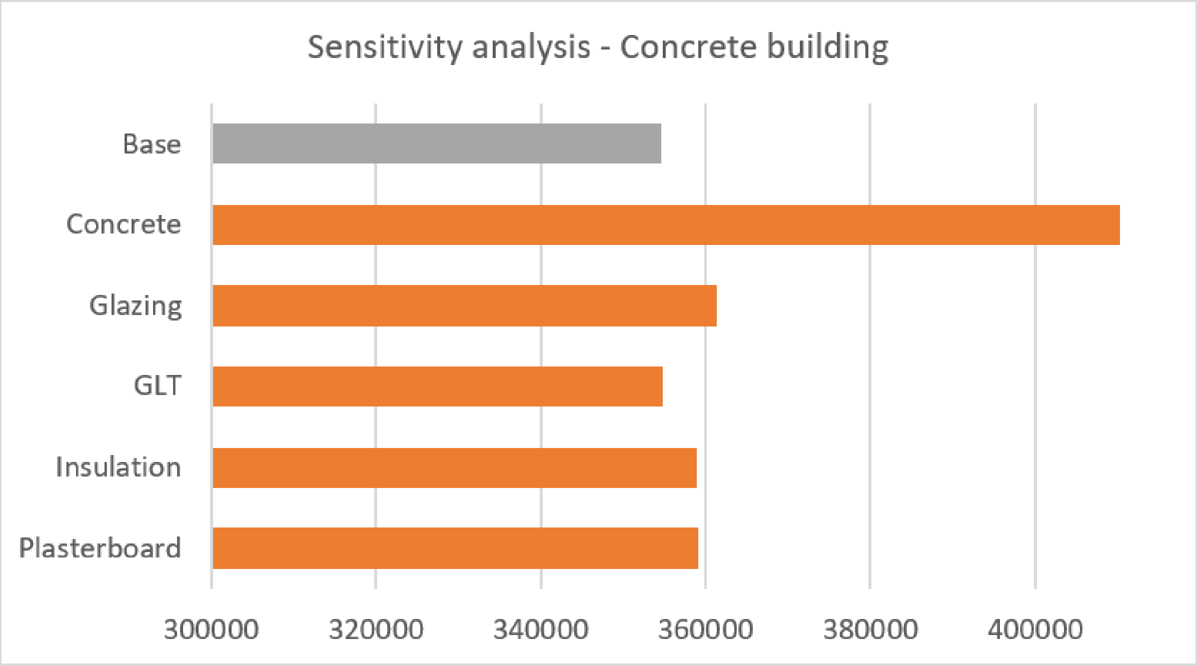


Figure 24: Emission results from sensitivity analysis – Concrete building.

5 Discussion

Life cycle assessment (LCA) is a well established tool for assessing the environmental impact of buildings, but the use of different functional units and system boundaries significantly affect the results. The importance of a clear scope and goal of the study becomes more important for such studies where several different functional units are being used.

Total emissions from the wooden building was found to be 354242,3 kg CO2-eq with the Arda calculation and 185 768,4 kg CO2-eq. The Arda calculation is higher then Skullestad, Bohne and Lohne (2016b) and Rønning et al. (2019), lower then Malmqvist et al. (2018a) and around the same result as Hofmeister et al. (2015). Differences in included building elements and system boundaries, makes it impossible to compare the buildings and come with a common result. Equal system boundaries are crucial to be able to compare different studies.

Total emissions from the concrete building was found to be 354 644,5 kg CO2-eq for the Arda calculation and 302 290,4 kg CO2-eq for the EPD calculation. The Arda calculation is lower then Skullestad, Bohne and Lohne (2016b), Hofmeister et al. (2015) and Malmqvist et al. (2018a), while its much higher then Rønning et al. (2019). All systems have different system or physical boundaries and uses different functional units. All studies does however use the same lifetime of buildings of 60 years and include the product phase of the buildings.

The sensitivity analysis for both buildings show that the result are sensitive to changes in the main building material. This correlates with the fact that both GLT and reinforced concrete are the materials that contribute the most to the total emissions from the buildings. Both of these materials contribute to more than 40% of the total emissions in both buildings and for both calculation methods. Including more of the building inventory would reduce the sensitivity for GLT and reinforced concrete.

Rønning et al. (2019) have three concrete options while only one wood option are studied. Two of the concrete solutions have been optimized or adjusted by communicating with architects or building engineers. Showing that its possible to decrease the embodied emissions from materials by communication in the design phase of the buildings. For the case studies no such communication was conducted, while structural adjustments to the inventory was made. Such adjustments will have large uncertainties when not performed by skilled professionals.

The results on a 3-digit building element resolution show the importance of having a as high resolution as possible to see the contribution from specific building elements and materials. Results on a 2-digit resolution can contain building elements having significantly different impacts. A higher resolution does however require more resources for the LCI and a extensive knowledge of the case object. However, the overall result of the study might not be greatly affected by a higher resolution for all building elements. Performing LCA is an iterative process where the resolution of the study can be continuously increased as the largest contributors become visible. The conducted LCAs do not include all building elements or life cycle phases and is thus not a complete LCA.

The biggest contributor is the slabs in the buildings. The gravel amounts in the slabs in the wood building is associated with a high uncertainty regarding the inventory parameter. This uncertainty is not included in the study, but the uncertainty associated with the emission intensity of gravel is low according to the uncertainty analysis. Including the uncertainty in the inventory data would increase the overall uncertainty of the model, but seeing that the uncertainties are small from the beginning, the inventory uncertainties would have to be significant to have a major impact on the systems uncertainty

EPDs can be easily used to compare the same products and materials from different producers, but there are no easily available programs for using EPDs in the calculation of the environmental impact of larger systems that consist of a number of EPDs. Using EPDs to calculate the impact from such systems is therefor a very time consuming method even though the EPDs themselves are easily available.

