Use of prefabricated building construction method to reduce construction waste and Global Warming Potential from residential buildings in Denmark

-Master thesis-

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7-01-2022

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Title:

Use of prefabricated building construction method to reduce construction waste And Global Warming Potential from residential buildings in Denmark

Project:

Master Thesis

Project period:

September 2021 – January 2022

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Pages:

Master thesis: 50
Appendix (pages): 4 (27)
Total page count: 77

Submission date:

7-01-2022

Synopsis:

Waste traditionally has been seen as an inevitable by-product of building construction. However, in the last decade an increasing number of new residential buildings has emerged, producing more construction waste and CO_2 emissions than ever. Therefore, a change of construction method is proposed, so the construction waste together with the CO_2 emissions are reduced.

Conventionally, building components are assembled directly on a building site. This method is widely known, but has several drawbacks considering material waste, building efficiency, and recycling of used building materials. Contrary, the buildings can be designed by prefabricated method, where the components are assembled in a factory and then delivered to the building site. This method provides a possibility to save, reuse, and recycle building materials as well as savings in construction time.

Previously, several studies have been made on traditional construction residential buildings, but fewer studies have been done on construction waste management and environmental impact of prefabricated residential buildings. So, this project aims to compare both aspects for two types of prefabricated residential buildings.

The construction waste analysis is performed based on total amount of construction materials used in prefabricated buildings and provic waste data from respective construct companies. The environmental impact analysis is performed in LCAbyg software for Global Warming Potential to recognize the emitted CO_2 amount.

Abstract

In the last decade, more buildings than ever have been built, therefore, construction waste and CO_2 emissions have drastically increased. The construction industry consumes the largest portion of material sources, and in exchange produces more than 1/3 of the total waste and CO_2 emissions in European Union. In Denmark the construction industry produces around 40% of the total waste, while also being responsible for more than half of CO_2 emissions. However, as the negative impacts rise, new approaches are needed for construction of residential buildings.

In general, there are two main methods to construct buildings - traditional on-site and prefabricated off-site method. Both methods have benefits and drawbacks, though it is unclear which method adapts better to the increasing construction waste and environmental impact problem. So, this master thesis provides a comparison between two types of prefabricated construction building complexes – concrete and timber – in connection to on-site construction method. The comparison between the prefabricated construction methods and on-site construction method is done for building waste quantities to see which construction type generates the most and least construction waste and which are the most frequently used construction materials. Then, an environmental impact measures are calculated through a life cycle assessment analysis for the most frequently used materials for the two prefabricated construction methods to identify which construction is more sustainable.

For the analyses, building material quantities from both prefabricated construction types are used as basis for further studies. The material quantities are estimated through building drawings, details, and material bills from the corresponding construction companies and from general building construction guidelines, material property specifications in Denmark. The information about construction waste quantities and waste sorting fractions is also acquired from the construction companies.

The waste analysis showed that concrete construction building complex generates less construction waste than timber construction building complex, 8.4% and 15.7%, respectively. The most waste for concrete construction is generated from combustible materials that are incinerated and concrete debris that is recycled. For timber construction the most waste comes from mixed materials that are recycled and wood that is also recycled. The on-site construction showed to have wide range of possible construction waste quantities, but generally 10% are accounted for it. So, the prefabricated concrete construction produces less waste and timber construction produces more waste than the on-site construction.

The environmental impact analysis for whole building life cycle showed that generally the concrete construction building complex has higher total Global Warming Potential than the timber construction building complex. However, the timber construction has higher Global Warming Potential during the construction stage. The highest Global Warming Potential for concrete construction comes from concrete and for timber construction – from timber as these are the most frequently used construction materials.

This research concluded that the prefabricated timber construction is more sustainable in long term than the prefabricated concrete construction because the construction materials can be easily reused, recycled, and recovered compared to the concrete construction materials.

Abbreviations

EU	European Union
CC	Concrete construction
CO_2	Carbon dioxide
CW	Construction Waste
GWP	Global Warming Protentional
LCA	Life Cycle Assessment
TC	Timber construction
WFD	Waste Framework Directive
WM	Waste Management

Contents

1 Introduction

Every year more buildings are constructed to accommodate rapidly growing population of the world. As human population increases, a consumption of various resources grows [1] [2]. In the last decade, an increasing number of residential buildings have emerged, producing more construction waste and CO_2 emissions than ever [3] [4]. Altogether, construction industry consumes the largest portion of materials, accounting for 35% of the total waste and 36% CO_2 emission generation in European Union (EU) yearly [3] [5] [6]. So, the construction industry must rethink possibilities to decrease the negative impacts from building industry to reduce both waste and CO_2 emissions.

Generally, waste is treated in three main categories: recycling, incineration, and landfill. Even though Denmark is a definite leader on reducing landfilled waste using it for energy production and by recovering 87% of the total waste, municipalities deal with an excess waste for incineration capacity. It means that the country is growing dependent on the generated waste [7].

Construction waste in Denmark makes on average 74% of the total waste amount from industries [2] [8]. Since 2012 the total construction waste has increased by 93%; from 7.3 million tons in 2012 to 14.2 million tons in 2019 (Figure 1). At the same time, waste from construction of new buildings has increased by 118% due to boosted building capacity [8].

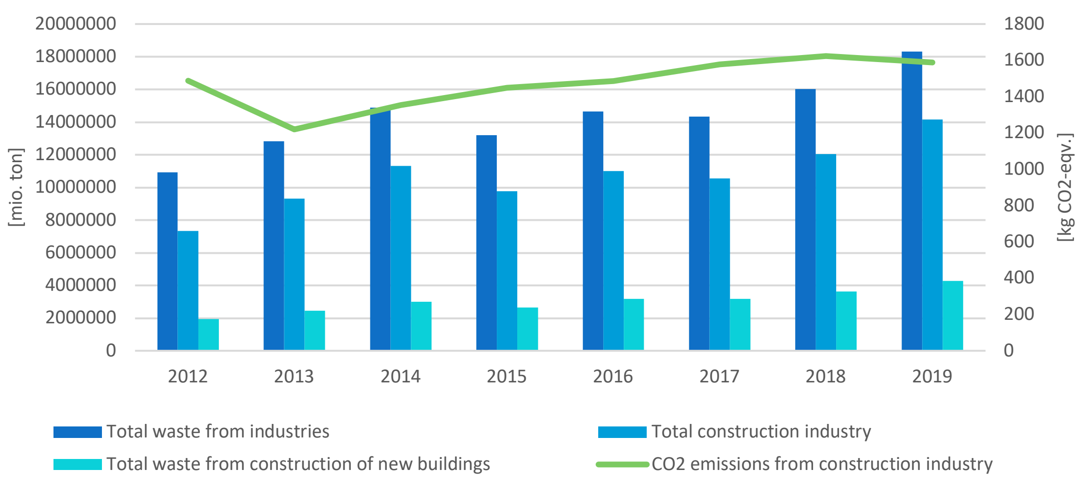


Figure 1 – Total waste and CO_2 emission increase in Denmark 2012-2019 [8] [9]

Moreover, the construction industry is responsible for 52% of total annual CO_2 emissions from industries that keep rising with every coming year [9]. Therefore, reduction of building construction waste and consequential CO_2 emissions is necessary. To reduce the increasing waste from construction industry, a change of building construction method is necessary.

There are two main construction methods – on-site and off-site used in Denmark. The on-site method refers to traditional or conventional way of building, where all components are assembled directly on a building site. However, the on-site construction buildings in Denmark are mainly built with timber elements, while other building elements, such as concrete, are primary used in prefabrication. For the on-site method, the building components are delivered to the site from diverse manufacturing companies, which have prepared the components for the specific project. The off-site or prefabrication method means that building components or modules are manufactured and preassembled before they are transported and installed on a permanent foundation at the building site. Each module is constructed with structural elements and insulation together with all mechanical, electrical, and plumbing installations. About 85-90% of the modular construction is done off-site, while the remaining 10-15% are done on-site [1] [10]. So, the modular method has a potential to decrease both construction waste and CO_2 emissions from the building construction stage.

This study is done because of poor existing data on construction waste quantities and their impacts from both on-site and prefabricated construction methods related to specific building projects. So, the reduction of construction waste and environmental impacts in residential buildings is evaluated by comparing two types of prefabricated buildings - concrete and timber. Both building types are compared in connection to generated waste amounts during the construction stage and total global warming potential from the building materials, performed in LCAbyg software.

2 Problem and research questions

Even though, the construction industry's approach in the last decade has been changing, the waste is still a big problem. Therefore, it is necessary to reduce the waste to lessen environmental impact with thoughtful construction methods. So, building by prefabricated method is proposed as an alternative to on-site construction method to reduce the construction waste and global warming potential.
This thesis aims to determine the construction waste amount from residential buildings built by two different prefabricated construction types compared to the on-site construction method. So, the project goal is to promote environmentally sustainable building construction methods to reduce building construction waste and to decrease total negative environmental impact from future buildings.

2.1 Research questions

Based on the problem formulation, two research questions are answered in this research project, as follows:

Which prefabricated construction method – concrete or timber – produces less construction waste by weight?

Which of the prefabricated construction methods has the lowest environmental impact in connection to Global Warming Protentional?

The following research questions are answered as part of the main research question:

- Which construction method produces less waste – prefabricated or on-site?
- How is construction waste treated and which fractions account for the most waste?
- Which are the most frequently used building materials?
- Which suggestions for further waste reduction can be applied to Danish building legislation?

3 Background

The background section presents relevant descriptions, terms, and information about building life cycle stages, prefabricated buildings, building material waste as well as environmental impact methodology. Firstly, life cycle of building is introduced as general explanation of report research area. Secondly, differences between prefabricated and on-site construction methods are explained. Then, building waste methodology in is described. Finally, environmental impact assessment of concrete and timber prefabricated construction types is introduced.

3.1 Life cycle methodology

The life cycle of a building compromises five stages of building: production, construction, use, end of life, and beyond as seen in Table 1. Generally, first four stages are considered as part of the building's system boundary, while beyond stage happens after the building has been disposed. The system boundary for building projects in Denmark is 50 years [11] [12]. From all the life cycle stages, this project investigates only construction and installation processes in construction process stage A5.

Table 1 – Life cycle stages [11]

A1 – A3	*A4 – A5*		*B1 – B7*	*C1 – C4*	*D*
PRODUCT stage	**CONSTRUCTION stage**		**USE stage**	**END OF LIFE stage**	**BEYOND system boundary**
A1 – A3	A4	A5	B1 - B7	C1 – C4	D
Raw material supply - Transport - Manufacturing	**Transport**	**Manufacturing / Installation process**	**Use – Maintenance – Repair – Replacement – Refurbishment - Operational energy and water use**	**De-construction/ demolition – Transport – Waste processing - Disposal**	**Reuse – Recovery – Recycling potential**

In this study the construction stage is represented by module A5, compromising two processes: manufacturing and installation. During the manufacturing or construction process the prefabricated building elements (modules) are made almost finished, and traditional building elements are assembled on a building site. During the installation process, prefabricated construction elements are assembled on a building site, finished with necessary outdoor coverings, and connected to prepared building installations. The on-site construction buildings are also connected to the building installation during the installation process.

It is considered that that prefabricated construction elements for investigated timber and concrete building complexes are fabricated during the manufacturing process, and only raw materials are produced in usable building materials in module A3 for further manufacturing of the prefabricated building elements. It means that for this research no prefabricated building element manufacturing is done in module A3 [13] [14].

3.1.1 Prefabricated versus on-site construction method

There are two main types of building construction – on-site and prefabricated – construction. However, the prefabrication is the main building construction method in Denmark. Both types of construction differ based on design, installation, energy efficiency, time, and money. Though, the building construction primarily differ according to way of construction method as seen in Figure 2. The construction methods consist of four main stages: production, construction, use, and end of life.

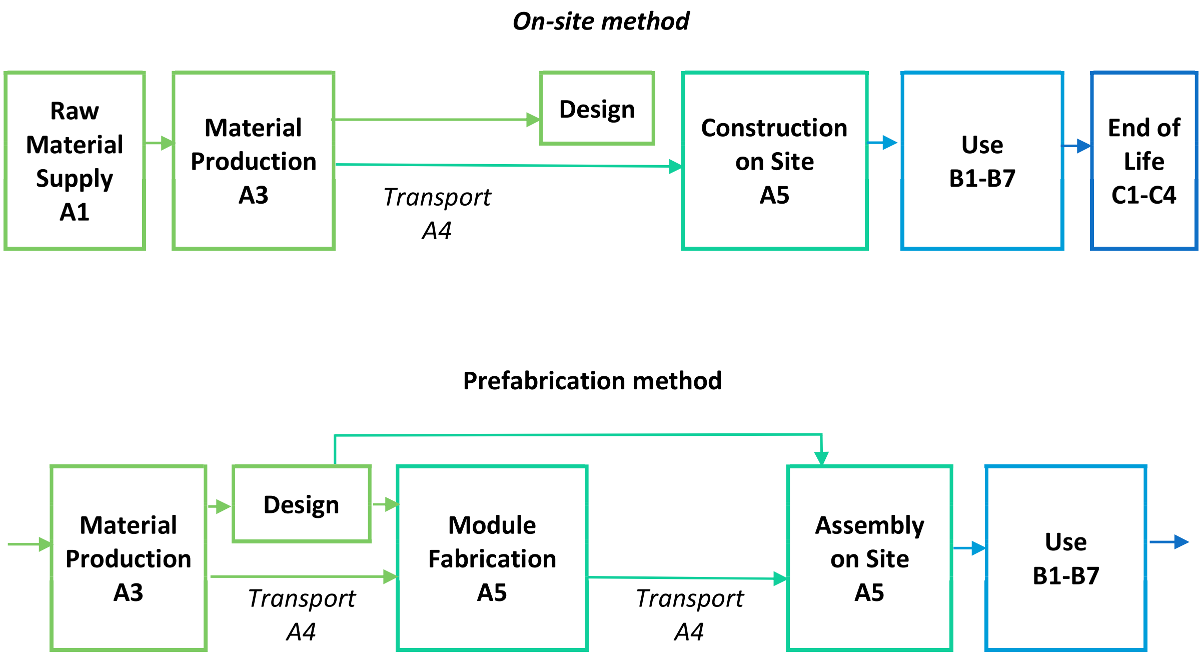


Figure 2 – Life cycle of on-site and prefabricated building [1]

Both models have the same activities for use and end of life stages. However, there are visible differences in the construction stage A5. The on-site building model consists of raw material supply, which are then used to produce materials used in the construction. From the material production location, the materials are delivered directly to building site. In meantime, a comprehensive building design is developed. For the on-site building, construction happens directly on the building site, where all previously produced materials are assembled. Similarly, for the prefabricated building, the raw materials and delivered to material production location. However, the design is made both for separate building elements and for the building assembly. After the design considerations, prefabricated modules are manufactured in a factory and then finished delivered to the building site. While the modules are made, building site is developed. Then the modules are installed on the building site to finish the building [1].

In general, the prefabrication method takes much shorter time to complete, 2-4 months compared to 6-12 months for the t on-site construction. Moreover, the on-site construction works seasonally because extreme heat or cold can influence both work hours and building material properties [15]. On contrary, the prefabricated modules are assembled indoors, in factory, where the weather is not a concern and material properties are not compromised [10]. Regarding flexibility, the prefabricated construction buildings can be disassembled easily, relocated, and reused for different building projects both permanent and temporary, providing unlimited number of opportunities to construct. The process significantly reduces demand for raw materials and consumed production energy, unlike on-site buildings. The on-site method uses materials that rarely can be reused for other projects due to storage on a building site. This can cause over-usage of building materials and so an increased construction waste. On the other hand, extra building materials used in prefabrication can be reused for other modules or projects entirely as well as recycled. In both construction methods waste occurs but is generally assumed that modular construction produces less waste compared to the on-site construction.

3.2. Waste management

The waste management (WM) deals with accumulated waste during all life cycle stages, including site planning, transportation, storage, material handling, on-site operation, segregation, reuse, recycling, and final disposal [3]. However, the most waste comes prom manufacturing of building materials and components, construction on a building site, and demolition of the building. It is handled by implementing waste management techniques, making sure that the waste materials are sorted in right fractions, and by differentiating the accumulated waste based on a construction method. Nevertheless, the building waste needs to be accounted for all life cycle stages and minimized throughout the building's lifetime.

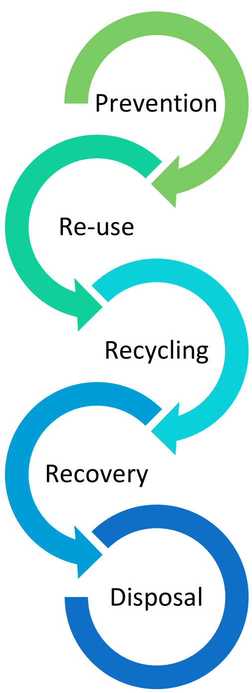


Figure 3 - EU waste hierarchy

In general, the WM is used to decrease growing material and product waste. To reduce and even prevent the waste accumulation, EU Waste Framework Directive (WFD) is used. It sets general concepts for the WM, including specific definitions of waste, recycling, and recovery. The target is to reduce the waste of households, construction and demolition, and municipalities by means of reuse, recycling, and recovery, but mainly – the waste prevention as showed in EU waste hierarchy (Figure 3). The WFD is used in all EU countries and implemented through methodological assurance of achievement of targets for WM every two years [16].

According to the WFD, at least 70% of all construction waste must be recycled [17]. Denmark fulfils this rule by actively minimizing at least 53% of landfilled waste and recovering 87% of the total waste through incineration with energy recovery [7]. [18]. Even though, the building waste treatment is highly efficient, general waste reduction in product and construction stages is necessary.

A great emphasis has been placed on waste prevention methods, including prevention, re-use, recycling, recovery, and disposal stages in the waste hierarchy. Prevention stage refers to reduction of material amounts in design and manufacture phases, general longer use of products, and reduced use of hazardous materials. Re-use stage is connected to checking, cleaning, repairing, refurbishing already used items and spare parts, so that they can be used again. Recycling stage uses generated waste and turns it into new substances or products that can be used in future manufacturing process. Recovery stage refers to waste use to produce energy, fuel, heat, and power, through incineration, gasification, and pyrolysis. Disposal stage means that waste is incinerated and disposed in a landfill with no possible energy recovery.

Generally, the construction waste can be reduced if building resources are used more efficiently. To do collaboration between different types of construction industry actors, such as manufacturers, architects, constructors, contractors, builders, and demolition companies, is necessary. Without this cooperation and no proper planning of building process, more resources than necessary are used, generating large amounts of construction waste. However, with the right dialogue and knowledge, buildings can be designed to be disassembled, recycled, and recovered [3].

3.2.1 Construction waste

In Denmark the construction waste is divided in several fractions. These fractions include materials according to their properties and sorting treatment, such as recycling, incineration, and landfill. Construction companies must sort the building and construction waste in minimum amount of waste sorting fractions, such as natural stone, unglazed brick, concrete, mixture of materials from natural stone, unglazed brick and concrete, iron and metal, gypsum board, mineral wool, soil, asphalt, mixtures of concrete and asphalt. In addition, construction companies must sort out hazardous waste, PCB- containing waste, and double glazes windows [19].