In this study all calculations have been done manually in Excel. Utilizing a LCA tool with a uncertainty calculation method would significantly reduce the labour intensity of the work. If the EPD calculations have small uncertainties it is evident that using EPD instead of generic data will greatly impact the result of your study.

5.1 Uncertainties and limitations

The assumed mistakes found in the given inventory was not discussed with anyone who had extensive knowledge of the case objects. All corrections made was based on literature and no third part was used to check any of the calculations. All assumptions regarding calculated building elements are therefor assigned high uncertainties. Building engineers and architects would have to be included in the work to improve the inventory and adjust material amounts for both buildings.

Incompleteness of the inventory have made it difficult to find and use the correct material inputs to the model. It is evident that communication between building engineers and architects, who make the inventory, and people conducting the LCA is a crucial part reducing uncertainties in the LCA.

Much time was used on fixing mistakes and completing the inventory of the case objects instead of focusing on building a robust model. At current point both inventory and model uncertainties are large. LCA is an iterative process and the focus when starting an LCA should be on building a robust model before focusing on completing and reducing uncertainties in the inventory.

This study use both generic data and EPDs to calculate the environmental impact of the buildings, but a average value is calculated and used in the EPD inventories. Using a average value will increase the uncertainty in the results, but the first focus should be on improving the building inventories and material information before utilizing more specific EPDs in the inventories. It is not possible to choose more specific EPDs without more information.

5.2 Further work

Several aspects on the field of performing LCAs for the purpose of material choices needs further work, and one of them is determining the placement of system boundaries and how this should be conducted. The link between making the inventory and source of LCA background data, either it is generic data or EPDs, is a important step towards making more robust models, reducing the use of general conversion factors.

Further work should be done on getting a complete inventory and including all building elements in both buildings. Such work should be conducted in communication with architects and building engineers to ensure correct inventory values for all building parts.

More building life-cycle modules should be included, especially transportation of materials and products (A4) to construction site as transportation is associated with large emissions. Including a more materials and products increase the importance of including replacements (B4).

Using generic background data for the materials increases the uncertainties in the results. Utilizing specific product EPDs will reduce the emissions uncertainties and increase the comparability to real life scenarios.

Changing the building material can also change the energy requirements of the building. Further research should incorporate equal energy requirements for the buildings for them to be comparable.

6 Conclusion

This study was conducted to better understand how the building materials wood and concrete can be used in the most environmentally friendly way. How these materials impact the life cycle assessment results of a building is a crucial step towards finding the best material combinations to minimize the environmental impact of buildings. The goal of the study have been to find the impact of changing the material choices in buildings, and to find the elements that have the largest contribution to climate change. As a starting point for the project, a literature study was performed to collect information on existing LCA studies of buildings. To research the impact of different building elements an LCA have been conducted on two case objects part of the Norwegian Zero Emission Research Centre by using an appropriate structure of inventory and modelling framework.

Although three out of four literature's reviewed in this study have concluded with a reduction in the environmental impact of a building when choosing a wooden structure instead of concrete in their respective studies, it is clear that the results can't be generalized for all buildings or building elements. Contextual parameters and boundaries highly impact the total impact result of the study. The effect of changing the materials is thus not clear.

Through the LCA conducted in this study it is possible to say that the building elements accounting for the larges volumes and weight also account for the largest environmental impacts. The floor structures of buildings not having load bearing external or internal walls will be a large contributor to the total environmental impact of the building. For the case studies, the prefabricated floor structures in both buildings accounted for the largest impact and had the highest sensitivity to total emissions.
This study show that including a uncertainty analysis can be very time consuming. The results also show that the uncertainties of EPDs are small and that EPDs is a great source for inventory data.

References

Baek, C.-Y., Tahara, K. and Park, K.-H. (2018) Parameter Uncertainty Analysis of the Life Cycle Inventory Database: Application to Greenhouse Gas Emissions from Brown Rice Production in IDEA, *Sustainability*, 10, p. 922. Available at: https://doi.org/10.3390/su10040922.

Bamber, N. et al. (2020) Comparing sources and analysis of uncertainty in consequential and attributional life cycle assessment: review of current practice and recommendations, *The International Journal of Life Cycle Assessment*, 25(1), pp. 168 –180. Available at: https://doi.org/10.1007/s11367-019-01663-1 (Accessed: 18/03/2020).

Borghi, A. Del (2013) LCA and communication: Environmental Product Declaration, *The International Journal of Life Cycle Assessment*, 18, Available at: https://doi.org/10.1007/s11367-012-0513-9.

British Plastics Federation (BPF) (n/a) *Polyethylene (Low Density) LDPE, LLDPE*. Available at: https://www.bpf.co.uk/plastipedia/polymers/LDPE.aspx (Accessed: 01/12/2019).

Buyle, M., Braet, J. and Audenaert, A. (2013) Life cycle assessment in the construction sector: A review, *Renewable and Sustainable Energy Reviews*, 26, pp. 379 – 388. Available at: https://doi.org/10.1016/j.rser.2013.05.001 (Accessed: 22/01/2020).

Byggforsk (2014) *523.251 Bindingsverk av tre i småhus. Dimensjonering og utførelse*. Available at: https://www.byggforsk.no/dokument/358/bindingsverk_av_tre_i_smaahus_dimensjonering_og_utfoerelse (Accessed: 06/01/2020).

Chau, C. K., Leung, T. M. and Ng, W. Y. (2015) A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings, *Applied Energy*, 143, pp. 395 –413. Available at: https://doi.org/10.1016/j.apenergy.2015.01.023 (Accessed: 2019).

Ciroth, A. et al. (2016) Empirically based uncertainty factors for the pedigree matrix in ecoinvent, *The International Journal of Life Cycle Assessment*, 21(9), pp. 1338–1348. Available at: https://doi.org/10.1007/s11367-013-0670-5 (Accessed: 09/04/2020).

Cobb, J. (2017) *NEPD-1260-406-EN: Gyproc (R) Normal - Standard plasterboard*. in Saint-Gobain Gyproc AS. Available at: https://www.gyproc.no/sites/gypsum.nordic.master/files/gyproc-site/document-files/Environmental-NO/NEPD-1260-406-Gyproc-Normal.pdf (Accessed: 06/01/2020).

Collins, F. (2010) Inclusion of carbonation during the life cycle of built and recycled concrete: influence on their carbon footprint, *The International Journal of Life Cycle Assessment*, 15(6), pp. 549–556. Available at: https://doi.org/10.1007/s11367-010-0191-4 (Accessed: 13/12/2019).

Dokka, T. H. et al. (2013) *A zero emission concept analysis of an office building*. (ZEB Project report No. 8). Oslo: SINTEF Academic Press. Available at: https://www.sintefbok.no/contents/index/30 (Accessed: 03/01/2020).

During, O. and Erlandsson, M. (2017) *NEPD-1299-419-SE: Betong för sandwichvägg*. in Svensk Betong. Available at: https://www.epd-norge.no/getfile.php/137271-1490684288/EPDer/Byggevarer/Betongvarer/NEPD-1299-419_Betong-f--r-sadwishv--gg.pdf (Accessed: 06/01/2020).

European Commmision (2010) *Energy Performance of Buildings Directive*. Available at: https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en.

FN-sambandet (2018) *Klimaendringer*. Available at: https://www.fn.no/Tema/Klima-og-miljoe/Klimaendringer (Accessed: 20/10/2018).

Fufa, S. M. et al. (2016) *A Norwegian ZEB Definition Guideline*. (ZEN Report No. No. 12): SINTEF Academic Press. Available at: https://www.zeb.no/index.php/en/news-and-events/256-a-norwegian-zeb-definition-guideline (Accessed: 02/10/2019).

Fuglseth, M. et al. (2018) *Utredning av livsløpsbaserte miljøkrav i TEK*. Sandvika, Norge: Asplan Viak.

Geng, S. et al. (2017) Building life cycle assessment research: A review by bibliometric analysis, *Renewable and Sustainable Energy Reviews*, 76, pp. 176 –184. Available at: https://doi.org/10.1016/j.rser.2017.03.068.

Global Alliance for Buildings and Construction, International Energy Agency and the United Nations Environment Programme (2019) *2019 global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector*:

Grusbutikken (n/a) *BEREGN SINGEL 8-16 MM*. Available at: https://www.grusbutikken.no/shop/maengd-beraeknar.asp?groupid=59&productid=793 (Accessed: 01/12/2019).

Hofmeister, T. B. et al. (2015) *Life cycle GHG emissions from a wooden load-bearing alternative for a ZEB office concept*. (ZEB Project report No. 20). Oslo: SINTEF Academic Press. Available at: https://www.sintefbok.no/book/index/1040 (Accessed: 16/03/2020).

IPCC (2013) Summary for Policymakers, in [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]

Climate Change 2013: The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. Pp. 1 –30.

IPCC (2014) Buildings, in [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J. C. Minx (eds.)] *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. Pp. 671 –738.

Kermit, P. H. and Mælen, J. (2019) *NEPD-1860-798-NO: Contiga, Hulldekke Lavkarbon A, X-treme*. in Contiga AS. Available at: `https://www.epd-norge.no/getfile.php/1311189-1569435263/EPDer/Byggevarer/Betongvarer/NEPD-1860-798_Contiga--Hulldekker-Lavkarbon-A--X-treme.pdf` (Accessed: 06/01/2020).

Knutsen, W. and Thomassen, O. M. (2016) *NEPD-1203-373-NO: Hulldekker - forspent dekke/etasjeskille av betong*. in Jaro AS. Available at: `https://www.epd-norge.no/getfile.php/138318-1512988323/EPDer/Byggevarer/Betongvarer/NEPD-1203-373_Hulldekker-HD265_1_1_1_1_1_1.pdf` (Accessed: 06/01/2020).

Kristjansdottir, T. F. et al. (2018) Is a net life cycle balance for energy and materials achievable for a zero emission single-family building in Norway?, *Energy and Buildings*, 168, pp. 457 –469. (Accessed: 23/01/2019).

Lausselet, C. et al. (2019) A life-cycle assessment model for zero emission neighborhoods, *Journal of Industrial Ecology*, 24(3), pp. 1–17. Available at: `https://doi.org/10.1111/jiec.12960` (Accessed: 16/03/2020).

Løvseth, M. (2019) *Hvordan realisere byggesystemet*. Available at: `https://static1.squarespace.com/static/5847ec32f7e0ab24d33879db/t/5c7d344df4e1fc6a4a8f470c/1551709267126/4_Realisere+byggesystemet_L\%C3\%B8vseth_Frokostseminar+20190213.pdf` (Accessed: 03/11/2019).

Løvseth+Parner (n/a) *WOODSOL and ZEN*. Available at: `http://lovsethpartners.no/?portfolio=woodsol-and-zen` (Accessed: 16/01/2020).

Majeau-Bettez, G. and Strømman, A. H. (2016) *Documentation for Arda Calculator, version XXXX*.

Malmqvist, T. et al. (2018a) *Minskad klimatpåverkan från flerbostadshus - LCA av fem byggsystem*. Stockholm, Sverige: Sveriges Byggindustrier. Available at: `https://cms.betongarhallbart.se/wp-content/uploads/2018/11/minskad-klimatpaverkan-flerbostadshus_180910_aho.pdf` (Accessed: 03/10/2019).

Malmqvist, T. et al. (2018b) Design and construction strategies for reducing embodied impacts from buildings – Case study analysis, *Energy and Buildings*, 166, pp. 35 –47. Available at: http://www.sciencedirect.com/science/article/pii/S0378778817321576 (Accessed: 24/10/2019).