Based on efforts from mid-1980s until nowadays, many development projects have been analysed in connection to waste sorting to prevent and recycle the construction waste. The waste information of these projects has been collected and the physical sorting fractions are known according to the sorted waste amount. The most recognised sorting fractions are, from largest to smallest: concrete (26%), asphalt (25%), brick (15%), iron and metal (8%), timber (3%), glass (1%), gypsum (1%), mineral wool (1%). These fractions account for 80% of all waste division, while the rest of 20% account for smaller fractions, such as cardboard, paper, plastic, hazardous waste, residual waste, spray cans, batteries, etc [20]. The fractions show general division from all sorted construction waste, but it differs for specific construction projects based on the materials used in the construction.

From the general fractions, most waste is recycled and reused, while only small fraction is incinerated and disposed in landfills. Concrete waste is reused for construction of other concrete structures and recycled in crushed form for base of roads and filler. Generally, concrete fraction is in demand, so it has not been a problem to dispose of clean crushed concrete. Asphalt is mainly recycled for new road construction in pure form and in mixture with gravel and stone. The asphalt from old road demolition is disposed in landfills. However, to fully recycle asphalt for new asphalt production, risk of pollution from the production needs to be eliminated. Brick waste is reused in form of masonry bricks and roof tiles in new construction projects and renovation. Furthermore, crushed bricks are recycled to make new bricks, to fill roads and form base layer for ground floor deck construction. Even though bricks are highly used for building construction in Denmark, market for reused and recycled brick products is niche. Metals are mainly reused for steel construction elements and profiles and recycled for installation pipes. A part of metal is used in scrap form in electronics. Most of timber waste is reused, as it can be reshaped according to needed dimensions in different products. Moreover, there is a big market of selling used timber construction materials for new building construction projects. Otherwise, old, and damaged timber elements are incinerated, while a minor fraction is recycled. Glass waste is generally disposed in landfills and partly recycled. The glass waste in construction comes from broken windows, glass façade elements, greenhouses etc. where the glass is separated from frame. Recycling of glass happens only if it is returned to the manufacturer. Gypsum is fully recycled as it can be sorted out and crushed into powder. It is used in new gypsum board and cement production. Mineral wool is also fully recycled for production of new insulation material. However, the mineral wool is mainly recycled by manufacturing companies, so specific products after demolition need to be separated and returned to the respective company [20].

3.2.2 Construction waste from prefabricated buildings

The material waste is accounted from different stages and processes based on a construction method. By analysing the construction stage, a construction waste (CW) is differentiated for different construction methods. The CW covers waste accumulated during module fabrication and installation on a building site for prefabricated buildings during construction stage A5.
For prefabricated construction the construction stage refers to module manufacturing process, when floor slab, wall, and roof modules are constructed. The manufacturing is carried out in a factory. Because of closed indoor environment, materials are stored in dry conditions, so no waste occurs due to weather damage. By storing the building materials indoors, it is ensured that they keep the same quality throughout the whole manufacturing process. Furthermore, the waste materials from one project can be used in another and it is also possible to reuse module moulds from one project to another, when the modules are the same size [10] [22]. A significant amount of material waste is generated also during module installation process, when the prefabricated modules are installed on previously prepared building site. However, foundation work is done on a building site before the installation of prefabricated modules. During the installation, the CW occurs from roofing, internal and external module finishes, installation connections to the building, stairs outside, solar curtains, landscape, and foundation work [1] [10]. During the construction stage, the material waste is unavoidable, because prefabricated modules need to be manufactured and installed on the site. Unfortunately, not enough studies have been made to distinguish prefabricated element construction waste, so it is generally estimated that all materials have 10% waste of total used building materials [20].

3.3 Life cycle assessment

Life cycle assessment (LCA) is an evaluation method to measure environmental impacts of a product, process, or service throughout all building life cycle stages - raw material production, element production, construction, building use, disposal, and beyond. The aim of LCA is to provide a holistic approach of environmental impact and give building professionals a possibility to choose between the different products based on their impact trade-offs. As an addition, LCA can show how a building contributes to climate change. However, the evaluation process is complicated due to challenges of collecting necessary building product data to produce comprehensive analysis results. This is due to scattered nature of construction industry organization to quantify various material types, assembly methods, site conditions etc. Therefore, uncertainties appear in LCA as it is with any complex modelling. So, it is necessary to look at LCA as an estimation and not as absolute measurement [1].
For the environmental impact analysis, LCAbyg software is used. The software measures different environmental impact criteria such as Global Warming Potential (GWP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP), acidification potential (AP), eutrophication potential (EP), abiotic depletion potential, elements (ADPe), abiotic depletion potential from elements, fossil fuel (ADPf), total primary energy (PEtot), use of renewable secondary fuels (Sek) [23].
For this report mainly the GWP is analysed for the construction stage, when results are compared for different materials used in the building construction between the two prefabricated methods.

Global warming describes a rise in average temperature of Earth's surface. It is caused because of emission of greenhouse gasses that include CO_2 and other 23 substances, such as CH_4, N_2O, CFC-113, CO and SF_6 [24] [25]. The GWP is calculated for emissions of kg CO_2 equivalent. To calculate the GWP, emission factors from each life cycle, material amounts for a building elements and replacements need to be known.

4 Method and materials

The method and material framework for this research compromises data sources, a general building information, a construction material and waste information, as well as a description of environmental impact calculation for further waste amount and environmental impact analyses. The framework is explained through multiple steps in this section.

4.1 Data sources

The project research is based on documents acquired from concrete (CC) and timber (TC) construction companies. Initially, around 30 prefabrication and traditional construction companies were contacted, from which only five companies were interested in this research. However, from the five companies only two could provide usable information for analytical research purposes. Other companies either did not have the requested information or stated it as confidential and not eligible for sharing. So, this thesis is based on acquired (limited) information from one prefabricated concrete construction and one prefabricated timber construction company based in Denmark.

Initial information about both prefabricated construction projects was acquired through interviews and digital meetings with construction companies' professionals as seen in Appendix A – Expert interviews. The interviews gave insight in company policies towards waste management and sustainability. The interviews were used as basis to acquire more specific information about the projects. The received information from both companies included:

1. General building plans
    a. Floor plans
    b. Façade plan
    c. Cross sections
2. Module drawings
3. Waste quantities
    a. Waste during construction stage
    b. Waste division in sorting fractions

All building plans and drawings from both companies included overall building dimensions and specific dimensions for separate modules. From the specific module drawings, it was possible to also determine windows and door sizes. However, the CC drawings included more detailed information than the TC, so more precise further data could be generated. The CC company also provided the project with specific information about materials used in the construction. From the TC drawings the building element construction had to be partly assumed. Altogether, the drawings were essential to know building element construction with distinct material layers that were used for material quantity analysis.

Waste quantity data from both companies included waste quantity data during the construction stage. The TC company provided information about waste quantities both during manufacturing and installation processes. The CC company provided the data only for installation process, so the waste amount during the manufacturing process was assumed. Both companies also provided information about waste division in sorting fractions. As both companies use City Container A/S for waste management and sorting, the waste treatment was found from the respective website [26]. Overall, the waste quantity measurements and sorting fractions were necessary to know which materials are the most used in the projects and how they are treated.

In general, several assumptions were made for different aspects of both projects:

1. Overall construction
    a. Construction of prefabricated timber construction
2. Construction materials
    a. Material thicknesses for prefabricated timber construction
    b. Material density for both prefabricated concrete and timber constructions
3. Construction waste
    a. Construction waste proportion between manufacturing and installation process for prefabricated concrete construction
    b. Construction waste quantities during manufacturing process for prefabricated concrete construction

As mentioned before, the specific construction for the TC project was not known from the provided documents, so it was assumed according to best industry practices taught at Architectural Technology and Construction Management, general construction books and guidelines [27] [28] [29], and material product webpages. From the different sources, the timber construction with necessary material thicknesses were acquired.

For both construction projects, the material densities were assumed by knowing the construction materials. The densities were assumed from Lambda values of frequently known construction materials [30]. It was necessary to have construction material densities to calculate construction material quantities and weight.

The construction waste proportion between manufacturing and installation processes for the CC was not known, so it was deduced according to the known TC construction of 55% for manufacturing and 45% for installation - process. Furthermore, from previous research and construction company interviews, it was discovered that the TC has higher waste quantities during installation process compared to the CC, so a proportion of 70% for manufacturing and 30% for installation – process was deduced. From the assumed proportion, the construction waste quantities during manufacturing process were calculated. It is, for the purposes of this research, essential to have construction waste data during both manufacturing and installation processes, so the waste results between prefabricated concrete and timer construction can be compared sufficiently.

For the environmental impact analysis, the data was acquired in connection to life cycle assessment. The data includes descriptions of life cycle assessment importance life cycle stages, environmental impact measures and calculation method [11] [23] [25]. The documents of the life cycle assessment provided this research with necessary information to create the environmental impact analysis for both prefabricated construction projects in connection to construction materials impact measures and global warming potential.

The on-site construction data about construction material waste was acquired from previously made research articles and projects [1] [31] [20]. The information was used to compare the waste from prefabricated construction buildings to on-site construction buildings, to identify which construction type generates less or more waste during the construction stage.

4.2 General building information

The concrete construction project consists of eight buildings with four levels and two apartments on each floor. There are two types of concrete buildings based on their size. Six buildings have no basement, and two of the buildings have a basement, so building areas are calculated differently. For the project the whole building complex and construction materials used are investigated.

The timber construction building complex consists of eight buildings with seven types of residential units and one common building unit. The apartments are placed in three and four levels depending on the building unit. For the project the whole building complex and construction materials are investigated. Both analysed projects' description data is showed in Table 2.

Table 2 – Description of investigated buildings

Description	Concrete construction	Timber construction
Building type	Residential	Residential
Structure system	Concrete	Timber
Number of buildings	8	8
Floor area [m^2]	11483	6241
Floors	4 + basement	3 - 4
Life cycle stages	Construction stage	Construction stage
System boundary	50 years	50 years

4.2 Construction materials

For the project, construction materials for both prefabricated construction building complexes are divided based on building element types and construction material properties. The construction of the CC and TC buildings differ, so the construction materials are different for each of the construction methods. Detailed information about both projects construction and building elements based on the construction materials is seen in Appendix B - Material quantities. The appendix provides of information of specific construction materials used in concrete and timber prefabricated construction buildings. Based on the materials used in the construction, several material categories with material specification are made as showed in Table 3.

Table 3 – Construction material specification for the CC and TC [30]

Construction material	Specification	Density [kg/m3]
Concrete	Concrete C20-25	2400
	Concrete C35-45	2400
Reinforcement	Steel reinforcement	7800
Cement	Cement	1440
Membrane	Damp proof membrane	0.13
	Bitumen	1000
Insulation	EPS insulation	15
	Mineral wool	18
Gravel	Crushed stone grit 16-32 mm	1
Bricks	Facade bricks	1800

Metal	Aluminium plate	2700
	Galvanised steel	7900
Timber	Timber cover/ flooring Timber joist/ stud Timber plate Parquet Laminate	500
Board	Gypsum board	900
Glass	3-layer window glass	2600

The material quantities are estimated from provided construction data and investigation of common construction types. The material quantities were collected for actual residential building projects made from concrete and timber constructions to determine total material amount and weight for further waste assessment. However, the amount and type of the data provided is different for concrete and timber constructions. Generally, the material quantities were calculated for building elements based on floor area, material thicknesses, density, and module sizes.

4.3 Construction waste

The amount of generated waste in both building construction projects was collected based on waste data provided by respective construction companies and waste management data according to sorting fractions. However, the investigated projects account for more waste fractions than stated in background section. The waste for each building project is sorted in different fractions as the materials used in the building construction differ. Furthermore, the construction waste of each of the fractions is either recycled, incinerated, or landfilled. The waste fractions with respective materials and sorting method are seen in Table 4.

Table 4 – Waste fractions for the CC and TC [26]

Waste fraction	Material	Sorting
Asphalt	Clean broken asphalt rubble, gravel	Recycling
Bricks	Tiles, bricks, concrete	Recycling
Cardboard	Different types of cardboard	Recycling
Combustible construction waste	Building wood, non-recyclable cardboard, plastic and paper	Incineration
Concrete rubble	Pure concrete rubble	Recycling
Hard plastic	Plastic packaging	Recycling
Hazardous waste	Hazardous waste	Recycling
Heavy fraction for sorting	Ceramics, porcelain, building glass, glazed tiles, lightweight concrete, Leca concrete, plaster with straw	Recycling
Insulation	Rock wool, glass wool, mineral wool	Recycling
Iron/ Metal	Iron and metal parts	Recycling
Mixed construction waste	Construction waste	Recycling

Mixed wood	Wood with paint and varnish, chipboard, and plywood	Recycling
Non-combustible construction waste	Glass, metal, tin cans, foils, bricks	Landfill
Paint	Paint	Incineration
Paper	Different types of paper, paper scraps	Recycling
Residual waste	Carboard packaging without food waste	Incineration
Spray cans	Spray cans	Recycling

For the CC buildings, the waste amount and sorting was done only for the construction stage, when prefabricated modules were installed on a building site. Therefore, module manufacture waste is estimated based on information from similar projects. It is assumed that waste during installation process of concrete elements is less than from the timber elements because of smaller amount of expected waste from packaging and element fitting. From provided materials of the TC, the waste management was done for both manufacturing and installation processes, so a specific waste division between the stages is known. The waste amount division between production and construction stages is seen in Table 5.

Table 5 – Waste division for CC between production and construction stage [32] [33]

	Manufacturing process	Installation process
Concrete construction	70%	30%
Timber construction	55%	45%

4.4 Life cycle assessment

For this project, the LCA is used to determine the environmental impact between two prefabricated residential buildings, made of concrete and timber. To calculate the environmental impact, LCAbyg software is used. For the analysis, building material inventory is made for both the CC and TC according to material densities in section 4.2 and total material quantities in section 5.1. Then, the LCA analysis is made by comparing concrete and timber construction buildings based on the GWP.

4.4.1 Inventory analysis

The inventory analysis shows building materials used in the LCA analysis for both the CC and TC buildings. The materials are taken from LCAbyg product library that consists of general dataset, GEN_DK, branch and product specific dataset, EPD_DK. The product source is predominantly Ökobaudat. The material quantities include previously measured construction waste amount for each of the construction types. Service life of the building materials is taken as average for the provided types of products. The construction materials and LCAbyg specifications are seen in Table 6.

Table 6 – Construction material specification from LCAbyg for the CC and TC [23] [34]

Construction material	LCAbyg material specification	Service life [years]
Concrete	Concrete C20/25	80

Reinforcement	Steel profile	110
Cement	Screed, cement-based	100
Membrane	Damp proof membrane PE (thickness 0.0002 m)	70
	Bitumen top layer	40
Insulation	EPS insulation (grey) with thermal absorbtion	70
	Mineral wool	90
Gravel	Gravel 16/32 (dry)	90
Bricks	Cement bricks	120
Metal	Aluminium plate	50
	Galvanised steel plate	50
Timber	Window/ door frame	50
	Construction timber KVH- quality (15% moisture/ 13% H20)	75
	Plasterboard plate, medium density, MDF	60
	Surface plate, timber colour, outdoors (topcoat-system)	60
	Timber floor, parquet, 22mm	100
	Laminate flooring 8 mm	100
Board	Gypsum board, 13 mm, impregnated	100
Glass	Glass 3 mm	50

The construction material use depends on building structural type, therefore, not all materials are used in either the CC or TC. To determine which materials are used for which construction, detailed information about both construction types is seen in Appendix A – Expert interviews.

4.4.2 Environmental impact calculation

To calculate the environmental impact of both prefabricated buildings, LCAbyg software is used. Even though the software calculates the impact automatically, the calculation method is explained. The GWP is calculated from production to end of life stages to determine which building elements and, therefore, materials used in the construction are more sustainable. However, the focus is placed on the GWP during construction stage compared to other life cycle stages.
The GWP is calculated for all building elements and construction materials for a reference period of 50 years. To calculate the environmental impact, building material quantities, properties, emission factors throughout the life cycle stages, and possible replacements are filled in LCAbyg software. From the inserted data, the GWP for each material layer is calculated as seen in Equation 1:

$$GWP_{material}\left[\frac{kgCO_2eq}{m^2}\right] = \left(emission\ factor\left[\frac{kgCO_2eq}{unit}\right]\right)\cdot\left(material\ quantity\ \left[\frac{unit}{m^2}\right]\right)\cdot(1+replacements)$$

Equation 1 – The GWP for building materials

For the software material quantities are applied in m^3 with suitable densities for each material type in kg/m^3. The GWP is measured in kg CO_2 equivalent/m^2, so recalculation of material quantities is necessary. Therefore, the software recalculates the material quantities in fitting unit of m^2, m^3 or kg. The emission factors are determined for each material based on the used material databases. The replacements are determined based on the average service time stated in the software - if the material lifetime is shorter than the reference study period, it needs to be replaced. The number of replacements needed depends on how many times the service time fits in the reference study period. For a whole building element, the GWP is summed up from all material layers included in the element as showed in Equation 2:

$$GWP_{element}\left[\frac{kgCO_2eq}{m^2}\right] = GWP_{material\ 1} + GWP_{material\ 2} + GWP_{material\ 3} + \cdots$$

Equation 2 – The GWP for building elements

From the LCAbyg the environmental impact results during construction stage are compared between the CC and TC to determine which construction is more sustainable based on the GWP. The results are compared for both element and material level. So, it is known which materials have the highest GWP and could be replaced with less polluting materials.

4.5 Limitations of the study

The scope of this study is not to analyse general building construction. Therefore, the focus is placed on generated waste and environmental impacts of building materials.

Overall, this study does not cover transport process A4 in the construction stage. For the waste analyses, only the waste generated during the construction stage – manufacturing and installation process - is analysed. The construction stage also compromises different activities, such as manufacturing and installation processes, for on-site and prefabricated construction methods, so only corresponding activities for each of the construction types are analysed.

Because of the specific construction method used in this research, the results cannot be generalized to other projects without considerations for used materials, site conditions, assembly method or different type of building.

PART 1

Construction waste

5.1 Analysis of total material quantities

This section presents total material quantities from prefabricated concrete and timber construction building complexes. The material quantities are used as a benchmark to further analyses of construction waste quantities. The material quantities are showed for concrete and timber constructions separately.

5.1.1 Prefabricated concrete construction

The total amount of construction materials used in the concrete construction (CC) building based on building element areas are showed in Table 7. The building element areas differ for a building type, depending, if there is a basement. The tables show the CC building elements and modules, their areas and calculated material weight according to dimensions, density, and area. Detailed building element construction and weight calculation is seen in Appendix B - Material quantities.

Table 7 – Total material bill of quantities for the CC

Building 1, 3, 4, 5, 6, 8		
Building element	**Area [m^2]**	**Weight [kg]**
Foundation	154	148737
Ground floor deck	304-343	100347
External walls	1057-1246	613128
Internal walls	704-831	255650
Floor deck	1059-1231	609357
Floor finish	1402-1535	20050
Windows	75	7963
Internal doors	57	28570
Outside doors	2	259
Roof	320-370	201592
Total for six buildings (without basement)	***8412***	***11913922***
Total for two buildings (with basement)	***3070***	***4408589***
TOTAL FOR ALL BUILDINGS	***11483***	***16322511***

Table 8 shows how big share and weight each of the building material constitutes to in whole concrete building complex. Altogether, 13 different materials are used in the building construction, from which concrete is used the most frequently.