Muller, S. et al. (2014) The application of the pedigree approach to the distributions foreseen in ecoinvent v3, *International Journal of Life Cycle Assessment*, 21(9), pp. 1327 –1337. Available at: https://doi.org/10.1007/s11367-014-0759-5 (Accessed: 15/04/2020).

Norman, J., MacLean, H. L. and Kennedy, C. A. (2006) Comparing High and Low Residential Density: Life-Cycle Analysis of Energy Use and Greenhouse Gas Emissions, *Journal of Urban Planning and Development*, 132(1), pp. 10 –21. Available at: https://doi.org/10.1061/(ASCE)0733-9488(2006)132:1(10).

Norwegian Ministry of Climate and Environment (2018) *Norway's Seventh National Communication*: Available at: https://unfccc.int/files/national_reports/annex_i_natcom/submitted_natcom/application/pdf/529371_norway-nc7-br3-1-nc7_-_br3_-_final.pdf (Accessed: 07/11/2019).

Olavsen, A. V. and Henriksen, F. (2019) *NEPD-1760-707-NO: Hulldekke Lavkarbon B*. in Norland Betongelement AS. Available at: https://www.epd-norge.no/getfile.php/1310314-1555405790/EPDer/Byggevarer/Betongvarer/NEPD-1760-707_Hulldekke-Lavkarbon-B.pdf (Accessed: 06/01/2020).

Ortiz, O., Castells, F. and Sonnemann, G. (2009) Sustainability in the construction industry: A review of recent developments based on LCA, *Construction and Building Materials*, 23(1), pp. 28 –39. Available at: https://doi.org/10.1016/j.conbuildmat.2007.11.012.

Research center on Zero Emission Buildings (2017) *Om ZEB*. Available at: https://www.zeb.no/index.php/no/om-zeb/about-the-zeb-centre (Accessed: 10/08/2019).

Research centre on Zero Emission Neighbourhoods (2017) *Om ZEN*. Available at: https://fmezen.no/about-us/ (Accessed: 10/08/2019).

Ricardo, J. (2003) *Simulasión 4.0*. Available at: https://ucema.edu.ar/~jvarela/index_eng.htm (Accessed: 27/04/2020).

Robertson, A., Lam, F. and Cole, R. (2012) A Comparative Cradle-to-Gate Life Cycle Assessment of Mid-Rise Office Building Construction Alternatives: Laminated Timber or Reinforced Concrete, *Buildings*, 2, pp. 245 –270. Available at: https://doi.org/10.3390/buildings2030245 (Accessed: 07/11/2019).

Rønning, A. and Tellnes, L. G. F. (2018) *Blir det bedre bygg ved bruk av LCA? Gjennomgang av noen utvalgte LCA studier*. No. OR.42.18): Østfoldforskning. Available at:

https://www.betongelement.no/siteassets/dokumenter/or-42.18-lca_review-bygg.pdf (Accessed: 20/08/2020).

Rønning, A. et al. (2019) *Klimagassregnskap av tre- og betongkostruksjoner*. (OR.26.19: Østfoldforskning. Available at: https://www.betongelement.no/siteassets/dokumenter/or-26-19-klimagassregnskap-av-tre--og-betongkonstruksjoner.pdf (Accessed: 20/08/2020).

Sandberg, Nina Holck et al. (2017) Using a segmented dynamic dwelling stock model for scenario analysis of future energy demand: The dwelling stock of Norway 2016–2050, *Energy and Buildings*, 146, pp. 220 –232. Available at: http://www.sciencedirect.com/science/article/pii/S0378778816308830.

Simapro Help Center (2020) *5 Features Every SimaPro User Should Know*. Available at: https://support.simapro.com/articles/Article/5-Features-Every-SimaPro-User-Should-Know# (Accessed: 19/05/2020).

Skaar, C. and Rønning, A. (2014) *NEPD00274N: Forestia Sponplater*. in Forestia AS. Available at: http://media.byggtjeneste.no/media/dokument/285983 (Accessed: 06/01/2020).

Skullestad, J. L., Bohne, R. A. and Lohne, J. (2016a) High-rise Timber Buildings as a Climate Change Mitigation Measure – A Comparative LCA of Structural System Alternatives, *Energy Procedia*, 96, pp. 112 –123. Available at: http://www.sciencedirect.com/science/article/pii/S1876610216307512 (Accessed: 15/10/2019).

Skullestad, J. L., Bohne, R. A. and Lohne, J. (2016b) High-rise Timber Buildings as a Climate Change Mitigation Measure – A Comparative LCA of Structural System Alternatives, *Energy Procedia*, 96, pp. 112 –123. Available at: http://www.sciencedirect.com/science/article/pii/S1876610216307512 (Accessed: 15/10/2019).

Stamatopoulos, H. and Malo, K. A. (2018) Wood frame solutions for free space design in urban buildings (WOODSOL), Växjö, Sweden: Available at: https://www.researchgate.net/publication/327652055_Wood_frame_solutions_for_free_space_design_in_urban_buildings_WOODSOL (Accessed: 22/11/2019).

Standard Norge (2006a) *NS-EN ISO 14040:2006 - Environmental management - Life cycle assessment - Principles and framework*. Available at: https://www.standard.no/no/Nettbutikk/produktkatalogen/Produktpresentasjon/?ProductID=195483 (Accessed: 20/11/2019).

Standard Norge (2010) *NS-EN ISO 14025:2010 - Environmental labels and declarations - Type III environmental declarations - Principles and procedures*. Available at: https://www.standard.no/no/Nettbutikk/produktkatalogen/Produktpresentasjon/?ProductID=438649 (Accessed: 21/11/2019).

Standard Norge (2018a) *NS 3720:2018 - Method for greenhouse gas calculations for buildings*. Available at: https://www.standard.no/no/Nettbutikk/produktkatalogen/Produktpresentasjon/?ProductID=1030812 (Accessed: 21/11/2019).