Table 8 - Total quantity and share of materials for the CC

	Material	**Total quantity of materials [kg]**	**Share**
1	Concrete	13550860	83.0%
2	Brick	1748819	10.7%
3	Cement	380806	2.3%
4	Steel	219307	1.3%
5	Timber	168690	1.0%

6	Reinforcement	93713	0.6%
7	Insulation	81213	0.5%
8	Aluminium	33667	0.2%
9	Bitumen	28597	0.2%
10	Glass	16210	0.1%
11	Stone	398	0.002%
12	Air	230	0.001%
13	Damp proof membrane	0.7	0.000004%
	TOTAL	16322511	100%

In the CC building complex, the most used materials are concrete, which is used for foundation and ground floor slab work, external, internal wall, floor slab, and roof elements, brick – for external wall finish, cement – for floor levelling, steel – for door construction, and timber – as laminate flooring.

5.1.2 Prefabricated timber construction

The total amount of materials used in the TC building are showed in Table 9. For the TC building element areas and total material, weight is calculated for all eight buildings together, even though they consist of several types of apartment units. The material weight is calculated according to element dimensions, density, and area. Detailed building element construction and weight calculation is seen in Appendix B - Material quantities.

Table 9 – Total material bill of quantities for the TC

Building		
Building element	**Area [m^2]**	**Weight [kg]**
Foundation	127	122592
Ground floor deck	1810	583511
External walls	5853	461612
Internal walls 100	7007	330398
Internal walls 300	728	42705
Floor deck	4314	304146
Windows	210	22125
Internal doors	192	96662
Outside doors	79	8308
Roof	1425	169785
TOTAL FOR ALL BUILDINGS	***6241***	***2141844***

Table 10 shows how big amount of building materials are used and what is their share compared to total material amount. Altogether, the TC uses 12 different building materials, from which gypsum board is the most frequently used in the building construction.

Table 10 – Total quantity and share of materials for the TC

	Material	Total quantity of materials [kg]	Share
1	Gypsum board	796370	37.2%
2	Concrete	643641	30.1%
3	Timber	488828	22.8%
4	Steel	92748	4.3%
5	Insulation	80570	3.8%
6	Aluminium	15577	0.7%
7	Bitumen	14251	0.7%
8	Glass	7500	0.3%
9	Air	1715	0.08%
10	Reinforcement	372	0.02%
11	Stone	270	0.01%
12	Damp proof membrane	0.4	0.00002%
	TOTAL	2141844	100%

For the TC building complex, the most used materials are gypsum board, used for internal, external wall, floor slab, and roof covering, different timber materials used mainly as structural elements, concrete – for foundation and ground floor deck, timber – as main structural material, steel – for door construction, insulation – for insulating all building elements.

5.2 Analysis of construction waste quantities

This section shows the analysed construction waste quantities from prefabricated concrete and timber construction projects. The waste for each of the projects is divided between manufacturing and installation processes, as well as measured in waste sorting fractions.

5.2.1 Prefabricated concrete construction

The measured waste amount from the concrete construction (CC) building in the construction stage is showed in Table 11 and Figure 4. The table shows results, when estimating that module manufacturing process represents 70% and installation process - 30% of total waste. The assumption is based on the interviews with construction company professionals and waste share between processes for the TC. For the CC, there is less waste during installation process, because no need of element packaging due to natural vapour barrier, the building elements can be finished with necessary claddings, small waste amounts occur from attached building installations and unexpected changes.

Table 11 – Total waste division between manufacturing and installation processes from the CC

	Total waste [kg]	Share between processes	Share from total materials
Manufacturing process	960090	70%	5.9%
Installation process	411467	30%	2.5%
Total waste	1371557	100%	8.4%

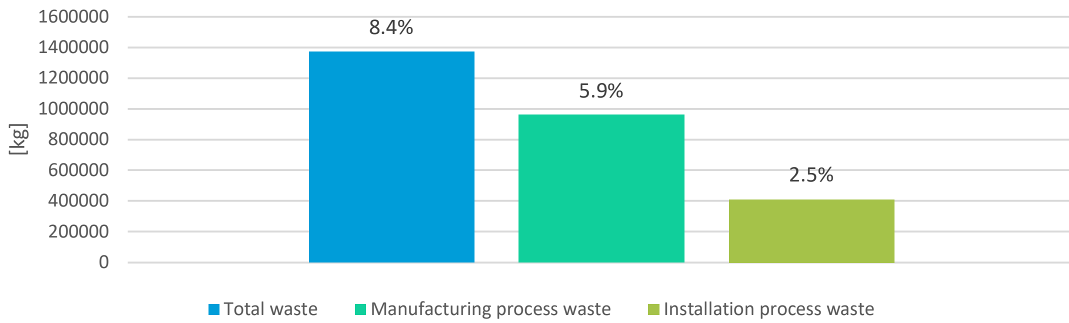


Figure 4 – Total waste division between manufacturing and installation processes from the CC

As the waste amount data from the CC was available only for installation process, it is assumed that during the manufacturing process the same fractions of waste are generated [32]. The total waste generated during the whole construction stage according to waste sorting categories is as seen in Table 12.

Table 12 – Construction waste quantity from the CC based on weight

Waste fraction	Construction waste [kg]	Share
Combustible construction waste	621971	45.4%
Concrete rubble	344467	25.1%
Heavy fraction for sorting	125587	9.2%
Mixed construction waste	112055	8.2%
Iron/ Metal	88399	6.4%
Asphalt	23843	1.7%
Residual waste	18881	1.4%
Bricks/ Concrete	14932	1.1%
Insulation	13332	1.0%
Asphalt/ Concrete rubble	7259	0.5%
Cardboard	483	0.04%
Spray cans	203	0.01%
Paper	3	0.0002%
Recycling		53.3%
Incineration		46.7%

For the CC building, the waste is divided in two categories – recycling and incineration – because according to the waste sorting data no waste is disposed in a landfill. From the waste sorting fractions the recycling accounts for most of the fractions, while incineration accounts only for combustible construction waste and residual waste.

According to the waste fractions, the combustible construction waste includes timber, cardboard, plastic, and paper, and is incinerated. The concrete rubble includes only clean concrete debris, which is recycled. The heavy fraction includes glass, tiles, and plaster, which are also recycled. The metal fraction includes iron and metals, while asphalt fraction includes asphalt debris that all is recycled.

5.2.2 Prefabricated timber construction

The measured waste amount from the TC building in the construction stage is showed in Table 13 and Figure 5. The waste share from total used materials is calculated based on measured actual material waste from manufacturing process of 55% and from installation process – 45% [33]. For the TC, the waste quantity during the installation process is bigger than for the CC, because of necessary building element packaging, building finishes, such as cladding and roofing, added on the building site, and attached building installations.

Table 13 – Total waste division between manufacturing and installation processes from the TC

	Total waste [kg]	Share between processes	Share from total materials
Manufacturing process	186222	55%	8.7%
Installation process	150445	45%	7.0%
Total waste	336667	100%	15.7%

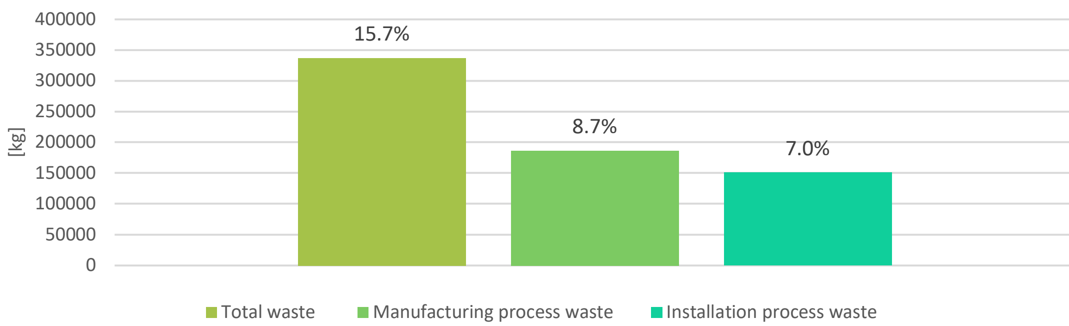


Figure 5 - Total waste division between manufacturing and installation processes from the TC

The total waste amount from the TC is divided in waste sorting fractions for both manufacturing and installation processes together as seen in Table 14. The waste share is calculated for the total waste amount including the waste from both manufacturing and installation processes.

Table 14 -Construction waste quantity from the TC based on weight

Waste fraction	**Construction waste [kg]**	**Share**
Mixed construction waste	65260	19.4%
Mixed wood	56830	16.9%
Non-combustible construction waste	27690	8.2%
Combustible construction waste	17560	5.2%
Paint waste	4480	1.3%
Corrugated cardboard	4380	1.3%
Iron/ metal	4350	1.3%
Hard plastic for packaging	4060	1.2%
Heavy fraction for sorting	1580	0.8%
Hazardous waste	32	0.01%
Mixed construction waste	103220	30.7%
Combustible construction waste	23280	6.9%
Heavy fraction for sorting	11520	3.4%

Iron/ metal	10280	3.1%
Residual waste	2145	0.6%
Recycling	261512	77.7%
Incineration	47465	14.1%
Landfill	27690	8.2%

The total construction waste is divided in three categories: recycling, incineration, and landfill. During manufacturing process recycling accounts for 73.3%, but for installation process – 83.1%. Incineration accounts for 11.8% and 16.9% for manufacturing and installation process, respectively. Waste is disposed in landfills only during manufacturing process, accounting for 14.9%. Most fractions are recycled, while paint waste, combustible construction waste, and residual waste is incinerated, and non-combustible construction waste is disposed in a landfill. Detailed in formation about waste quantity division of the TC can be found in Appendix C - Waste quantities

Based on the waste fractions from the TC, construction waste, mixed wood, and metals are recycled, while timber, paper, cardboard, and plastic are incinerated, and glass and different metals are disposed in a landfill.

5.3 Comparison of construction waste quantities

For this section construction waste is compared between prefabricated concrete (CC) and timber (TC) construction types. The waste is compared based on used construction materials and accumulated waste in each of the methods.

In general, the construction waste from both the prefabricated CC and TC buildings is compared as seen in Table 15. The construction waste share is calculated based on total waste amount and total material amount for each of the building complexes.

Table 15 – Total waste and its share for the CC and TC

	CC	**TC**
Total floor area [m^2]	11483	6241
Total material [kg]	16322511	2141844
Total waste [kg]	1371557	336667
Total waste [kg/m^2]	119	54
Total waste share	8.4%	15.7%

The table shows the CC uses more construction materials, because the gross is of the building complex in bigger than for the TC. Therefore, the construction waste quantity in generally higher for the CC. However, when the waste quantity is compared to the materials, it is seen that the CC generates less waste than the TC. Nevertheless, the waste for the TC is much lighter when considering the waste weight per m^2. This is due to differences in main structural materials – concrete and timber.

When comparing construction waste by fraction, results differ greatly between the two construction types, but the most frequent waste fraction are visible as seen in Table 16.

Table 16 – Waste fraction comparison between the CC and TC

Waste fraction	Share of CC	Share of TC
Asphalt	1.7%	
Asphalt/ Concrete rubble	0.5%	
Bricks/ Concrete	1.1%	
Cardboard	0.04%	1.3%
Combustible construction waste	45.4%	12.1%
Concrete rubble	25.1%	
Hard plastic		1.2%
Hazardous waste		0.01%
Heavy fraction for sorting	9.2%	0.8%
Insulation	1.0%	
Iron/ Metal	6.4%	4.4%
Mixed construction waste	8.2%	50.1%
Mixed wood		16.9%
Non-combustible construction waste		8.2%
Paint		1.3%
Paper	0.0002%	
Residual waste	1.4%	0.6%
Spray cans	0.01%	

The table shows that the highest waste amounts from the CC come from combustible construction waste, concrete rubble, heavy fraction, mixed construction waste, and metals. While for the TC the highest amount of waste is generated in mixed construction waste, mixed wood, combustible and non-combustible construction waste, and metals. Both construction types generate the most waste included in mixed construction waste, combustible construction waste, and metal fractions.

When looking at waste sorting treatment – recycling, incinerated, landfill -, the results also differ greatly for the CC and TC as seen in Table 17.

Table 17 – Construction waste treatment categories for the CC and TC

	Share of CC	Share of TC
Recycling	53.3%	77.7%
Incineration	46.7%	14.1%
Landfill	-	8.2%

The table shows that more materials are recycled in the TC buildings than in the CC buildings. Furthermore, almost half of all CC waste is incinerated, while incinerated waste from the TC accounts for a three times smaller small fraction. However, none of CC waste is disposed in a landfill, while disposed waste from the TC is significant. There is no disposed waste in the landfill because of previously made assumption that the total construction waste and fractions are the same for manufacturing and installation processes, and there is no landfilled waste during the installation process for the CC.

When looking at most frequently used materials in both construction methods, differences are visible as showed in Figure 6 and Figure 7. For both construction types, the waste is sorted in different fractions according to previously showed sorting fractions. Both prefabricated construction types use concrete and steel as one of main materials. Furthermore, for the CC the main construction materials are concrete (83.0%, 13550860 kg) and brick (10.7%, 1748819 kg), cement (2.3%, 380806 kg), steel (1.3%, 219307 kg), and timber (1%, 168690 kg). For the TC the main construction materials are gypsum board (37.2%, 796370 kg), concrete (30.1%, 643641 kg), timber (22.8%, 488828 kg), steel (4.3%, 92748 kg), and insulation (3.8%, 80570 kg).

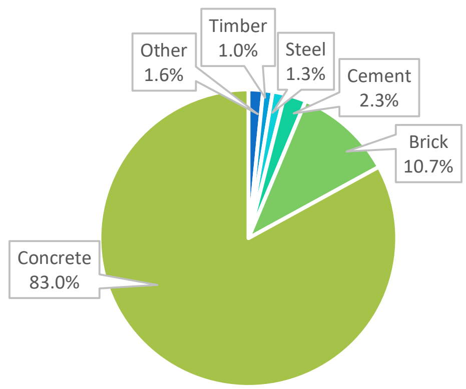


Figure 6- Most frequently used materials in the CC

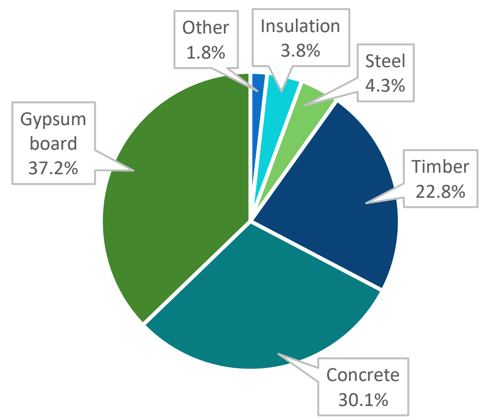


Figure 7 - Most frequently used materials in the TC

From the most used materials, for the CC, concrete would be sorted in concrete rubble, while brick would be recycled in brick/concrete fraction. Cement would be sorted in mixed construction waste, while steel – in metal fraction. Timber would be sorted together with combustible construction waste. For the TC, gypsum boards and concrete would be sorted in mixed construction waste, timber parts – in mixed wood fraction, steel – in metal fraction, and insulation – in insulation fraction.

5.3.1 Prefabricated versus on-site construction

To compare the prefabricated and on-site construction buildings several studies of on-site construction waste were investigated. However, the studies showed various results from buildings in EU and Denmark. It is generally assumed that on-site construction generates more waste than off-site construction. One source indicated that on-site construction waste is between 3 and 8%, while another source state that 10 - 15% of materials are wasted on-site. However, construction companies in general account for waste of 10% of all ordered materials [20]. Other studies indicated that construction waste from on-site construction building sites peek up to 30% [3]. The construction waste comparison between two prefabricated construction and the on-site construction type is showed in Table 18.

Table 18 – Construction waste from the CC, TC, and on-site construction

	Prefabricated CC	Prefabricated TC	On-site construction
Construction waste	8.4%	15.7%	3 - 30%

The comparison shows that the least construction waste is generated from the concrete construction (CC) and possibly on-site construction. The timber construction (TC) accounts for more waste than concrete construction, but still within a margin of on-site construction waste. However, the on-site construction has the margin that includes waste measurement results from both prefabricated constructions. If general 10% of construction waste is accounted in on-site building construction, then the CC fulfils the limit, while the TC exceeds it.

PART 2

Environmental impact assessment

6.1 Analysis of environmental impact assessment

The environmental impact analysis is done according to Global Warming Potential (GWP) for both types of prefabricated construction buildings performed by LCAbyg software. The GWP is measured as total per m^2 for each building complex with a focus on building element and material impacts. Figure 8 shows the total GWP per m^2 for each of the prefabricated construction types throughout the building life cycles.

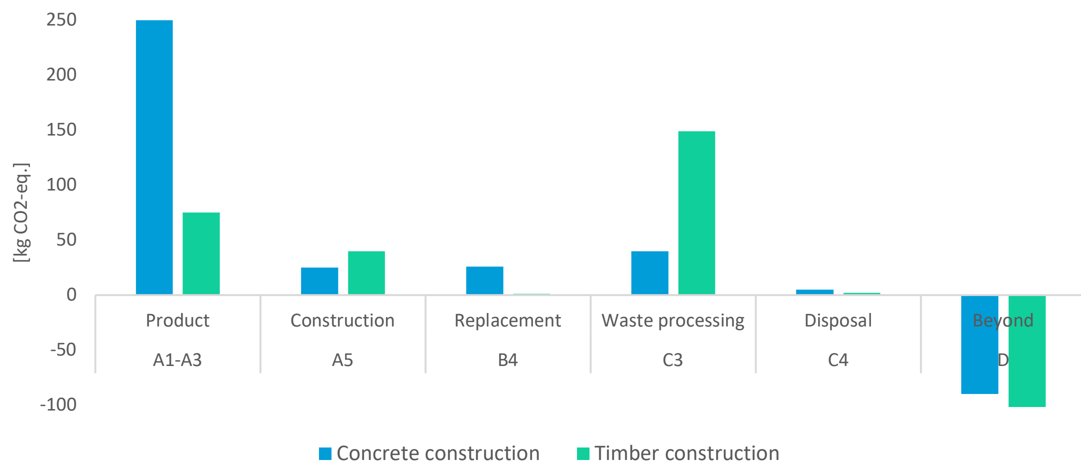


Figure 8 - Total GWP per m^2 for the CC and TC throughout life cycle stages

The figure shows that the most GWP from the CC is generated during product stage A1-A3, while for the TC – during waste processing stage C3. The least GWP is generated during beyond stage D, when building materials are processed after disposal. The beyond stage shows that materials from both construction types can be reused and recycled for new building products. In general, the results show the higher GWP from the CC than from the TC even though the TC has higher GWP during the construction stage A5.

6.2 Analysis of environmental impact for construction materials

For this section the environmental impact assessment is done for building elements and materials used in both concrete and timber building constructions. The GWP is measured according to simulated data from LCAbyg software at building, element, and material level. The analysis shows which materials have the highest GWP and, therefore, highest impact on environment. The concrete construction (CC) and timber construction (TC) are analysed separately based on most used material in the building construction.

6.1.1 Prefabricated concrete construction

For the CC, the GWP per m^2 is looked at each building element in order of contribution towards the total GWP per m^2 as showed in Figure 9. The highest GWP is seen from floor deck (22%) and doors (21%), while other building elements compare correspondingly: external walls (18%), roof (14%), windows (11%), internal walls (7%), ground floor deck (4%), and foundation (3%).

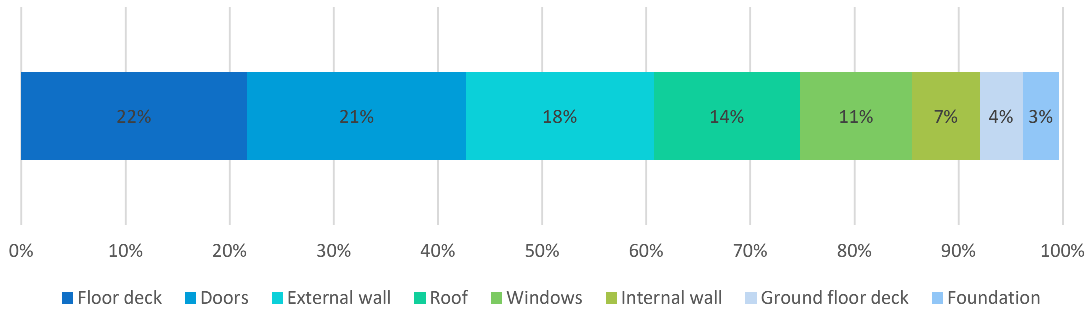


Figure 9 – Total GWP per m² for building elements of the CC

The floor decks have the highest GWP, because they have the biggest area compared to other building elements. Furthermore, the floor decks are mainly constructed with concrete that has the highest GWP from all construction materials as seen in Table 19. Even though doors do not account for a big element area, they are made of steel and aluminium that have high GWP.

Table 19 - Most frequently used construction materials in the CC; total GWP per m² and share

	GWP per m² [kg CO_2-eq]	Share
Concrete	146.3	42.8%
Steel	81.2	23.7%
Aluminium	33.1	9.7%
Insulation	28.3	8.3%
Brick	21.1	6.2%
Timber	18.2	5.3%
Cement	7.1	2.1%
Bitumen	4.8	1.4%
Glass	2.1	0.6%
Gravel	0.002	0.0005%
DPM	0.0005	0.0002%

As concrete is the most used construction material, used in all structural elements, its overall impact throughout building's lifetime is investigated as seen from Figure 10 to Figure 18.

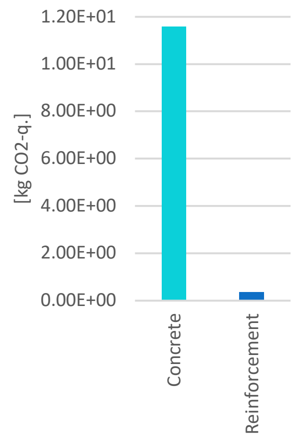


Figure 10 - GWP per m² for foundation of the CC

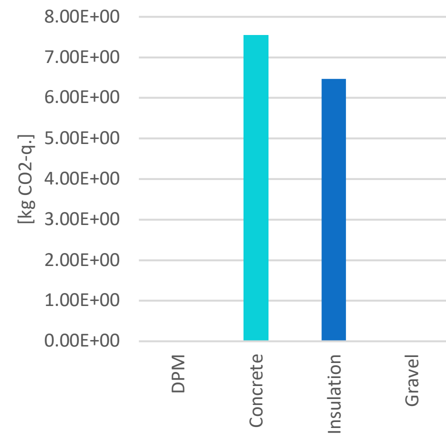


Figure 11 - GWP per m² for ground floor deck of the CC

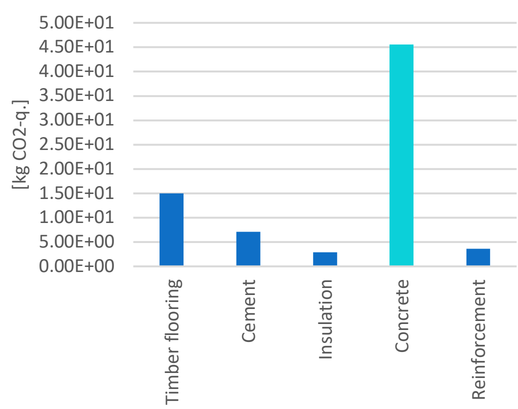


Figure 12 - GWP per m² for floor deck of the CC

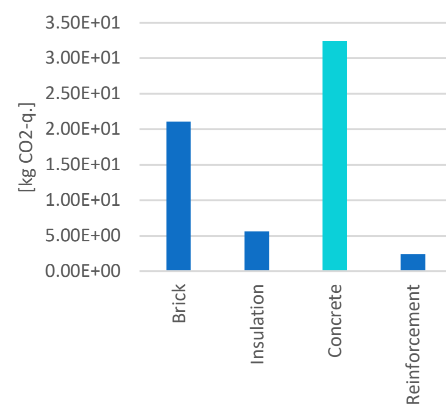


Figure 13 - GWP per m² for external walls of the CC

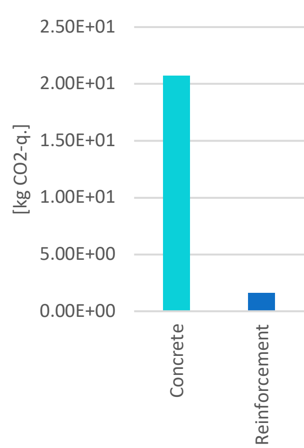


Figure 14 - GWP per m² for internal walls of the CC

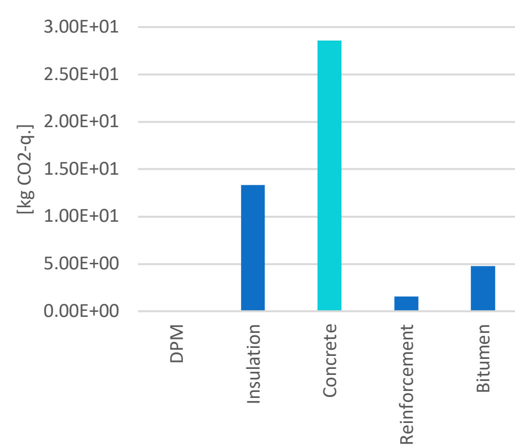


Figure 15 - GWP per m² for roof of the CC

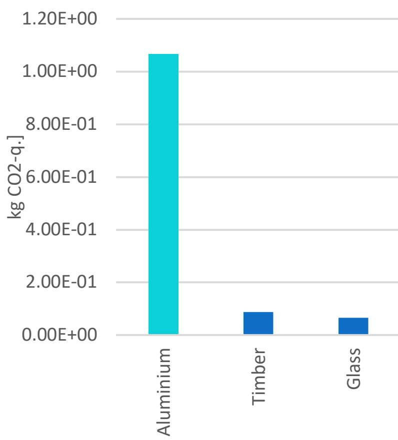


Figure 16 - GWP per m² for external doors of the CC

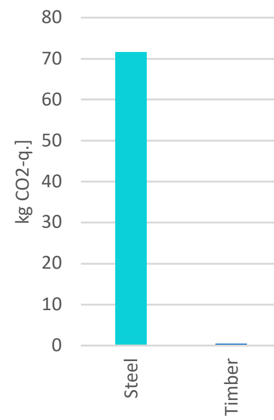


Figure 17 - GWP per m² for internal doors of the CC

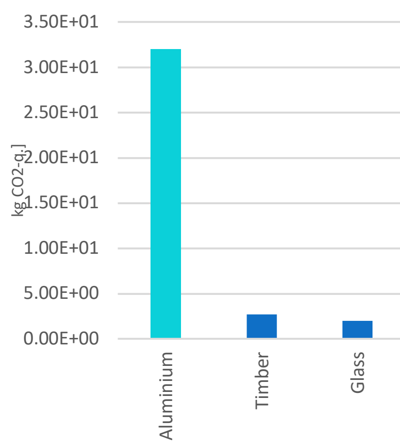


Figure 18 - GWP per m² for windows of the CC

The figures show that the concrete has the highest GWP per m^2 from all materials in all building elements, which means that it emits the most CO_2 during the building's lifetime. However, the aluminium and steel have the highest GWP per m^2 in doors and windows. It means that usage of these materials should be minimised in the building construction to reduce the overall GWP. Detailed information about the environmental impact for the CC can be found in Appendix D – LCA analysis.

6.1.2 Prefabricated timber construction

For the TC, the GWP per m^2 is looked for all building elements based on contribution towards total GWP per m^2 as showed in Figure 19. The highest GWP share is seen from doors (27%), external walls (25%), and floor decks (14%). Other building elements include a ground floor deck (10%), windows (9%), roof (8%), internal walls (5%), and foundation (2%).

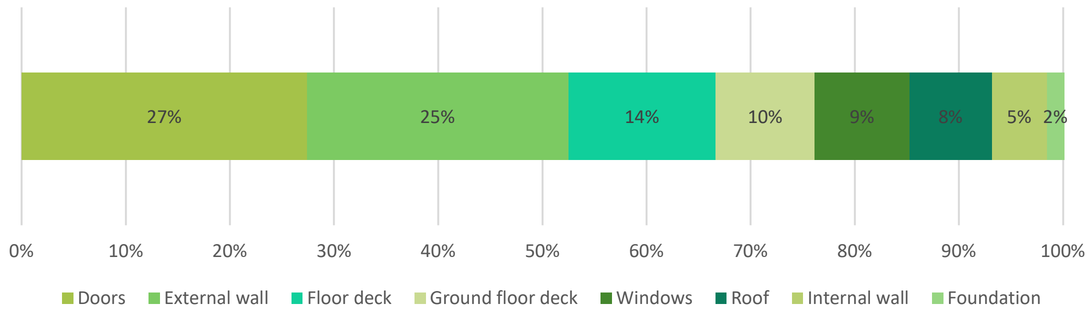


Figure 19 – Total GWP per m² for building elements of the TC

The doors have the highest GWP from the building elements, because of high impact from metals used in the construction as seen in Table 20. Furthermore, external walls show to have second highest GWP, Because of mixed construction of timber, gypsum board, and insulation.

Table 20 – Most frequently used construction materials in the TC; total GWP per m² and share

	GWP per m² [kg CO_2-eq]	Share
Timber	104.01	39.3%
Steel	64.6	24.4%
Aluminium	31.4	11.9%
Gypsum board	26.32	9.9%
Insulation	22.6	8.5%
Concrete	12.3	4.6%
Bitumen	2.2	0.8%
Glass	1.0	0.7%
Gravel	0.002	0.001%
DPM	0.0004	0.0002%

The analysis shows that timber has the highest GWP of all construction materials. Therefore, the highest GWP from construction materials throughout building's lifetime is investigated further as seen from Figure 20 to Figure 28.

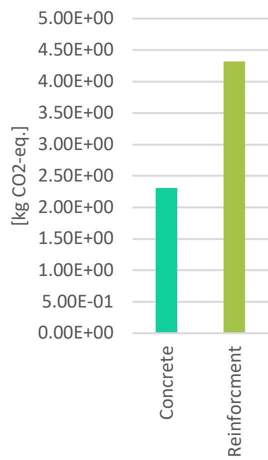


Figure 20 - GWP per m² for foundation of the TC

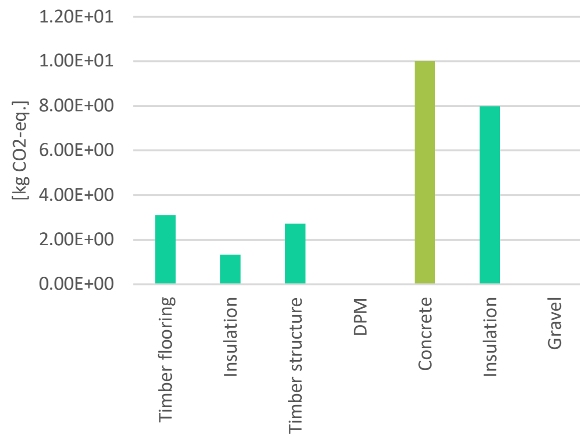


Figure 21 - GWP per m² for ground floor deck of the TC

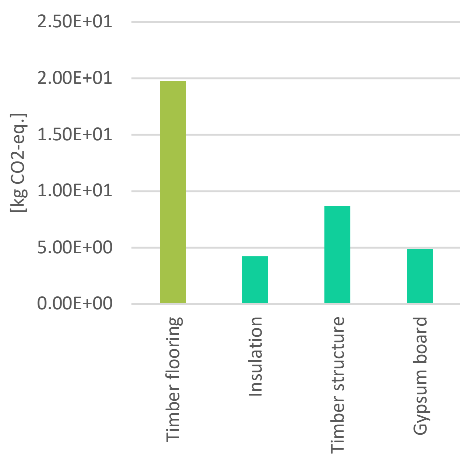


Figure 22- GWP per m² for floor deck of the TC

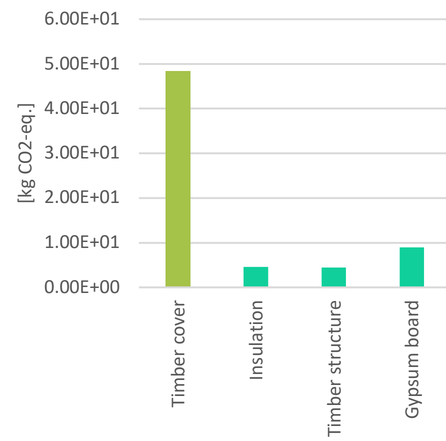


Figure 23 - GWP per m² for external walls of the TC

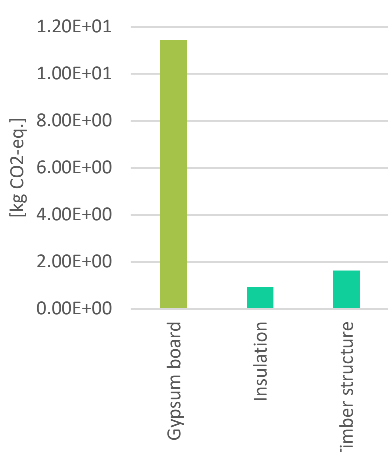


Figure 24 - GWP per m² for internal walls of the TC

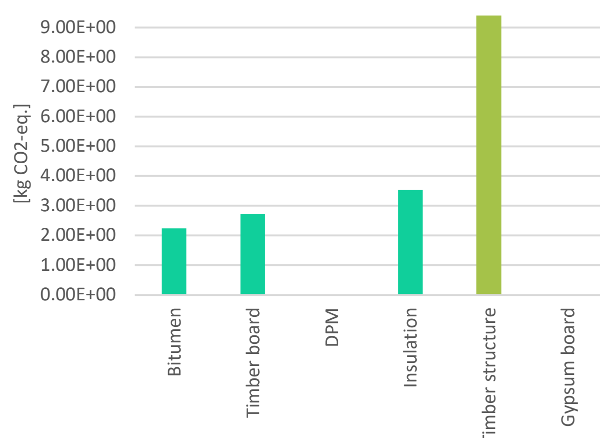


Figure 25 - GWP per m² for roof of the TC

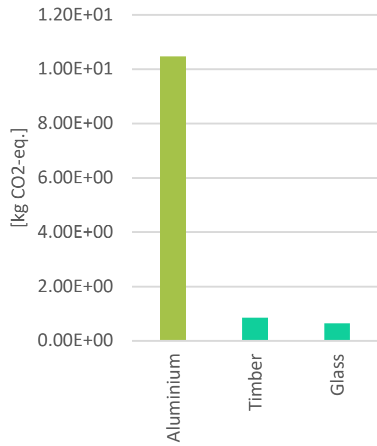


Figure 26 - GWP per m² for external doors of the TC

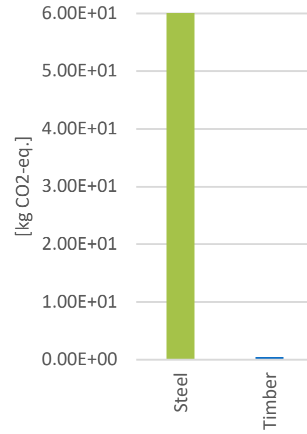


Figure 27 - GWP per m² for internal doors of the TC

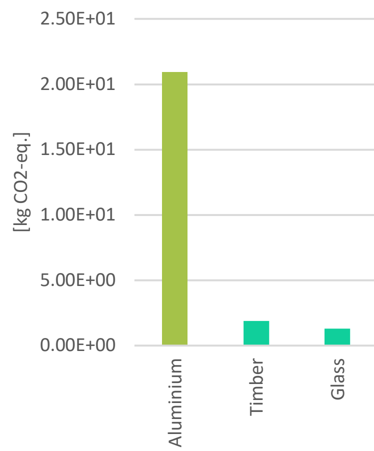


Figure 28 - GWP per m² for windows of the TC

The figures show that the timber is one of the materials that have the highest GWP per m^2. However, also steel and gypsum board show to have high GWP. The aluminium and steel have the highest GWP for doors and windows. So, these construction materials emit the most CO_2 during building's lifetime. To decrease the building's GWP, materials with the highest GWP per m^2 should be reduced.

6.3 Comparison of environmental impact assessment

For this section, the environmental impact of both prefabricated construction types is compared in connection to total GWP per m^2 and the GWP from building elements, as well as materials.

The total GWP per m^2 throughout the whole building life cycle for both construction types are showed in Figure 29. Based on the figure, the CC building emits more kg of CO_2 due to bigger floor area than the TC building, corresponding to 3929000 and 1654000 kg CO_2-eq., respectively. However, when comparing the GWP for construction stage A5, the results show that the timber construction (TC) has higher GWP per m^2, 40 and 25 kg CO_2-eq., respectively. The previous analyses showed that the TC generates more construction waste, which could influence the GWP during the construction stage.

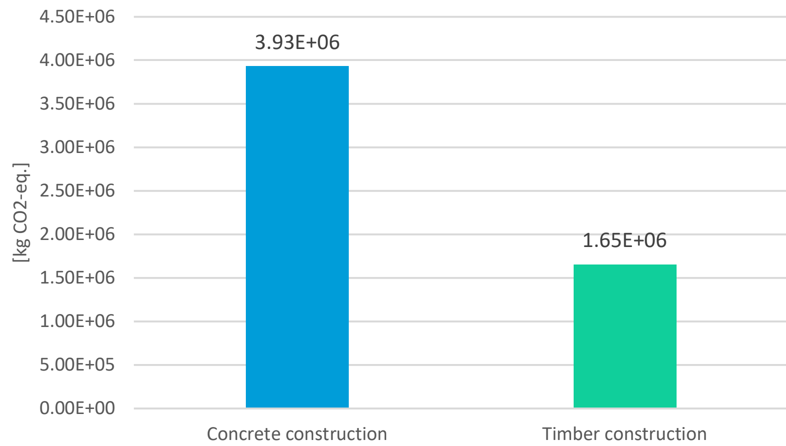


Figure 29 – Total GWP for the CC and TC

When the GWP per m^2 is compared between the two building complexes, the concrete construction (CC) still has higher GWP than the TC as showed in Table 21.

Table 21 - GWP per m^2 for the CC and TC

	CC	TC
Total GWP [kg CO_2-eq.]	3929000	1654000
GWP per m^2 [kg CO_2-eq./m^2]	342.2	254.0
GWP per m^2/year [kg CO_2-eq./m^2/year]	6.84	5.30

The comparison of building element impact during the construction stage from both construction types shows that the highest GWP in both building complexes is from external walls, doors, and floor decks as seen in Table 22. The lowest GWP comes from foundation, which could be due to the smallest quantity of material used compared to other building elements.