Standard Norge (2019a) *NS 3451:2009+A1:2019 - Table of building elements*. Available at: https://www.standard.no/no/Nettbutikk/produktkatalogen/Produktpresentasjon/?ProductID=1107100 (Accessed: 01/12/2019).

Steine, O. Å. and Larsen, L. (2017) *NEPD-1477-495-NO: Byggimpuls fiberbetong fasadeelementer M4.Norregaard.* in Byggimpuls AS. Available at: https://www.epd-norge.no/getfile.php/138343-1513714258/EPDer/Byggevarer/Betongvarer/NEPD-1477-495_Byggimpuls-fiberbetong-fasadeelemeter-M-4-Norregaard_1.pdf (Accessed: 06/01/2020).

The Norwegian EPD Federation (2019) *General Programme Instructions for The Norwegian EPD Foundation/EPD-Norge*. No. 3). Oslo, Norway: EPD Norge. Available at: https://www.epd-norge.no/getfile.php/1310675-1560232266/Dokumenter/GPI\%20Det\%20norske\%20EPD\%20programmet\%20med\%20vedlegg\%20approved240419.pdf (Accessed: 23/08/2020).

Thue, J. V. (2019) *Glassull*. Available at: https://snl.no/glassull (Accessed: 01/12/2019).

UNFCCC (2018) *The Paris Agreement*. Available at: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (Accessed: 22/11/2018).

Vinje, L., Wilberg, J. and Alexander, S. (2010) *Betongelementboken*. Oslo: Betongelementforeningen.

Weidema, B. P. et al. (2013) *Overview and methodology - Data quality guideline for the ecoinvent database version 3*. (3 No. 1). St. Gallen: Ecoinvent Centre. Available at: https://www.ecoinvent.org/files/dataqualityguideline_ecoinvent_3_20130506.pdf (Accessed: 23/03/2020).

Wiik, M. K. et al. (2018) Lessons learnt from embodied GHG emission calculations in zero emission buildings (ZEBs) from the Norwegian ZEB research centre, *Energy and Buildings*, 165, pp. 25–34. Available at: https://doi.org/10.1016/j.enbuild.2018.01.025 (Accessed: 14/03/2020).

Østnor, T., Faanes, S. and Lædre, O. (2018) Laminated timber versus on-site cast concrete: a comparative study. Chennai, India: Available at: http://doi.org/10.24928/2018/0313 (Accessed: 22/11/2019).

Østrem, O. G. and Skårland, T. (2019) *NEPD-1870-807-NO: Hulldekke lavkarbon A.* in Block Berge Bygg AS. Available at: https://www.epd-norge.no/getfile.php/1311097-1568718363/EPDer/Byggevarer/Betongvarer/NEPD-1870-807_Hulldekke--lavkarbon-A.pdf (Accessed: 06/01/2020).

Appendices

A NS3451:2009 - Table of building elements

Table 10: The minimum requirement of main building elements specified on a 2-digit level (column 2), that are to be included in a GHG calculation according to the standard NS3451:2009 (Standard Norge, 2019a)

1-digit building element number	**2-digit building element number** *minimum requirement for a comprehensive GHG emission calculation according to the standard*	**3-digit building element number** *example on detailing that is not required but should be given if possible*
2 Building	20 Building general	
	21 Ground and foundation	211 Preperation of site 212 Construction pit 213 Ground reinforcement 214 Supporting construction [...]
	22 Load-bearing systems	221 Frames 222 Columns 223 Beams 224 Bracing constructions [...]
	23. External walls	231 Load-bearing external walls 232 Non-load-bearing external walls 233 Glass facades 234 Windows, doors and gates 235 Outside cladding and surfacing 236 Inside surfacing [...]
	24 Internal walls	241 Load-bearing internal walls 242 Non-load-bearing internal walls 243 System walls 244 Windows doors, folding walls

Table 10 continued from previous page

1-digit building element number	2-digit building element number	3-digit building element number
		245 Skirt 246 Cladding and surface [...]
	25 Slabs	251 Cantilevered slabs 252 Floor on ground 253 Raised floor, screeds 254 Floor systems 255 Floor surface [...]
	26 Roof	261.AB Primary structures 262 Roofing 263 Glass roof, skylight, sunroof 264 Roof structures 265 Cornies, gutters and down-pipes 266 Ceilings and inside surfacing 267 Prefabricated roof elements [...]
	27 Fixed inventory	271 Bricked pipes and fireplaces 272 Assembly-ready fireplaces [...]
	28 Stairs, balconies, etc.	281 Internal staris 282 External stairs 283 Ramps 284 Balconies and verandas [...]

B Floor plans of wood building

The next three pages show the floor plans for the wood building. The drawings are made by Løvseth+Partner for the research project Woodsol, retrived from Løvseth (2019).

Page VIII - 2. - 8. floor

Page IX - Ground floor

Page X - Parking basement


19150
5950
7050
6150
2400
1150
2400
2400
2250
2400
2400
1350
2400
1
2
3
4
5
6
7
8
9
10
11
D
C
B
A
2205
225
7340
12690
5350
225
BALKONG
7.8 m²
BALKONG
9.8 m²
BALKONG
12.6 m²
29.02.001
29.01.003
DETALJ I 1 ETG.
29.02.005
28.02.001
29.T.001
DETALJ I 8 ETG.
28.02.005
KJØK/STUE
29.7 m²
KJØK/STUE
21.5 m²
SOV
8.9 m²
29.02.101
KJØK/STUE
30.7 m²
29.02.115
T
BAD
5.0 m²
BOD
4.1 m²
BOD
4.2 m²
NEDSENKET
HIMLING
ENTRE
4.6 m²
29.02.105
29.02.110
BAD
3.8 m²
BOD
4.5 m²
BAD
3.8 m²
EL-SKAP
29.02.120
29.02.110
28.02.101
NEDSENKET
HIMLING
ENTRE
12.6 m²
AKUSTISK
HIMLING
FEELES GANG
7.1 m²
NEDSENKET
HIMLING
ENTRE
9.0 m²
WC
1.6 m²
WC
1.6 m²
SOV
12.5 m²
SOV
7.3 m²
SOV
8.1 m²
SOV
8.1 m²
HEIS
SOV
12.4 m²
29.01.001
DETALJ I 1 ETG.
29.01.002
DETALJ I 1 ETG.
29.02.008

PLAN 2.-8. ETG.