Table 22 – GWP per m^2 from building elements for the CC and TC during construction stage

Building element	Share from CC	Share from TC
Foundation	3%	2%
Ground floor deck	4%	10%
Floor deck	22%	14%
External wall	18%	25%
Internal wall	7%	5%
Roof	14%	8%
Doors	21%	27%
Windows	11%	9%

However, when comparing the construction materials from the CC and TC, differences are visible, seen in Figure 30 and Figure 31.

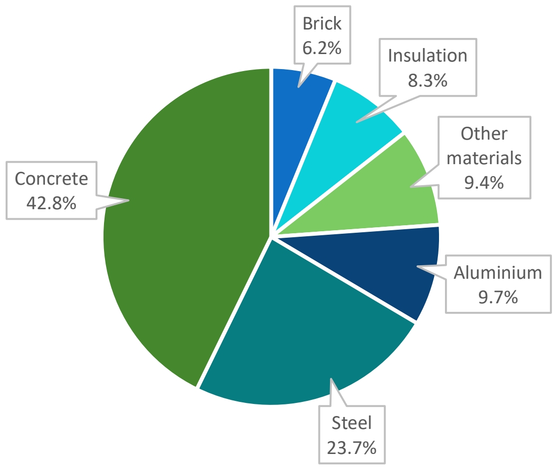


Figure 30 – Total GWP per m² from the most frequently used materials for the CC

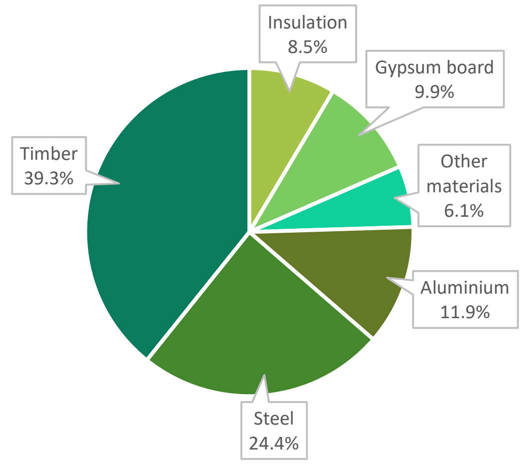


Figure 31 – Total GWP per m² from the most frequently used materials for the TC

The figures show that unsurprisingly the material with the highest GWP for the CC is the concrete and for the TC – timber. In both prefabricated construction types, metals, steel and aluminium, have a significant GWP per m^2. Generally, the CC has higher GWP per m^2 for the materials than the TC, which explains higher total GWP from the CC. However, the TC has higher GWP during the construction stage due to higher waste amounts.

6.4 Construction waste and environmental impact

The previous construction waste and global warming potential analyses are combined to see a comprehensive results of building material impacts as showed in Table 23. The table shows the construction materials, their waste shares based on the waste quantities and sorting fraction and the GWP shares based on environmental impact analysis.

Table 23 – Construction waste and GWP shares for the CC and TC

	CC		**TC**	
Construction material	*Waste share*	*GWP share*	*Waste share*	*GWP share*
Aluminium	6.4%	9.7%	4.4%	11.9%
Steel		23.7%		24.4%
Bitumen	1.7%	1.4%	8.2%	0.8%
Glass	9.2%	0.6%		0.7%
Brick	1.1%	6.2%%		0%
Cement	8.2%	2.1%		0%
Gravel		0.0005%		0.001%
Gypsum board		0%	50.1%	9.9%
Insulation	1.0%	2.0%		8.5%
Concrete	25.1%	44.0%	4.2%	4.6%
DPM	45.4%	0.0002%	12.1%	0.0002%
Timber		5.3%	16.9%	39.3%
Other	1.90%	0%	12.3%	0%

The construction materials are sorted according to waste fractions, where aluminium and steel correspond to iron/ metal fraction, bitumen – asphalt fraction for the CC or non-combustible waste fraction for the TC, glass - non-combustible waste fraction, brick – brick/ concrete fraction, cement, gravel, and gypsum board – mixed construction waste fraction, insulation – insulation fraction for CC or mixed construction waste fraction for the TC, concrete – concrete rubble fraction for CC or heavy fraction for sorting for the TC, damp proof membrane – combustible waste, timber – combustible waste fraction for CC or mixed wood fraction for the TC. The waste share includes construction materials from the same waste sorting fraction compared to the total amount of waste generated per each building complex.

According to the acquired data from Table 23, Figure 32 is showed. In the figure the overall impacts of the most frequently used construction materials in both prefabricated construction types are seen. The materials are showed from the highest overall impact to – lowest: concrete, timber, steel, aluminium, insulation, and other materials.

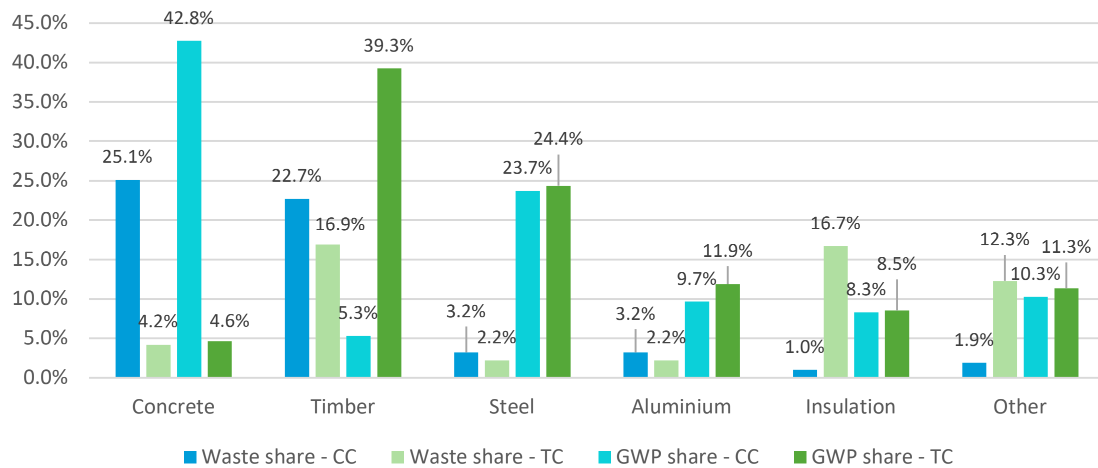


Figure 32 - Construction waste and GWP shares for the most frequently used construction materials

The figure shows mixed results, where concrete has the highest waste and GWP share for CC, but timber has the highest construction waste and GWP share for the TC. Both concrete and timber are sorted in their own waste fractions, which makes them easily recyclable. From other construction materials, timber has one of the highest GWP, while waste share is relatively small compared to the concrete. Steel and aluminium both have high GWP while their waste shares are small, but GWP is very high. In general, the waste share is higher for the TC, while the GWP share – for CC.

7 Discussion

In this master thesis report one prefabricated residential concrete (CC) and one prefabricated residential timber building (TC) complex was investigated. The building projects were investigated in connection to construction waste quantities and environmental impact assessment.

For both the construction waste and environmental impact analyses, the research results were heavily dependent on construction material quantities and properties. Because of insufficient data from involved construction companies, the primary data about both projects were based on mixture of obtained information and made assumptions about construction methods, building materials and quantities, that influenced both analyses. Because of possible differences in actual construction and material properties, the calculated construction material quantities would change, if more specific material properties are applied for both prefabricated construction types.

The waste analysis for the CC was done according to detailed information about construction materials as well as waste management during module installation process in the construction stage. For the TC, the waste analysis was based on overall building, module drawings and recognized timber construction details as well as waste management throughout the whole construction stage. Furthermore, for the CC, the construction waste quantities would show a different result if a precise division of accumulated waste between manufacturing and installation process is known, since the generated waste during the manufacturing process was assumed based on the installation process waste quantities. It was also assumed that during the manufacturing process the concrete construction generates waste in the same waste fractions as during the installation process, which would change the waste division in the fractions and may introduce unaccounted fractions in this research. As the TC material quantities were roughly calculated, the overall construction waste percentage compared to all used materials could change, if the material quantities are recalculated based on exact quantities of used materials.

The environmental impact analysis was done based on construction material quantities and properties acquired from the respective construction companies and assumptions, the same way as for the waste analysis. For the environmental analysis, the material quantities and properties can influence different aspects of the building impact as whole and based on separate elements, and materials. So, the more accurate data about a building, will produce more reliable results of the environmental impact assessment. As the assumptions were made for construction material quantities and properties, the overall building environmental impact and specific impact from the materials could change, if more precise data is known.

When reducing both construction waste and environmental impact, it is important to look at building material properties and quantities, and there is a clear correlation between the two factors. The waste can be reduced by reusing, recycling, and recovering, while environmental impact can be reduced by choosing the building materials with low global warming potential (GWP). The comparison between the CC and TC showed that the CC has lower percentage of recycled construction materials, while the TC shows very high results of material recyclability. Furthermore, the CC shows not to fulfil the WFD guidelines for recycling of building materials. So, it is encouraged to choose construction materials with possible reuse, recycling, and recovery options in all building construction, but especially in the CC.

When comparing the prefabricated and on-site construction buildings, differences can be seen. The results from previous analyses of on-site construction waste show highly variable results. From the reviewed literature, the on-site construction seems to have higher waste quantities due to unclear material and waste management, and conditions on a building site compared to the prefabricated building construction. Generally, the construction materials are re-used and recycled in larger quantities for prefabricated construction and simply disposed for on-site construction. On a building site, construction materials can be stored inadequately, in wet, dirty conditions, causing increased waste, while in factories, the materials are mainly stored in dry, controlled conditions, reducing this unnecessary waste. Furthermore, in indoor conditions, the waste materials can be directly reused in other projects, modules or sorted in corresponding containers, while it is harder to reuse materials directly and to sort on-site construction waste in all necessary fractions due to no specific purpose for cut-off materials and limited space on a building site. It is more likely that the on-site construction waste would be sorted in less fractions, so that less waste is recycled, but more is incinerated. However, more detailed analysis needs to be done to know the waste management on the on-site building site.

Even though, the initial purpose for the environmental impact analysis was to see the GWP from materials used in the construction stage, the LCAbyg software could not provide detailed information about the impacts during different life cycle stages. From the software, general information about the total GWP per m^2 for each life stage was acquired, mainly focusing on the construction stage. Therefore, the impact analysis was made for the building element and material impact throughout each building complexes lifetimes, without differentiating between the life cycle stages. Nevertheless, it was possible to compare the GWP for building elements and materials from both construction types, recognising which building complex is more sustainable based on the building material use. To improve this analysis further, detailed environmental impact analysis could be done for the different life cycle stages.

The combination of both waste and environmental impact analyses showed the overall impact of each building materials. Even though, the waste and GWP shares were accounted for all elements, there are uncertainties in the results. The waste shares are based on waste sorting fractions. It is possible to see how big share a material makes, if it is sorted in a specific fraction, such as concrete or timber. However, the uncertainties appear when different construction materials are sorted in one fraction, such as different metals. Then it is not possible to distinguish each separate material waste share within the one fraction. So, the research could show more accurate results, if it is known how big share each material makes, even when sorted in combined waste fractions.

7.1 Regulation suggestions for construction waste reduction

From the performed interviews with construction company professionals and studied researches about the construction waste, it is clear that the building waste reduction and regulation implementation is a complicated process, and in many cases based on voluntary legislation. Furthermore, from the project research applicable waste regulations were not encountered. Therefore, suggestions for further regulation implementation in Danish building legislation are presented.

On the one hand, the waste is measured based on weight and how much this weight costs to dispose of. This gives the construction waste a monetary cost instead of an environmental value. By labelling the waste only with monetary value, the waste quantities do not matter to the companies involved. The construction companies can keep using excessive amounts of materials as long as they pay their way out of waste handling. A concern here is that natural resources are not infinite. With no limitations for the waste quantities, the constructing companies can continue to exploit the natural resources for profit until they are depleted. So, there is need for compulsory regulations, stating the maximum quantity of waste for a building project, based either on percentage of materials used or per square meter finished construction.

On the other hand, the environmental impact analysis showed that there is a correlation between the waste and global warming potential of the building materials. So, when sorting the waste in different fractions, there should be a limitation of how much waste can generated of each fraction. For example, the building materials with high environmental impact should have lower maximum waste quantities and higher price per weight, while the waste materials with higher environmental impact would have higher maximum waste quantities and lower price. This would push construction companies to choose building materials with lower environmental impact over high impact materials.
Nevertheless, to control and succeed in waste management, there needs to be mandatory waste management regulations and control for all construction companies and fines for the companies that exceed the legislation waste quantities.

To sum up, to reduce the building waste, numerous waste management regulations are proposed:

1. Maximum quantities for waste, based on percentage of materials consumed
2. Waste quantity sizes based on material environmental impact
3. Waste material and fraction disposal pricing based on material environmental impact
4. Mandatory waste management and fines for exceeded waste quantities

7.2 Future research possibilities

For continuous research, construction waste quantities and environmental impact from the materials in residential buildings should be investigated.
To gain more precise data about the construction waste from on-site construction building, a case study should be made. Furthermore, the waste quantities could be compared between prefabricated and on-site construction buildings built with the same main structural materials, for instance, timber, concrete, brick, steel. This would contribute towards more detailed understanding about waste management in different construction building, and possibility to reduce the construction waste from specific construction residential buildings. In addition, a comparison of construction type efficiency could be done by evaluating construction time span, energy usage, transport, possible expenses, etc. To more extent, the different construction residential buildings can be compared throughout whole lifecycle to see which type is more sustainable and cost-efficient in a long term.

8 Conclusion

The waste management and environmental impacts play significant roles in sustainability of buildings. Even though the current waste management practices in Denmark are becoming more efficient, and the environmental impacts of building materials are being recognized, both waste and CO_2 emissions from building construction is a growing problem. Therefore, this master thesis presented construction waste and environmental impact assessment comparison in two prefabricated building complexes – concrete and timber. The building complexes were chosen as representatives of residential buildings for prefabricated concrete (CC) and timber construction (TC) methods. As the main differences appear in the prefabricated construction methods and, the projects were analysed in connection to waste quantities during the construction stage and in connection to environmental impact during overall project service life. The results of this paper can be used in construction industry to reduce negative environmental impacts in connection to construction waste and global warming potential of residential prefabricated buildings.

The total material quantities were used for both construction waste and environmental impact analyses. The waste analyses were performed based on construction waste amounts and waste sorting fractions acquired from the construction companies, while the environmental impact assessment was performed by LCAbyg software to calculate the total global warming potential (GWP) for each building complex, building element and material. The results from the waste and environmental impact were compared between the concrete and timber construction building complexes.

The construction waste analyses showed that the CC generates less waste than the TC during the construction stage compared to total material quantities, 8.4% and 15.7%, respectively. Even though the CC building complex generates less waste, the waste is twice as heavy per m^2 compared to the TC, 119 and 54 kg, respectively.

According to waste fractions, for the CC during the construction stage, combustible construction waste and concrete rubble make the biggest shares of 45.4% and 25.1%, which include timber, cardboard, plastic, paper, and concrete, respectively. From all CC construction waste, 53.3% is recycled and 46.7% is incinerated. The biggest waste shares for the TC are mixed construction waste and mixed wood, representing 50.1% and 16.9%, respectively. The mixed construction waste fraction consists of mixed materials that can be recycled, and mixed wood consists of different wood materials that also can be recycled. From all construction waste in the TC, 77.7% are recycled, 14.1% are incinerated, and 8.2% are filled in landfills.

In general, more construction waste is recycled from the TC than from CC, and less waste is incinerated from the TC than from the CC, which means that the TC is more sustainable. When looking at Waste Framework Directive, the TC exceeds the limit of 70% of recycled waste while the CC falls short and does not fulfil the framework.

The environmental impact analyses showed that the CC has higher total GWP compared to the TC, corresponding to 3929000 and 1654000 kg CO_2-eq., respectively. When the GWP is compared for each building complex floor area, the results show that the TC generates less GWP per m^2 than the CC, 342.2 and 254.0 kg CO_2-eq./m^2, respectively. Throughout the building lifetime, the TC generates 5.30 kg CO2-eq./m^2/ year and the CC generates - 6.84 kg CO_2-eq./m^2/ year, considering that the lifetime of a building is 50 years. However, the TC has higher GWP during the construction stage compared to the CC, corresponding to 45 and 25 kg CO_2-eq., respectively. The CC generates more GWP through the building lifetime, while the TC generates more GWP during the construction stage due to more accumulated waste.

When comparing building elements and their total GWP per m^2, external walls, doors, and floor decks show to have the highest impact in both construction types. This is due to higher quantities and/ or higher GWP from construction materials.
In the CC, concrete is the most frequently used construction material, and it has the highest GWP per m^2 from all construction materials used in the building complex. In the TC, the most frequently used material is gypsum board, but it has relatively low GWP compared to other construction materials, such as timber, which is used for most building elements and has the highest GWP per m^2. As concrete has the highest GWP from all construction materials in the CC building complex and it is the most frequently used material, the overall building complex has higher total GWP per m^2. While for the TC building complex, different construction materials with different grades of GWP are used frequently, minimizing the total GWP per m^2.

To sum up, there are many factors that influence sustainability of researched construction methods, such as construction waste quantities, waste sorting fractions, frequently used construction materials, GWP from the construction materials and, therefore, waste. The TC generates more construction waste and has higher GWP per m^2 during the construction stage than the CC. However, more construction waste from the TC can be recycled than from the CC. The CC has higher total GWP and higher construction waste weight per m^2 than the TC. It means that the TC generates more construction waste that has less environmental impact, respectively GWP, while the CC generates less construction waste that has a higher GWP. Furthermore, more construction waste from the TC can be recycled than from the CC.

The best way to reduce the construction waste and environmental impact is by choosing more building materials that have lower waste quantities and environmental impact and that can be recycled after disposal in construction or end-of-life stage and less materials with higher waste quantities and environmental impact.

9 Bibliography

[1] M. Kamali, K. Hewage, and Re Sedaq “Conventional versus modular construction methods: A comparative cradle-to gate LCA for residential buildings” *Elsevier,* p. 16, 2019.

[2] Miljøministeriet, “Danmark uden affald II” *Strategi for affaldsforebyggelse,* p. 16.

[3] M. Osmani, P. Villoria-Saez “Waste: A Handbook for Management” *Current and Emerging Construction Waste Management Status, Trends and Approaches,* p. 16, 2019.

[4] Global Alliance of Buildings and Construction, “2020 GLOBAL STATUS REPORT” *Executive summary,* p. 7, 2020.

[5] S. O. Ajayi, L. O. Oyedele “Waste-efficient materials procurement for construction projects: A structural equation modelling of critical success factors” *Elsevier,* p. 10, 2018.

[6] European Comission, “The Energy Performance Buildings Directive”.

[7] OECD iLibrary, “Chapter 4. Waste, materials management and the circular economy” [Online]. Available: https://www.oecd-ilibrary.org/sites/d1eaaba4en/index.html?itemId=/content/component/d1eaaba4-en.

[8] StatBank Denmark, “Statistics Denmark” 2012-2019. [Online].

Available: https://www.statbank.dk/DMR1O.

[9] StatBank Denmark, “Statistics Denmark” 1990-2019. [Online].

Available: https://www.statbank.dk/statbank5a/selectvarval/saveselections.asp.

[10] Timber construction company, *Interview of prefabricated timber construction buildings.* [Interview]. 28 September 2021.

[11] Traffik og Byggestyrelsen, Introduction to LCA of Buildings, 2016.