1
2
3
4
5
6
7
8
9
10
11
D
C
B
A
TERRASSE
11.5 m²
TERRASSE
12.9 m²
TERRASSE
11.8 m²
SKILLEVEGG
29.01.003
2205
225
7340
12690
5350
KJØK/STUE
29.8 m²
KJØK/STUE
21.6 m²
SOV
8.9 m²
KJØK/STUE
30.9 m²
BOD
4.2 m²
NEDSENKET
HIMLING
ENTRE
4.6 m²
T
BAD
5.0 m²
EL-SKAP
BAD
3.8 m²
BOD
4.1 m²
BOD
4.5 m²
ENTRE
5.2 m²
BAD
3.8 m²
NEDSENKET
HIMLING
ENTRE
12.6 m²
AKUSTISK
HIMLING
FELLES GANG
18.3 m²
NEDSENKET
HIMLING
WC
1.6 m²
WC
1.6 m²
SOV
12.6 m²
SOV
7.4 m²
SOV
8.0 m²
POSTKASSER
SOV
12.8 m²
29.01.001
29.01.002
INNGANG

PLAN 1. ETG.

KJELLERPLAN

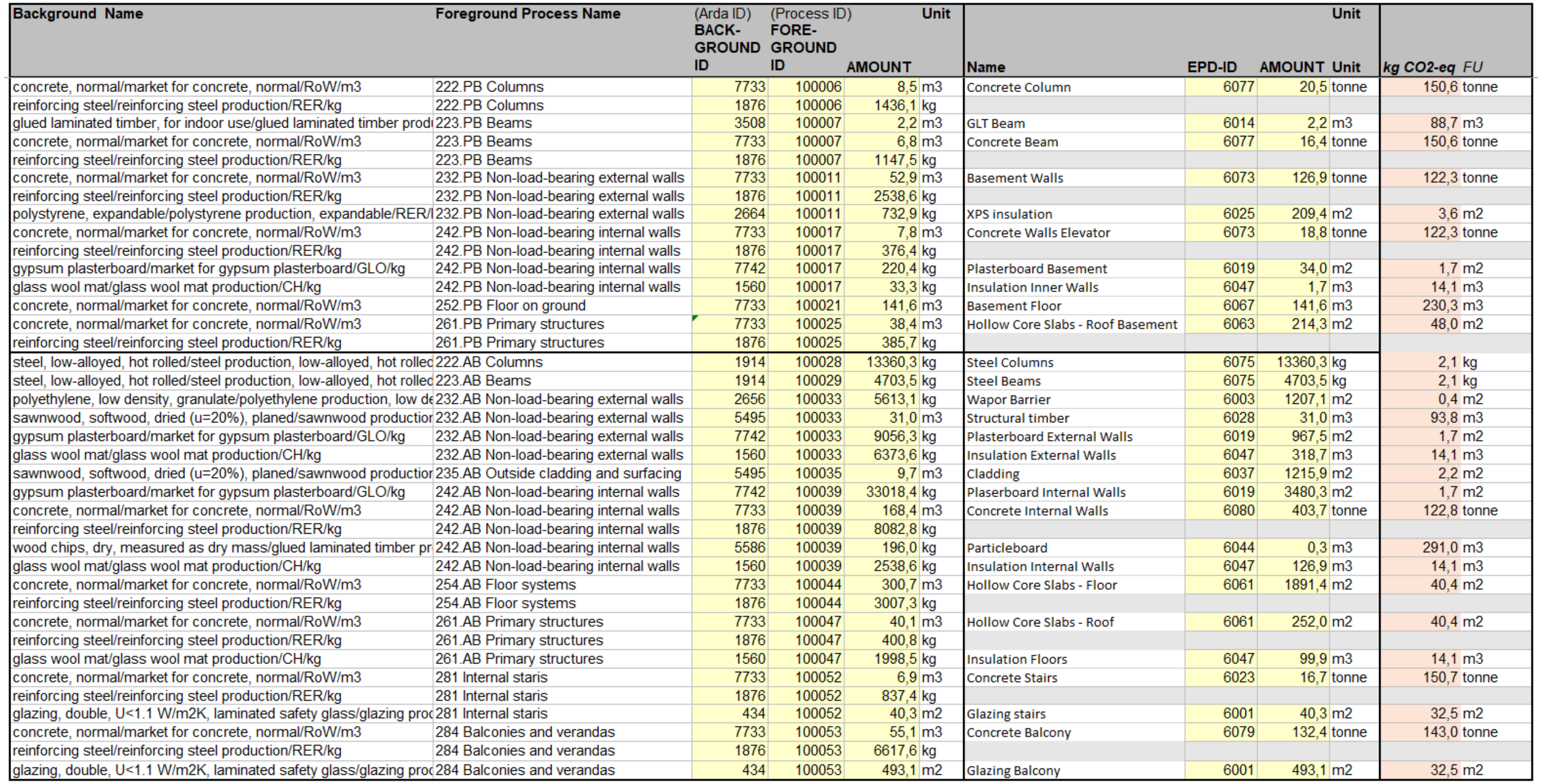
C Inventory data

The next two pages show the inventory data used to calculate the environmental impact from the buildings

Page V - Wood building

Page VI - Concrete building

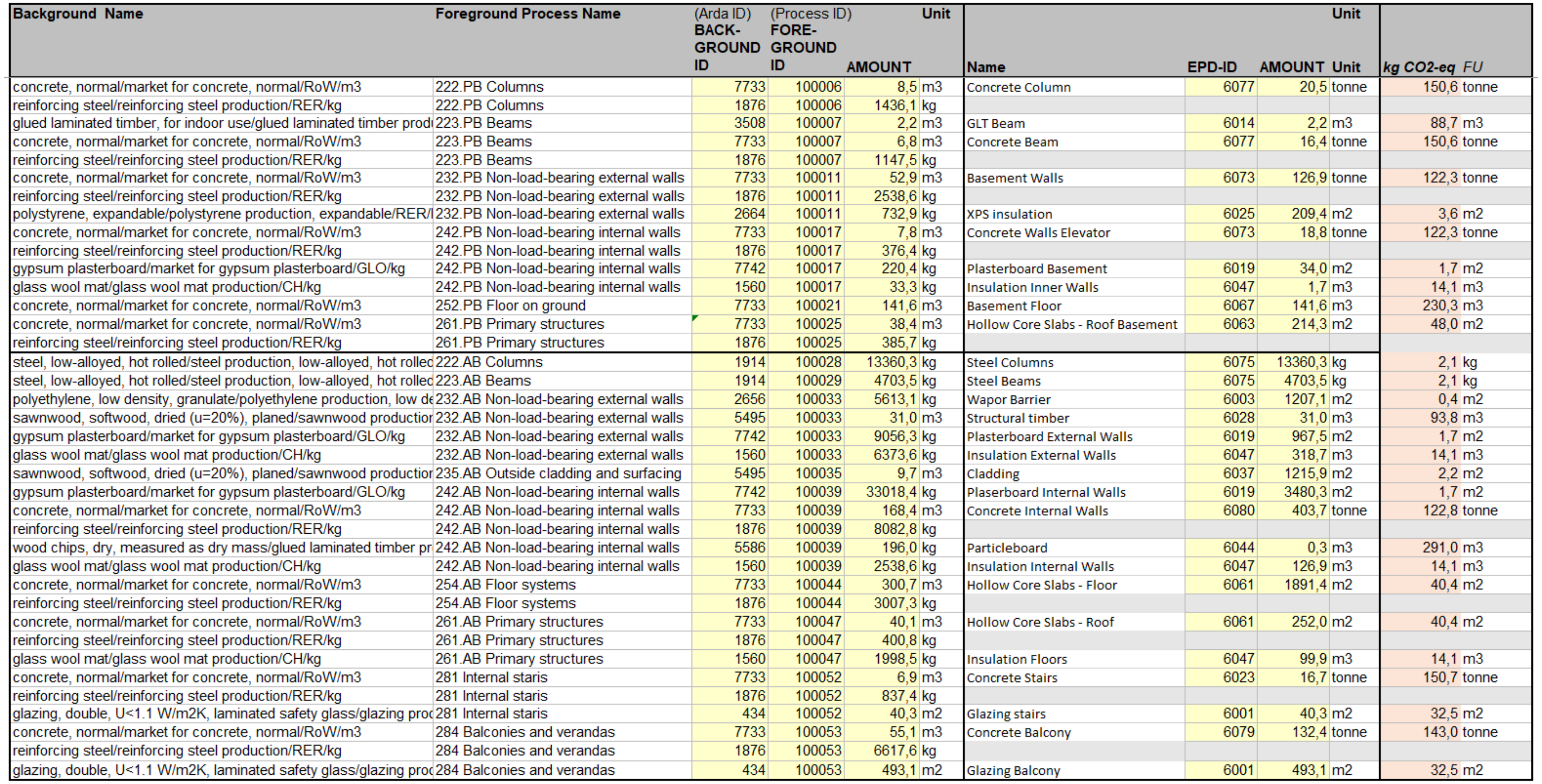
Wood building



Background Name	Foreground Process Name	(Arda ID) BACK-GROUND ID	(Process ID) FORE-GROUND ID		Unit				Unit		
				AMOUNT		Name	EPD-ID	AMOUNT	Unit	*kg CO2-eq*	*FU*
concrete, normal/market for concrete, normal/RoW/m3	222.PB Columns	7733	100006	8,5	m3	Concrete Column	6077	20,5	tonne	150,6	tonne
reinforcing steel/reinforcing steel production/RER/kg	222.PB Columns	1876	100006	1436,1	kg						
glued laminated timber, for indoor use/glued laminated timber prod	223.PB Beams	3508	100007	2,2	m3	GLT Beam	6014	2,2	m3	88,7	m3
concrete, normal/market for concrete, normal/RoW/m3	223.PB Beams	7733	100007	6,8	m3	Concrete Beam	6077	16,4	tonne	150,6	tonne
reinforcing steel/reinforcing steel production/RER/kg	223.PB Beams	1876	100007	1147,5	kg						
concrete, normal/market for concrete, normal/RoW/m3	232.PB Non-load-bearing external walls	7733	100011	52,9	m3	Basement Walls	6073	126,9	tonne	122,3	tonne
reinforcing steel/reinforcing steel production/RER/kg	232.PB Non-load-bearing external walls	1876	100011	2538,6	kg						
polystyrene, expandable/polystyrene production, expandable/RER/	232.PB Non-load-bearing external walls	2664	100011	732,9	kg	XPS insulation	6025	209,4	m2	3,6	m2
concrete, normal/market for concrete, normal/RoW/m3	242.PB Non-load-bearing internal walls	7733	100017	7,8	m3	Concrete Walls Elevator	6073	18,8	tonne	122,3	tonne
reinforcing steel/reinforcing steel production/RER/kg	242.PB Non-load-bearing internal walls	1876	100017	376,4	kg						
gypsum plasterboard/market for gypsum plasterboard/GLO/kg	242.PB Non-load-bearing internal walls	7742	100017	220,4	kg	Plasterboard Basement	6019	34,0	m2	1,7	m2
glass wool mat/glass wool mat production/CH/kg	242.PB Non-load-bearing internal walls	1560	100017	33,3	kg	Insulation Inner Walls	6047	1,7	m3	14,1	m3
concrete, normal/market for concrete, normal/RoW/m3	252.PB Floor on ground	7733	100021	141,6	m3	Basement Floor	6067	141,6	m3	230,3	m3
concrete, normal/market for concrete, normal/RoW/m3	261.PB Primary structures	7733	100025	38,4	m3	Hollow Core Slabs - Roof Basement	6063	214,3	m2	48,0	m2
reinforcing steel/reinforcing steel production/RER/kg	261.PB Primary structures	1876	100025	385,7	kg						
steel, low-alloyed, hot rolled/steel production, low-alloyed, hot rolled	222.AB Columns	1914	100028	13360,3	kg	Steel Columns	6075	13360,3	kg	2,1	kg
steel, low-alloyed, hot rolled/steel production, low-alloyed, hot rolled	223.AB Beams	1914	100029	4703,5	kg	Steel Beams	6075	4703,5	kg	2,1	kg
polyethylene, low density, granulate/polyethylene production, low de	232.AB Non-load-bearing external walls	2656	100033	5613,1	kg	Wapor Barrier	6003	1207,1	m2	0,4	m2
sawnwood, softwood, dried (u=20%), planed/sawnwood productior	232.AB Non-load-bearing external walls	5495	100033	31,0	m3	Structural timber	6028	31,0	m3	93,8	m3
gypsum plasterboard/market for gypsum plasterboard/GLO/kg	232.AB Non-load-bearing external walls	7742	100033	9056,3	kg	Plasterboard External Walls	6019	967,5	m2	1,7	m2
glass wool mat/glass wool mat production/CH/kg	232.AB Non-load-bearing external walls	1560	100033	6373,6	kg	Insulation External Walls	6047	318,7	m3	14,1	m3
sawnwood, softwood, dried (u=20%), planed/sawnwood productior	235.AB Outside cladding and surfacing	5495	100035	9,7	m3	Cladding	6037	1215,9	m2	2,2	m2