[12] Dansk Standard, DS/EN 15978:2012 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method, Dansk Standard, 2012.

[13] EPD Danmark, “Træ.dk,” in *EPD Danmark*, 2020, p. 9.

[14] EPD Danmark, “Betonelement-Foreningen,” in *EPD Danmark*, 2021, p. 14.

[15] Vanguard Modular Company, “Modular vs Traditional Construction: What’s the Difference?” 4 May 2018. [Online].

Available: https://vanguardmodular.com/blog/modular-vs-traditional-construction-whats-the-difference/.

[16] European Comission, “Waste Framework Directive” [Online]. Available: https://ec.europa.eu/environment/topics/waste-and-recycling/waste-framework-directive_en.

[17] European Commission, EU Construction & Demolition Waste Management Protocol, European Commission, 2016.

[18] StatBank Denmark, “Statistics Denmark” 2012-2019. [Online].

Available: https://www.statbank.dk/affald01.

[19] Videncenter for Cirkulær Økonomi i Byggeriet, “Sorting of construction waste” [Online]. Available: https://vcob.dk/vcob/cirkulaer-nedrivning/love-regler/sortering/.

[20] Miljø- og Fødevareministeriet, “Affaldsforebuggelse i byggeriet: Forprojekt” NIRAS; Copenhagen Ressource Institute; Lauritzen Advising, 2017.

[22] Concrete construction company, Interviewee, *Interview of prefabricated concrete construction buildings.* [Interview]. 30 September 2021.

[23] Aalborg Universitet BUILD - Institut for Byggeri, By og Miljø “Brugervejledning til LCAbyg version 5.1” 2020.

[24] W.-J. Park, R. Kim, S. Roh and H. Ban, “Identifying the Major Construction Wastes in the Building Construction Phase Based on Life Cycle Assessments” *sustainability,* p. 14, 2020.

[25] K. Kanafani, *LCA1,* Aalborg University, 2021.

[26] City Container, “Guide to construction and demolition waste” [Online]. Available: https://citycontainer.dk/affaldsguide/.

[27] B. L. Johansen, “Timber frame houses” in *Wood*, Horsens, 2008, pp. 1-79.

[28] Statens Byggeforskningsinstitut, SBi direction 237: Sound insulation between dwellings - new buildings, Aalborg Universitet, 2011.

[29] S. Emmitt and C. A. Gorse, Barry's introduction to construction of buildings, Oxford: Blackwell Publishing Ltd, 2005.

[30] Icopal, Icopal Håndbog 9 - Lambda værdier, 2012.

[31] V. Tavares, N. Soares, N. Raposo, P. Marques and F. Freire, “Prefabricated versus conventional construction: Comparing life-cycle impacts of alternitive structural materials” *Elsevier,* p. 15, 2021.

[32] *Waste quantities and sorting fractions from prefabricated concrete construction company,* 2021.

[33] *Waste quantities and sorting fractions from prefabricated timber construction company,* 2021.

[34] LCAbyg, “LCAbyg,” [Online].

Available: https://www.lcabyg.dk/da/.

[35] T. M. Letcher and D. A. Vallero, Waste: A handbook for Management, Elsevier Inc., 2019.

[36] V. S. Daniel A. Vallero, “Waste: A Handbook for Management,” *Introduction to Waste Management,* p. 12, 2019.

[37] StatBank Denmark, “Statistics Denmark,” 2016. [Online].

Available: https://www.statbank.dk/DMR1O.

Appendix

Appendix A – Expert interviews

For this master thesis interviews with prefabricated building professions were conducted. The interview transcripts are seen from concrete and timber construction company's professionals. The interviews were conducted to gain information about prefabricated construction methods, waste management and building material sustainability considerations.

A.1 Concrete construction

For the research the concrete company's project leader was interviewed on 30.09.2021.

1. Does the company work with prefabricated building elements?

Yes, we do.
- Walls and slabs (roof and floor) as a part of the structural construction. Manufacturers: *Spæncom, Contiga, CRH Concrete, Ambercon*. Please note, that sometimes we also let the bricks be mounted directly on the concrete walls from the factory. This saves time on the construction site but cost a lot.
- Bath cabins. Manufacturers: *Badelement, Hellweg Badsysteme, Modulbad* (a part of *CRH Concrete*)
-Staircases. Manufacturers: *PL Beton, Dalton.*

2. What is construction of these elements and which building materials are used?

The material that is used for the constructional part of the building is primarily concrete.

3. Why is the concrete mainly used? Does it have any advantages and downsides compared to other structural elements?

It is the cheapest material. Besides that, it is complicated to achieve the law requirements regarding to sound insulation, if wood is used as the primary material for the construction.

4. For which purposes does the company uses wood?

Wood is used for terraces, wooden floors, in basements it is sometime used for walls etc.

5. How big fraction of all materials is wood?It is hard to tell. We don't have numbers for that, but a guess would be around 5-10% of the complete building mass.

But we do see an increased interest in using wood (CLT) as a structural part of the construction. I find CLT very interesting but have not got the opportunity to build with CLT-element yet.

6. Are all mentioned materials assembled in factory or something is also assembled on-site?

The production of each element takes place in a factory. But the assembly is done on the costruction site.

7. How finished are elements in the factory and how much needs to be done at construction site?

This differs. Normally, an element comes as raw concrete, but sometimes we get them with already applied insulation and bricks. This is expensive, so it is only chosen when we have a short time schedule. The prefabricated bath cabins are delivered from factory with every component mounted inside, for instance, lighting, sink, toilet, tiles, and so on.

8. Do you have standardized size for the elements or are they custom made?

Regarding the concrete slabs, these are standardized in width (1200 mm and 2400 mm) and height (from 200 mm to 400 mm) with a maximum length of 18 meters. The walls and bath cabins er special made for each project.

9. Is there a reason why concrete slabs are standardized while wall elements are not?

Economy. As much you can standardize the better / cheaper.

10. Is it easier to work with standardized size elements or individual for each project?

It is easier to work with standardized elements.

11. Does standardization impact waste amount from prefabricated elements?

Not necessary. It really depends on how the architects design the house.

12. How are materials for the modules chosen? Are they sustainable? Are they chosen according to price? Any other reasons?

This depends on the customer.
In Denmark we have a long tradition (in the modern era) of using prefabricated concrete elements. This is because of the high wage (hourly rate) you must pay employees in Denmark. And since prefabricated elements are cheap and a fast way to build, this is the preferred type of material and way to build.

13. Are prefabricated elements cheaper and faster to build compared to conventional construction methods? Do you have any comparisons?

Yes, they are cheaper, and it is much faster to build compared to conventional construction methods. To cast the concrete on site, you need to put up formwork on site. And that is more time consuming to do on site compared to doing it in a production hall.

14. How much cheaper are prefabricated elements compared to conventional construction method?

A guess would be 20-30% cheaper.

15. Why are prefabricated elements cheaper?

It is faster to produce the elements in a production hall compered to do it on site.

16. How much faster is it to construct prefabricated element compared with construction on site?

Twice as fast.
It is chosen because of the price. But, as mentioned before, CLT-elements have been requested more and more from the customer. But there is some trouble by using CLT-elements regarding to the Danish law. Especially the sound requirements.

17. How is material waste managed in general? Is it reused, recycled simply thrown out, etc.

This differs from project to project.

18. How is waste amount registered? Do you keep count of exact waste amount for each project?

I will try to find data for the project I am building now. Waste material is sorted in to 5-10 fragments and reused in every possible way.

19. What are these fragments?

1. Brick
2. Concrete
3. Metal
4. Gypsum
5. Rockwool
6. Soil
7. Asphalt

20. Why is waste sorted exactly in these fragments?

I don't know why, but I could imagine that these fragments is the hardest to reuse if they are combined with other fragments.

21. Can all materials be 100% recycled or there is a waste in recycling process?

I cannot give you an answer for this. If you want to know more about this, I recommend you contact HC Container or City Container. This is two companies who deals with waste management.

22. What are company policies to decrease the building material waste?

It is very embarrassing, but the company does not have any policies to decrease the material waste.

23. Are there any plans to reduce material waste in the future?

No. Unfortunately.

24. How much material waste do you reduce working with prefabricated elements compared to convention building construction method? Do you have any examples?

It is not easy to say, but the production lines of prefabricated elements do recycle the molds for the elements. This is not the case when you cast the elements on construction site (in-situ).

25. How do you manage building material waste in other LCA stages? Which stage produces the highest and lowest waste?

I am not aware of each of the LCA-stages.

A.2 Timber construction

For the research the timber company's HSE manager was interviewed on 28.09.2021.

1. What type of prefabricated elements does the company work with?

All of types.

We manufacture our own elements, which we assemble to construct a module. We source prefabricated bathroom modules. We do not purchase other prefabricated elements from suppliers.

2. What type of buildings do you work with?

Mainly residential builds and housing. We also construct modules for kindergartens, schools, social housing, and student accommodation.

We work with buildings 3-4 floors high. The new regulations allow us to build up to 6 stories, if fire regulations are considered. Higher buildings need extra structure materials in base floor.

3. How long time does it take to produce one module?

It depends on a project size and difficulty. For a project of app. 5000 m^2 module production is around 4-5 months. In the meantime, construction site is prepared. Module assembly on site takes around 2 months after the modules are produced.
It is better for surroundings/ neighbors to build with prefabricated elements, because it takes less time to assemble and, therefore, there is less disturbance, noise etc.

4. Do you have standardized size for the elements or are they custom made?

We don't have standardized sizes for modules; all is customized for the project at hand.
We can request both standard and custom sizes for building materials, depending on a project. However, it is always cheaper to order a truckload of materials and adjust them for the specific project. Mainly all products are purchased in standard sizes, e.g. lime-plates (gypsum), insulation bats, façade-boards, construction wood. For example, windows are custom made in some cases.

5. Does it mean that then there is material waste in scandibyg, because you would need to adjust the standartised sizes from producers?

There would always be some waste, because of adjustments. Specific amounts of adjustments are not accounted for.
We have recently developed a concept where module sizes are more fixed, together with an external architect. Read more: https://www.scandibyg.dk/projekter/domino/

6. How are module sizes more fixed? Are material dimensions fixed?

The module sizes are fixed. The aim of the concept is to help those builders, who have a limited budget for architects.

7. Does external architect design the modules?

It is done on cooperation. Building with modules require that you adjust or consider upfront that the building should suit into the modular architecture.

8. So does module size influence amount of material waste. For example, if module is smaller, is there less or more waste?

The larger the module, the less it needs to be cut, so there is less material waste. Bigger modules, therefore, are better than the small ones.

9. What is construction of these elements and which building materials are used? What type of construction is used?

Main material is wood (C24 etc). In addition, gypsum/lime plates, insulation (either glass wool, rockwool or "paper wool"), wood plates eg. MDF, plywood, windows, doors, "tagpap".
Sealant products, putty, paint

10. Are all mentioned materials assembled in factory or something is also assembled on-site?

Most assembled in factory, 80% completed when leaving factory.

11. What is included in 20% of on-site assembly?

Roofing, connections between modules, stairs outside, solar curtains outside, electricity and plumbing, landscape work, foundation work.

12. How are materials for the modules chosen? Are they sustainable? Are they chosen according to price? Any other reasons?

Price, availability of material, approved for Nordic Ecolabel, depending on customer requirement (e.g. paper for insulation)

13. How is material waste managed? Is it reused, simply thrown out, etc.

Following our certification under the Nordic Ecolabel, we must document that minimum 70% of all waste is recycled. We sort our waste into 27 different fractions.
Ongoing introduction of new take-back solutions with suppliers, most recently façade plates from Rockpanel and flooring products (Tarkett).

14. That means that each producer/ supplier receives back waste products to deal with them at their own facilities?

Yes

15. Why 70%? What happens with the rest 30%?

That is the limit set by Nordic Ecolabel. Rest is incinerated for energy purposes or put into landfill. EU requires 70% for recycling and energy purposes, so not as high at the Nordic Ecolabel.

16. What are these 27 fractions? Could you explain more about division and why is it exactly 27?

I will add our waste segregation guide for you to see. 27 because that is the number of options, we have agreed on with waste handler so far, and what is possible.
Examples: Gypsum is recycled into new plates, wood recycled into new wood plates. Rockwool waste is returned to Rockwool and recycled to new material.
Yes, 75% of all our waste is recycled. Rest: Incineration or landfill.

17. Do you know how Rockwool waste is managed?

We collect and return to them, then they process it (remelt it, I guess).

18. What are company policies to decrease the building material waste? How is it done?

Optimization of what is purchased, eg making sure gypsum plates are sourced in right sizes.
Ongoing cooperation with waste management company to ensure further possibilities for recycling are explored.

19. So, you only purchase what is necessary? Or do you order some extra materials to be sure not to run out?

We will normally source extra materials, but if not used for the project it was sourced for, we will use it for the next instead and buy less for that.

20. What are further possibilities for waste management?

Depends a lot on what is possible, what we become aware of, sometimes, by coincidence, we realize new opportunities.
Development projects to reduce material use with our development team.

21. How is material use reduced? Could you explain more and give some examples?

For example, by reducing number of gypsum plates in construction from 2 to one.
Ensuring correct storage of wooden building materials, to ensure correct quality and dry materials.

22. Is correct storage necessary only for wooden materials?

No, relevant for most materials, you cannot just put it outside, but for wood we measure moisture, and it is critical for the quality of the construction.

23. How do you ensure that the storage is correct? What measures do you use?

Monitor moist in the construction, ongoing audit outside, training of logistics department in correct storage.
Materials stored outside are wrapped in plastic to ensure that they do not get damaged. Most materials are stored indoors. However, sometimes materials stored outdoors get damaged and cannot be used in construction. Spoiled materials go to waste.

24. How much material waste do you reduce working with prefabricated elements compared to convention building construction method?

I don't know the ratio. However, I do know that we have much cleaner fractions which can more easily be taken back and made into new products.

25. What are these fractions?

Rockwool, gypsum, flooring material, wood

26. How are they cleaner?

Not wet, not mixed or with other types of building waste on a building site where you have limited space for waste segregation. Since most of the construction takes place under roof, we don't have wet materials.
I also know that we have an easier task bringing surplus materials from one project into the next, as we have an ongoing production on the same site.

27. So, you use materials from one project to another, right? Is that the case in all projects or do you still have other waste?

All materials will need to be cut, reduced in length etc, to fit, so you will always have some waste from the process.
All modules can be reused to make new construction. We use our modules to make temporary buildings, which later can be disassembled and used again. However, there are sometimes replacements needed if the building has been used up.

28. Would it be possible to know approximately how much waste is always left, even if extra materials are reused?

It is not known; it is specific for a project.

Building on a construction site, it is more difficult to pass on materials of high quality, as materials might have been exposed to wind and weather.
By the end of 2021 I will have updated figures on the amount of waste against m^2, to start tracking our performance and ability to reduce amounts. I also have numbers from 2019, but they are based on estimates.

Appendix B - Material quantities

The material quantities are calculated for concrete and timber construction building complexes according to acquired data from construction companies and assumptions based on a construction type.

Total material quantities are calculated according to building material dimensions, density, and area. The calculation is seen in Equation B 1:

$$Weight\ [kg] = \text{Thickness[m]} * \text{Area [m2]} * \text{Density } [\frac{\text{kg}}{\text{m3}}]$$

Equation B 1 – Building material weight

The material amount/ weight has been calculated for both concrete and timber construction buildings separately-

B.1 Concrete construction

The concrete construction includes 6 buildings without a basement and 2 buildings – with basement. Altogether, there are 8 buildings with 4 floors, 2 apartments on each floor. The material quantities are calculated for two types of buildings separately.

Building 1, 3, 4, 5, 6, 8					
Element	**Material**	**Thickness [m]**	**Density [kg/m³]**	**Area [m²]**	**Total [kg]**
Foundation	Concrete C20-25	0.4	2400	154.46	148285.44
	Steel reinforcement	0.025	7800	2.32	451.81
Ground floor deck	Damp proof membrane	0.001	0.13	343.42	0.04
	Concrete C20-25	0.120	2400	343.42	98904.96
	EPS insulation	0.270	15.0	343.42	1390.85
	Crushed stone grit 16-32 mm	0.149	1	343.42	51.17
External walls	Bricks	0.110	1800	1056.62	209211.55
	Mineral wool	0.240	18	1056.62	4564.62
	Air	0.020	1.3	1056.62	27.47
	Concrete C20-25	0.150	2500	1056.62	396234.00
	Steel reinforcement	0.025	7800	15.85	3090.63
Internal walls	Concrete C20-25	0.180	2000	704.42	253589.76
	Steel reinforcement	0.025	7800	10.57	2060.42
Floor deck	Concrete C35-45	0.220	2400	1058.67	558977.76
	Cement screed	0.03	1440	1058.67	45734.54
	Steel reinforcement	0.025	7800	15.88	3096.61
	Steel reinforcement	0.025	7800	7.94	1548.3
Floor finish	Laminate flooring	0.025	500	1402.09	17526.13
	Mineral wool	0.1	18	1402.09	2523.76
Windows	Aluminium plate	0.02	2700	75.48	4075.76
	Timber	0.051	500	75.48	1924.66
	3-layer window glass	0.01	2600	75.48	1962.40
Internal doors	Timber	0.051	500	45.36	1156.68
	Galvanised steel	0.051	7900	68.04	27413.32

Outside doors	Aluminium plate	0.02	2700	2.46	132.68
	Timber	0.051	500	2.46	62.65
	3-layer window glass	0.01	2600	2.46	63.88
Roof	Damp proof membrane	0.001	0.13	369.91	0.05
	EPS insulation	0.270	15.0	369.91	1498.14
	Concrete C35-45	0.220	2400	369.91	195312.48
	Steel reinforcement	0.025	7800	5.55	1081.99
	Bitumen membrane	0.01	1000	369.91	3699.10
Total per building					***1985654***
Total all buildings					***11913922***

Building 2, 7					
Element	**Material**	**Thickness [m]**	**Density [kg/m^3]**	**Area [m^2]**	**Total [kg]**
Foundation	Concrete C20-25	0.4	2400	154.46	148285.44
	Steel reinforcement	0.025	7800	2.32	451.81
Ground floor deck TD5	Damp proof membrane	0.001	0.13	303.78	0.04
	Concrete C20-25	0.120	2400	303.78	87488.64
	EPS insulation	0.270	15.0	303.78	1230.31
	Crushed stone grit 16-32 mm	0.149	1	303.78	45.26
External walls	Bricks	0.110	1800	1246.34	246774.92
	Mineral wool	0.240	18	1246.34	5384.18
	Air	0.020	1.3	1246.34	32.40
	Concrete C20-25	0.150	2500	1246.34	467376.75
	Steel reinforcement	0.025	7800	18.70	3645.54
Internal walls	Concrete C20-25	0.180	2000	830.89	299121.12
	Steel reinforcement	0.025	7800	12.46	2430.36
Floor deck	Concrete C35-45	0.220	2400	1231.47	650216.16
	Cement screed	0.03	1440	1231.47	53199.50
	Steel reinforcement	0.025	7800	18.47	3602.05
	Steel reinforcement	0.025	7800	9.24	1801.02
Floor finish	Laminate flooring	0.025	500	1535.25	19190.63
	Mineral wool	0.1	18	1535.25	2763.45
Windows	Aluminium plate	0.02	2700	75.48	4075.76
	Timber	0.051	500	75.48	1924.66
	3-layer window glass	0.01	2600	75.48	1962.40
Internal doors	Timber	0.051	500	45.36	1156.68
	Galvanised steel	0.051	7900	68.04	27413.32
Outside doors	Aluminium plate	0.02	2700	2.46	132.68
	Timber	0.051	500	2.46	62.65
	3-layer window glass	0.01	2600	2.46	63.88
Roof	Damp proof membrane	0.001	0.13	320.13	0.04
	EPS insulation	0.270	15.0	320.13	1296.53
	Concrete C35-45	0.220	2400	320.13	169028.64
	Steel reinforcement	0.025	7800	4.80	936.38

	Bitumen membrane	0.01	1000	320.13	3201.30
Total per building					***2204295***
Total all buildings					***4408589***

B.2 Timber construction

The timber construction consists of 8 types of units, from which 7 are residential units and one – common unit. The material quantities are calculated for all building units together.

Element	**Material**	**Thickness [m]**	**Density [kg/m^3]**	**Area [m^2]**	**Total [kg]**
Foundation	Concrete C20-25	0.4	2400	127.31	122219.52
	Steel reinforcement	0.025	7800	1.91	372.39
Ground floor deck 300 mm	Wood cover	0.025	500	1810.49	22631.15
	Mineral wool	0.15	18	1810.49	4888.33
	Wood joist	0.2	500	271.57	27157.38
	Air	0.15	1	1810.49	353.05
	Damp proom membrane	0.001	0.13	1810.49	0.24
	Concrete C20-25	0.120	2400	1810.49	521421.64
	EPS insulation	0.250	15.0	1810.49	6789.34
	Crushed stone grit 16-32 mm	0.149	1	1810.49	269.76
External walls 400 mm	Wood cover	0.025	2000	5853.19	292659.50
	Mineral wool	0.150	18	5853.19	15803.61
	Wooden studs	0.150	500	585.32	43898.93
	Gypsum boards	0.013	900	5853.19	68482.32
	Air	0.050	1.3	5853.19	380.46
	Gypsum boards	0.013	900	5853.19	68482.32
	Wooden studs	0.150	500	585.32	43898.93
	Mineral wool	0.150	18	5853.19	15803.61
	Gypsum boards	0.025	900	5853.19	131696.78
Internal walls 100 mm	Gypsum boards	0.025	900	7007.39	157666.28
	Mineral wool	0.050	18	7007.39	6306.65
	Wooden studs	0.050	500	350.37	8759.24
	Gypsum boards	0.025	900	7007.39	157666.28
Internal walls 300 mm	Gypsum boards	0.025	900	727.94	16378.65
	Mineral wool	0.100	18	727.94	1310.29
	Wooden studs	0.100	500	72.79	3639.70
	Air	0.050	1.3	727.94	47.32
	Mineral wool	0.100	18	727.94	1310.29
	Wooden studs	0.100	500	72.79	3639.70
	Gypsum boards	0.025	900	727.94	16378.65
Floor deck 515 mm	Wood boards	0.025	500	4314.44	53930.48
	Mineral wool	0.15	18	4314.44	11648.98
	Wood joist	0.2	500	647.17	64716.57
	Air	0.15	1	4314.44	841.32
	Gypsum boards	0.013	900	4314.44	50478.92

	Wood joist	0.1	500	431.44	21572.19
	Mineral wool	0.05	18	4314.44	3882.99
	Gypsum boards	0.025	900	4314.44	97074.86
Windows	Aluminium plate	0.02	2700	209.72	11324.88
	Timber	0.051	500	209.72	5347.86
	3-layer window glass	0.01	2600	209.72	5452.72
Internal doors	Timber	0.051	500	153.47	3913.43
	Galvanised steel	0.051	7900	230.20	92748.39
Outside doors	Aluminium plate	0.02	2700	78.75	4252.50
	Timber	0.051	500	78.75	2008.13
	3-layer window glass	0.01	2600	78.75	2047.50
Roof 600 mm	Gypsum boards	0.025	900	1425.12	32065.20
	Air	0.025	1.3	1425.12	46.32
	Wood studs	0.025	500	35.63	445.35
	Mineral wool	0.050	18	1425.12	1282.61
	Wooden studs	0.050	500	71.26	1781.40
	Mineral wool	0.150	18	1425.12	3847.82
	Wooden studs	0.150	500	1425.12	106884.00
	Damp proof membrane	0.001	0.13	1425.12	0.19
	Wooden studs	0.300	500	213.77	32065.20
	Mineral wool	0.300	18	1425.12	7695.65
	Air	0.025	1	1425.12	46.32
	Wood stud	0.100	500	142.51	7125.60
	Wood plate	0.025	500	1425.12	17814.00
	Bitumen membrane	0.01	1000	1425.12	14251.20
Total for all buildings					***2141844***

Appendix C - Waste quantities

The waste quantities are calculated for concrete and timber construction building complexes. The waste amounts and sorting fractions are acquired from corresponding construction companies. The construction material-waste proportion is calculated for each material type.

C.1 Concrete construction

Waste fraction	Construction waste (kg)	Share
Combustible construction waste	622033	45.4%
Concrete rubble	344467	25.1%
Heavy fraction for sorting	125600	9.2%
Mixed construction waste	112067	8.2%
Iron/ Metal	88400	6.4%
Asphalt	23867	1.7%
Residual waste	18900	1.4%
Tiles, bricks, and concrete (clean)	14933	1.1%
Insulation	13333	1.0%
Asphalt/ Concrete rubble	7267	0.5%

Cardboard	483	0.04%
Spray cans	203	0.01%
Paper	3	0.0002%
Recycling		53.3%
Incineration		46.7%

C.2 Timber construction

Waste fraction	Manufacturing waste [kg]	Share
Mixed construction waste	65260	35.0%
Mixed wood	56830	30.5%
Non-combustible construction waste	27690	14.9%
Combustible construction waste	17560	9.4%
Paint waste	4480	2.4%
Corrugated cardboard	4380	2.4%
Iron/ metal	2380	1.3%
Hard plastic for packaging	2060	1.1%
Hard plastic for packaging	2000	1.1%
Iron/ metal	1640	0.9%
Heavy fraction for sorting	1580	0.8%
Iron/ metal	330	0.2%
Hazardous waste	32	0.02%
Recycling	136492	73.3%
Incineration	22040	11.8%
Landfill	27690	14.9%

Waste fraction	Installation waste [kg]	Share
Mixed construction waste	103220	68.6%
Combustible construction waste	23280	15.5%
Heavy fraction for sorting	11520	7.7%
Iron/ metal	10280	6.8%
Residual waste	2145	1.4%
Recycling	125020	83.1%
Incineration	25425	16.9%

Appendix D – LCA analysis

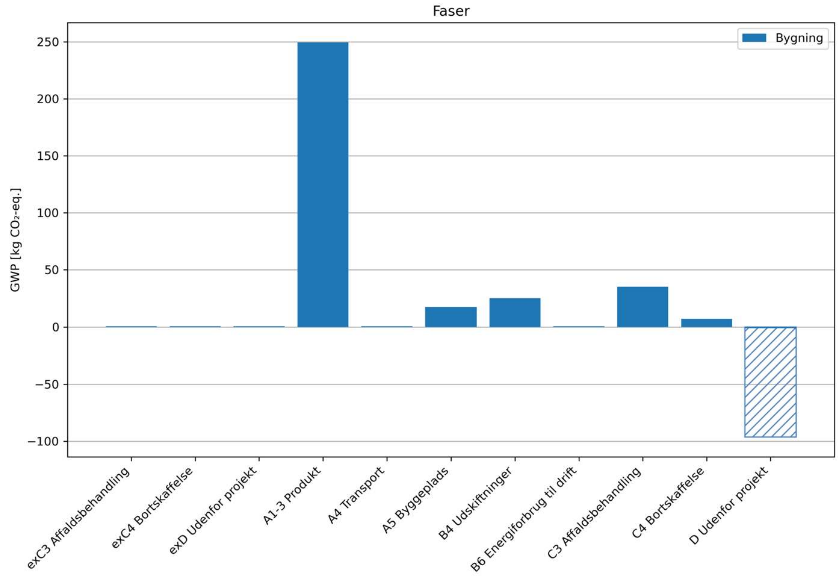
The life cycle assessment analysis is done in LCAbyg according to previously made construction material and waste analyses. The results include quantities, replacements, weight, lifetime, and environmental impact of each used material and building element, as well as total for the building. The following sections show LCA analyses for concrete and timber construction buildings.

D.1 Concrete construction

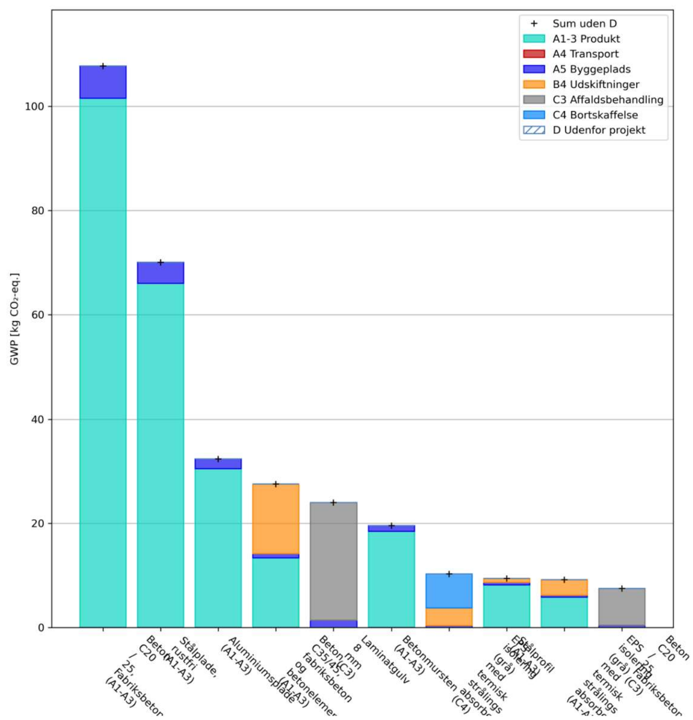
D.1.1 Building construction

	Usikkerhedsfaktor	Udskiftninger	Indtastet mængde	Udregnet mængde	Vægt	Levetid
Bygning					1,632e+07 kg	
Bygningsdele					1,632e+07 kg	
Dæk					6,016e+06 kg	
Etagedæk					5,237e+06 kg	
Floor deck					5,237e+06 kg	
Cement			264,00 m³		3,802e+05 kg	
Afretningslag, cementbaseret	1	0	1440,00 kg/m³	380160,00 kg	3,802e+05 kg	100 år
Concrete			1939,00 m³		4,654e+06 kg	
Beton C20/25, Fabriksbeton	1	0	2400,00 kg/m³	1971,86 m³	4,654e+06 kg	100 år
Floor			287,00 m³		1,435e+05 kg	
Laminatgulv 8 mm	1	0	500,00 kg/m³	19261,74 m²	1,435e+05 kg	100 år
Mineral wool			1148,00 m³		2,066e+04 kg	
Loftspanel, Mineraluld	1	0	18,00 kg/m³	8610,00 m²	2,066e+04 kg	100 år
Reinforcement			5,00 m³		3,900e+04 kg	
Stålprofil	1	0	7800,00 kg/m³	39000,00 kg	3,900e+04 kg	100 år
Kælderdæk					7,792e+05 kg	
Terrain deck					7,792e+05 kg	
Concrete			320,00 m³		7,680e+05 kg	
Beton C20/25, Fabriksbeton	1	0	2400,00 kg/m³	325,42 m³	7,680e+05 kg	100 år
DPM			3,00 m³		3,900e-01 kg	
Dampspærre PE (tykkelse 0,0002 m)	1	0	0,13 kg/m³	1,95 m²	3,900e-01 kg	50 år
EPS insulation			720,00 m³		1,080e+04 kg	
EPS isolering (grå) med termisk strålings abso...	1	0	15,00 kg/m³	650,60 m³	1,080e+04 kg	50 år
Stone grit			398,00 m³		3,980e+02 kg	
Grus 16/32 (tørret)	1	0	1,00 kg/m³	398,00 kg	3,980e+02 kg	80 år
Fundamenter					1,190e+06 kg	
Randfundamenter					1,190e+06 kg	
Foundation					1,190e+06 kg	
Concrete			494,00 m³		1,186e+06 kg	
Beton C20/25, Fabriksbeton	1	0	2400,00 kg/m³	502,37 m³	1,186e+06 kg	120 år
Reinforcement			0,50 m³		3,900e+03 kg	
Stålprofil	1	0	7800,00 kg/m³	3900,00 kg	3,900e+03 kg	120 år
Indervægge					2,137e+06 kg	
Ikke-bærende indervægge					2,137e+06 kg	
Internal wall					2,137e+06 kg	
Concrete			1060,00 m³		2,120e+06 kg	
Beton C20/25, Fabriksbeton	1	0	2000,00 kg/m³	898,31 m³	2,120e+06 kg	100 år
Reinforcement			2,20 m³		1,716e+04 kg	
Stålprofil	1	0	7800,00 kg/m³	17160,00 kg	1,716e+04 kg	100 år
Tage					1,559e+06 kg	
Tage					1,559e+06 kg	
Roof					1,559e+06 kg	
Bitumen			29,00 m³		2,900e+04 kg	
Tagpap, bitumen toplag, skiferbestrøet	1	1	1000,00 kg/m³	4677,42 m²	2,900e+04 kg	40 år
Concrete			629,00 m³		1,510e+06 kg	
Beton C35/45, fabriksbeton og betonelementer	1	1	2400,00 kg/m³	629,00 m³	1,510e+06 kg	40 år
DPM			3,00 m³		3,900e-01 kg	
Dampspærre PE (tykkelse 0,0002 m)	1	1	0,13 kg/m³	1,95 m²	3,900e-01 kg	40 år
EPS insulation			772,00 m³		1,158e+04 kg	
EPS isolering (grå) med termisk strålings abso...	1	1	15,00 kg/m³	697,59 m³	1,158e+04 kg	40 år
Reinforcement			1,10 m³		8,580e+03 kg	
Stålprofil	1	1	7800,00 kg/m³	8580,00 kg	8,580e+03 kg	40 år
Vinduer, døre, glasfacader					2,963e+05 kg	
Døre					2,328e+05 kg	
External door					2,100e+03 kg	
Aluminium			0,40 m³		1,080e+03 kg	
Aluminiumsplade	1	0	2700,00 kg/m³	1080,00 kg	1,080e+03 kg	50 år
Glass			0,20 m³		5,200e+02 kg	
Glas 3 mm	1	0	2600,00 kg/m³	52,00 m²	5,200e+02 kg	50 år
Timber			1,00 m³		5,000e+02 kg	
Vinduesramme, træ	1	0	500,00 kg/m³	236,97 m	5,000e+02 kg	50 år
Internal door					2,307e+05 kg	
Steel			28,00 m³		2,212e+05 kg	
Stålplade, rustfri	1	0	7900,00 kg/m³	221200,00 kg	2,212e+05 kg	50 år
Timber			19,00 m³		9,500e+03 kg	
Konstruktionstræ, KVH-kvalitet (15% fugt / 13...	1	0	500,00 kg/m³	17,96 m³	9,500e+03 kg	50 år
Vinduer					6,350e+04 kg	
Window					6,350e+04 kg	
Aluminium			12,00 m³		3,240e+04 kg	
Aluminiumsplade	1	0	2700,00 kg/m³	32400,00 kg	3,240e+04 kg	50 år
Glass			6,00 m³		1,560e+04 kg	
Glas 3 mm	1	0	2600,00 kg/m³	1560,00 m²	1,560e+04 kg	50 år
Timber			31,00 m³		1,550e+04 kg	
Vinduesramme, træ	1	0	500,00 kg/m³	7345,97 m	1,550e+04 kg	50 år
Ydervægge					5,126e+06 kg	
Ydervægge					5,126e+06 kg	
External wall					5,126e+06 kg	
Brick			972,00 m³		1,750e+06 kg	
Betonmursten	1	0	1800,00 kg/m³	874,80 m³	1,750e+06 kg	120 år
Concrete			1325,00 m³		3,312e+06 kg	
Beton C20/25, Fabriksbeton	1	0	2500,00 kg/m³	1403,60 m³	3,312e+06 kg	120 år
Mineral wool			2120,00 m³		3,816e+04 kg	
Mineraluld, facadesystem	1	0	18,00 kg/m³	825,08 m³	3,816e+04 kg	120 år
Reinforcement			3,30 m³		2,574e+04 kg	
Stålprofil	1	0	7800,00 kg/m³	25740,00 kg	2,574e+04 kg	120 år

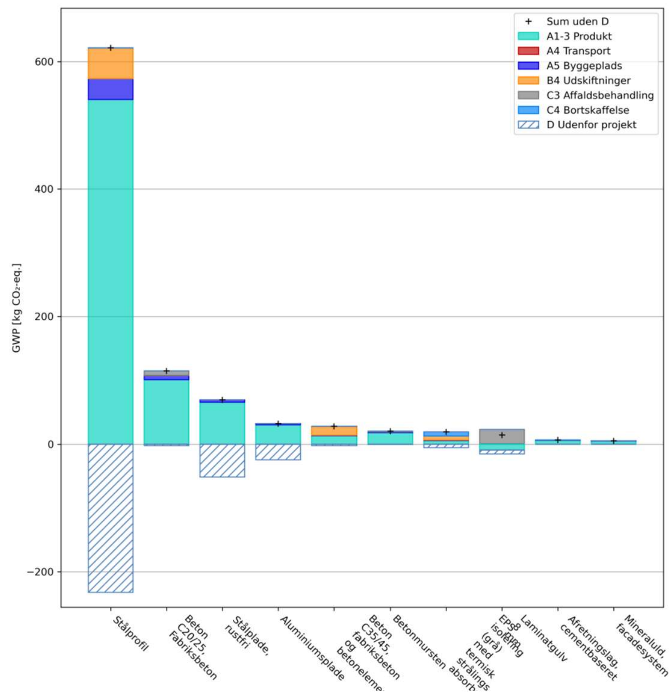
D.1.2 GWP for building elements and materials