gypsum plasterboard/market for gypsum plasterboard/GLO/kg	242.AB Non-load-bearing internal walls	7742	100039	33018,4	kg	Plaserboard Internal Walls	6019	3480,3	m2	1,7	m2
concrete, normal/market for concrete, normal/RoW/m3	242.AB Non-load-bearing internal walls	7733	100039	168,4	m3	Concrete Internal Walls	6080	403,7	tonne	122,8	tonne
reinforcing steel/reinforcing steel production/RER/kg	242.AB Non-load-bearing internal walls	1876	100039	8082,8	kg						
wood chips, dry, measured as dry mass/glued laminated timber pr	242.AB Non-load-bearing internal walls	5586	100039	196,0	kg	Particleboard	6044	0,3	m3	291,0	m3
glass wool mat/glass wool mat production/CH/kg	242.AB Non-load-bearing internal walls	1560	100039	2538,6	kg	Insulation Internal Walls	6047	126,9	m3	14,1	m3
concrete, normal/market for concrete, normal/RoW/m3	254.AB Floor systems	7733	100044	300,7	m3	Hollow Core Slabs - Floor	6061	1891,4	m2	40,4	m2
reinforcing steel/reinforcing steel production/RER/kg	254.AB Floor systems	1876	100044	3007,3	kg						
concrete, normal/market for concrete, normal/RoW/m3	261.AB Primary structures	7733	100047	40,1	m3	Hollow Core Slabs - Roof	6061	252,0	m2	40,4	m2
reinforcing steel/reinforcing steel production/RER/kg	261.AB Primary structures	1876	100047	400,8	kg						
glass wool mat/glass wool mat production/CH/kg	261.AB Primary structures	1560	100047	1998,5	kg	Insulation Floors	6047	99,9	m3	14,1	m3
concrete, normal/market for concrete, normal/RoW/m3	281 Internal staris	7733	100052	6,9	m3	Concrete Stairs	6023	16,7	tonne	150,7	tonne
reinforcing steel/reinforcing steel production/RER/kg	281 Internal staris	1876	100052	837,4	kg						
glazing, double, U<1.1 W/m2K, laminated safety glass/glazing proc	281 Internal staris	434	100052	40,3	m2	Glazing stairs	6001	40,3	m2	32,5	m2
concrete, normal/market for concrete, normal/RoW/m3	284 Balconies and verandas	7733	100053	55,1	m3	Concrete Balcony	6079	132,4	tonne	143,0	tonne
reinforcing steel/reinforcing steel production/RER/kg	284 Balconies and verandas	1876	100053	6617,6	kg						
glazing, double, U<1.1 W/m2K, laminated safety glass/glazing proc	284 Balconies and verandas	434	100053	493,1	m2	Glazing Balcony	6001	493,1	m2	32,5	m2

Figure 25: Inventory of material inputs used as input data in Arda for the wood building.

Concrete building



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polyethylene, low density, granulate/polyethylene production, low de	232.AB Non-load-bearing external walls	2656	100033	5613,1	kg	Wapor Barrier	6003	1207,1	m2	0,4	m2
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glass wool mat/glass wool mat production/CH/kg	242.AB Non-load-bearing internal walls	1560	100039	2538,6	kg	Insulation Internal Walls	6047	126,9	m3	14,1	m3
concrete, normal/market for concrete, normal/RoW/m3	254.AB Floor systems	7733	100044	300,7	m3	Hollow Core Slabs - Floor	6061	1891,4	m2	40,4	m2
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glazing, double, U<1.1 W/m2K, laminated safety glass/glazing pro	284 Balconies and verandas	434	100053	493,1	m2	Glazing Balcony	6001	493,1	m2	32,5	m2

Figure 26: Inventory of material inputs used as input data in Arda for the concrete building.

NTNU
Norwegian University of
Science and Technology