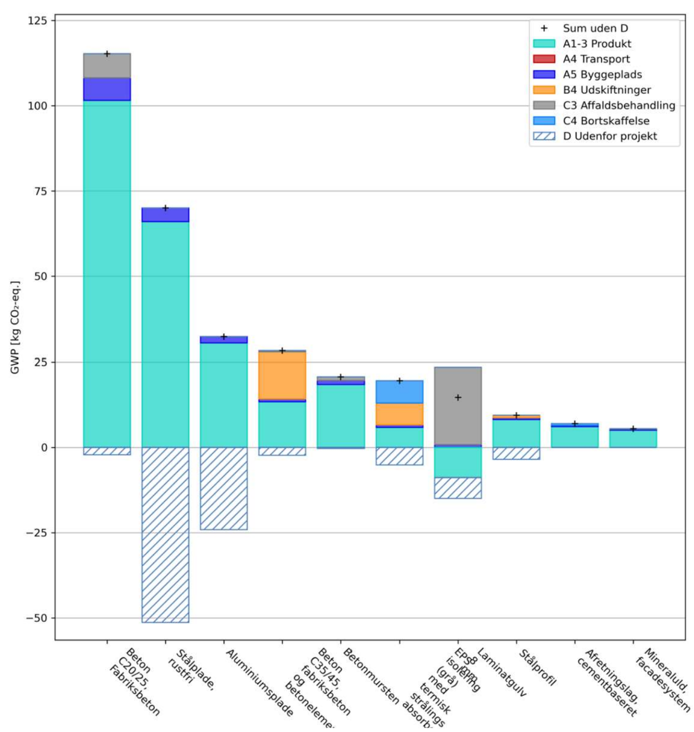
Building stages GWP per m²



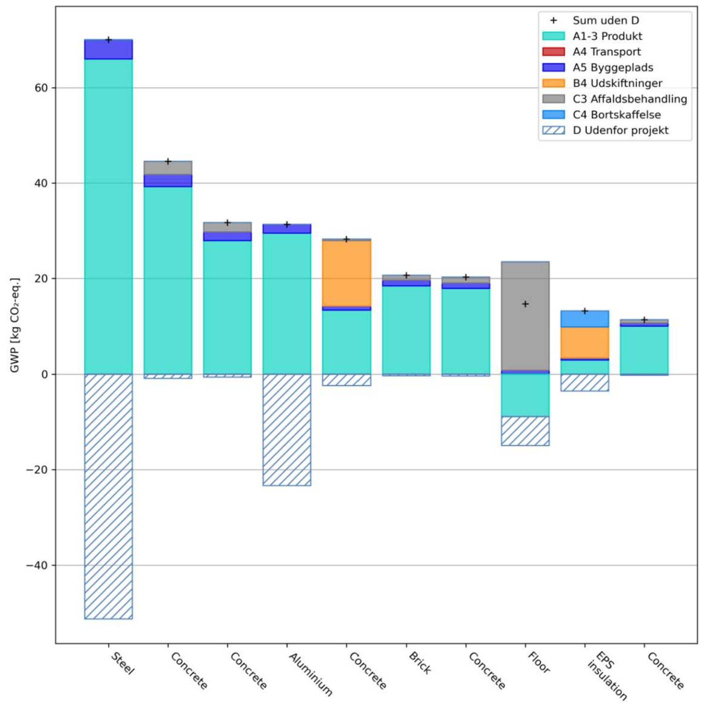
Building stages GWP per m²



Building elements GWP per m2



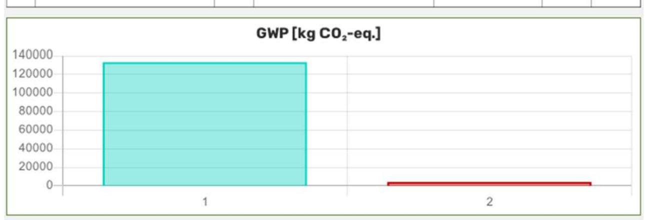
Construction materials GWP per m²



Construction materials GWP per m²

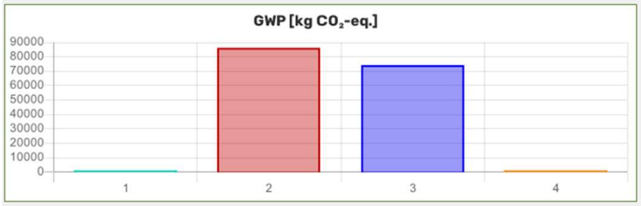
D.1.3 GWP for building elements

	Navn	Lag	Beskrivelse	Mængde	Gruppe	Kilde
1	Concrete	1		494 m³	Randfunda…	Bruger
2	Reinforcement	1		0,5 m³	Randfunda…	Bruger



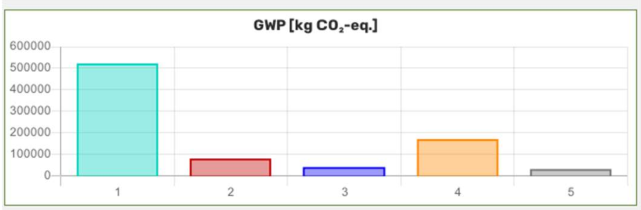
GWP for foundation

	Navn	Lag	Beskrivelse	Mængde	Gruppe	Kilde
1	DPM	1		3 m³	Andet	Bruger
2	Concrete	1		320 m³	Kælder dæk	Bruger
3	EPS insulation	1		720 m³	Kælder dæk	Bruger
4	Stone grit	1		398 m³	Kælder dæk	Bruger



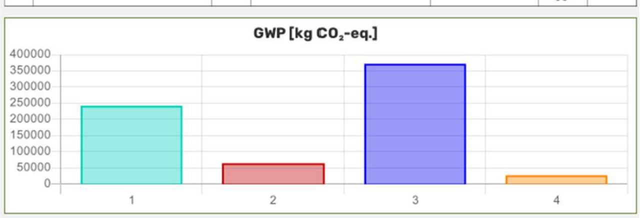
GWP for ground floor deck

	Navn	Lag	Beskrivelse	Mængde	Gruppe	Kilde
1	Concrete	1		1939 m³	Etaged æk	Bruger
2	Cement	1		264 m³	Etaged æk	Bruger
3	Reinforcement	1		5 m³	Etaged æk	Bruger
4	Floor	1		287 m³	Etaged æk	Bruger
5	Mineral wool	1		1148 m³	Etaged æk	Bruger



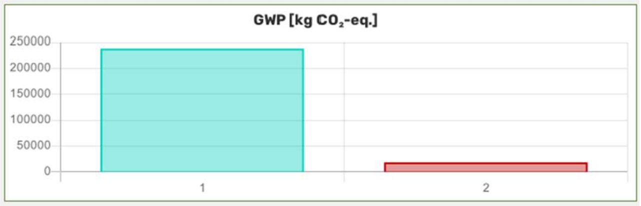
GWP for floor deck

	Navn	Lag	Beskrivelse	Mængde	Gruppe	Kilde
1	Brick	1		972 m³	Yderv ægge	Bruger
2	Mineral wool	1		2120 m³	Yderv ægge	Bruger
3	Concrete	1		1325 m³	Yderv ægge	Bruger
4	Reinforcement	1		3,3 m³	Yderv ægge	Bruger



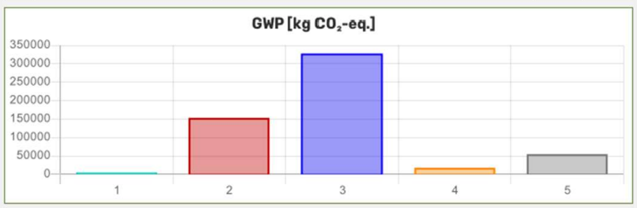
GWP for external wall

	Navn	Lag	Beskrivelse	Mængde	Gruppe	Kilde
1	Concrete	1		1060 m³	Ikke-bær...	Bruger
2	Reinforcement	1		2,2 m³	Ikke-bær...	Bruger



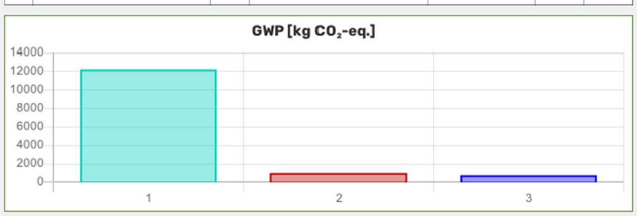
GWP for internal wall

	Navn	Lag	Beskrivelse	Mængde	Gruppe	Kilde
1	DPM	1		3 m³	Tage	Bruger
2	EPS insulation	1		772 m³	Tage	Bruger
3	Concrete	1		629 m³	Tage	Bruger
4	Reinforcement	1		1,1 m³	Tage	Bruger
5	Bitumen	2		29 m³	Tage	Bruger



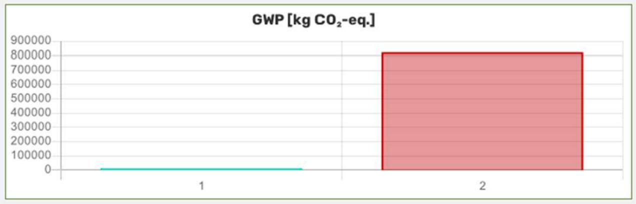
GWP for roof

	Navn	Lag	Beskrivelse	Mængde	Gruppe	Kilde
1	Aluminium	1		0,4 m³	Døre	Bruger
2	Timber	1		1 m³	Døre	Bruger
3	Glass	3		0,2 m³	Døre	Bruger



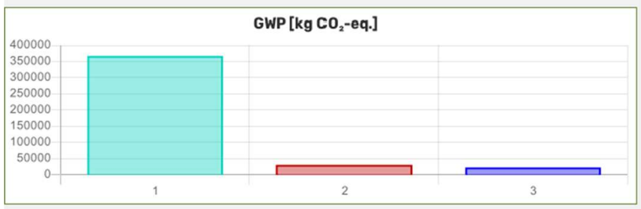
GWP for external door

	Navn	Lag	Beskrivelse	Mængde	Gruppe	Kilde
1	Timber	1		19 m³	Døre	Bruger
2	Steel	1		28 m³	Døre	Bruger



GWP for internal door

	Navn	Lag	Beskrivelse	Mængde	Gruppe	Kilde
1	Aluminium	1		12 m³	Vinduer	Bruger
2	Timber	1		31 m³	Vinduer	Bruger
3	Glass	3		6 m³	Vinduer	Bruger



GWP for window

D.2 Timber construction

D.2.1 Building construction

Bygning					2,072e+06 kg	
Bygningsdele					2,072e+06 kg	
Dæk					9,749e+05 kg	
Etagedæk					3,926e+05 kg	
Floor deck					3,926e+05 kg	
Floor			287,00 m³		1,435e+05 kg	
Trægulv, stavparket, 22 mm	1	0	500,00 kg/m³	12478,26 m²	1,435e+05 kg	100 år
Gypsum board			164,00 m³		1,476e+05 kg	
Gipskartonplade 13 mm, imprægneret	1	0	900,00 kg/m³	14760,00 m²	1,476e+05 kg	100 år
Mineral wool			863,00 m³		1,553e+04 kg	
Loftspanel, Mineraluld	1	0	18,00 kg/m³	6472,50 m²	1,553e+04 kg	100 år
Wood joist			172,00 m³		8,600e+04 kg	
Konstruktionstræ, KVH-kvalitet (15% fugt / 13...	1	0	500,00 kg/m³	162,57 m³	8,600e+04 kg	100 år
Kælderdæk					5,823e+05 kg	
Terrain deck					5,823e+05 kg	
Concrete			217,00 m³		5,208e+05 kg	
Beton C20/25, Fabriksbeton	1	0	2400,00 kg/m³	220,68 m³	5,208e+05 kg	100 år
DPM			2,00 m³		2,600e-01 kg	
Dampspærre PE (tykkelse 0,0002 m)	1	0	0,13 kg/m³	1,30 m²	2,600e-01 kg	100 år
EPS insulation			453,00 m³		6,795e+03 kg	
EPS isolering (grå) med termisk strålings abso...	1	0	15,00 kg/m³	409,34 m³	6,795e+03 kg	100 år
Floor			45,00 m³		2,250e+04 kg	
Trægulv, stavparket, 22 mm	1	0	500,00 kg/m³	1956,52 m²	2,250e+04 kg	100 år
Mineral wool			272,00 m³		4,896e+03 kg	
Loftspanel, Mineraluld	1	0	18,00 kg/m³	2040,00 m²	4,896e+03 kg	100 år
Stone grit			270,00 m³		2,700e+02 kg	
Grus 16/32 (tørret)	1	0	1,00 kg/m³	270,00 kg	2,700e+02 kg	100 år
Timber joist			54,00 m³		2,700e+04 kg	
Konstruktionstræ, KVH-kvalitet (15% fugt / 13...	1	0	500,00 kg/m³	51,04 m³	2,700e+04 kg	100 år
Fundamenter					2,352e+04 kg	
Randfundamenter					2,352e+04 kg	
Foundation					2,352e+04 kg	
Concrete			0,05 m³		1,200e+02 kg	
Beton C20/25, Fabriksbeton	1	0	2400,00 kg/m³	0,05 m³	1,200e+02 kg	120 år
Reinforcement			3,00 m³		2,340e+04 kg	
Stålprofil	1	0	7800,00 kg/m³	23400,00 kg	2,340e+04 kg	120 år

Indervægge					3,666e+05 kg	
Ikke-bærende indervægge					3,666e+05 kg	
Internal wall					3,666e+05 kg	
Gypsum board			386,00 m³		3,474e+05 kg	
Gipskartonplade 13 mm, imprægneret	1	0	900,00 kg/m³	34740,00 m²	3,474e+05 kg	100 år
Mineral wool			176,00 m³		3,168e+03 kg	
Mineraluld, facadesystem	1	0	18,00 kg/m³	68,50 m³	3,168e+03 kg	100 år
Wooden studs			32,00 m³		1,600e+04 kg	
Konstruktionstræ, KVH-kvalitet (15% fugt / 13...	1	0	500,00 kg/m³	30,25 m³	1,600e+04 kg	100 år

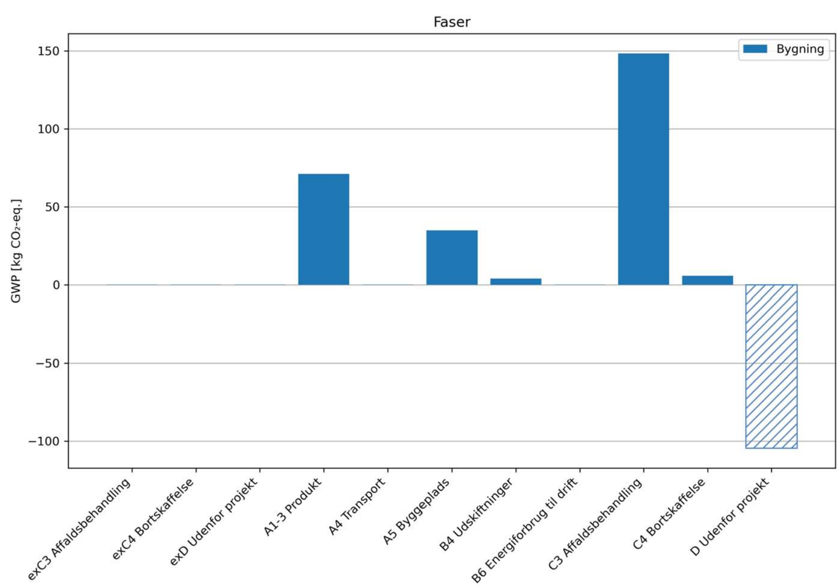
Tage					1,702e+05 kg	
Tage					1,702e+05 kg	
Roof					1,702e+05 kg	
Bitumen			14,00 m³		1,400e+04 kg	
Tagpap, bitumen toplag, skiferbestrøet	1	1	1000,00 kg/m³	2258,06 m²	1,400e+04 kg	40 år
DPM			1,00 m³		1,300e-01 kg	
Dampspærre PE (tykkelse 0,0002 m)	1	1	0,13 kg/m³	0,65 m²	1,300e-01 kg	40 år
Gypsum board			36,00 m³		3,240e+04 kg	
Gipskartonplade 13 mm, imprægneret	1	0	900,00 kg/m³	3240,00 m²	3,240e+04 kg	60 år
Mineral wool			713,00 m³		1,283e+04 kg	
Mineraluld, trykfast til tagsystem	1	0	18,00 kg/m³	88,51 m³	1,283e+04 kg	60 år
Wood plate			36,00 m³		1,800e+04 kg	
Træfiberplade, medium densitet, MDF	1	0	500,00 kg/m³	24,41 m³	1,800e+04 kg	60 år
Wood stud			186,00 m³		9,300e+04 kg	
Konstruktionstræ, KVH-kvalitet (15% fugt / 13...	1	0	500,00 kg/m³	175,80 m³	9,300e+04 kg	60 år

Vinduer, døre, glasfacader					1,303e+05 kg	
Døre					1,088e+05 kg	
External door					1,000e+04 kg	
Aluminium			2,00 m³		5,400e+03 kg	
Aluminiumsplade	1	0	2700,00 kg/m³	5400,00 kg	5,400e+03 kg	50 år
Glass			1,00 m³		2,600e+03 kg	
Glas 3 mm	1	0	2600,00 kg/m³	260,00 m²	2,600e+03 kg	50 år
Timber			4,00 m³		2,000e+03 kg	
Vinduesramme, træ	1	0	500,00 kg/m³	947,87 m	2,000e+03 kg	50 år
Internal door					9,880e+04 kg	
Steel			12,00 m³		9,480e+04 kg	
Stålplade, rustfri	1	0	7900,00 kg/m³	94800,00 kg	9,480e+04 kg	50 år
Timber			8,00 m³		4,000e+03 kg	
Konstruktionstræ, KVH-kvalitet (15% fugt / 13...	1	0	500,00 kg/m³	7,56 m³	4,000e+03 kg	50 år

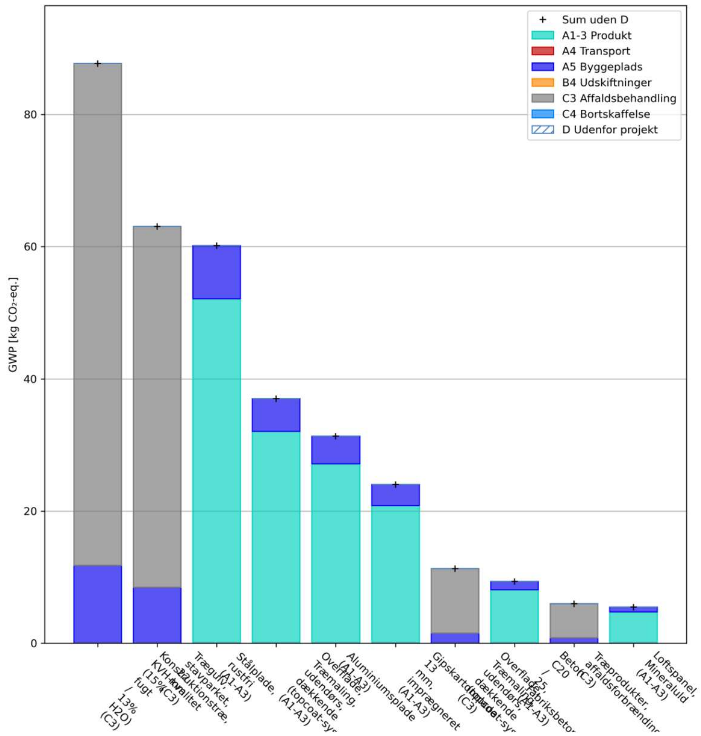
Vinduer					2,150e+04 kg	
Window					2,150e+04 kg	
Aluminium			4,00 m³		1,080e+04 kg	
Aluminiumsplade	1	0	2700,00 kg/m³	10800,00 kg	1,080e+04 kg	50 år
Glass			2,00 m³		5,200e+03 kg	
Glas 3 mm	1	0	2600,00 kg/m³	520,00 m²	5,200e+03 kg	50 år
Timber			11,00 m³		5,500e+03 kg	
Vinduesramme, træ	1	0	500,00 kg/m³	2606,64 m	5,500e+03 kg	50 år

Ydervægge					4,064e+05 kg	
Ydervægge					4,064e+05 kg	
External wall					4,064e+05 kg	
Gypsum board			304,00 m³		2,736e+05 kg	
Gipskartonplade 13 mm, imprægneret	1	0	900,00 kg/m³	27360,00 m²	2,736e+05 kg	60 år
Mineral wool			878,00 m³		1,580e+04 kg	
Mineraluld, facadesystem	1	0	18,00 kg/m³	341,71 m³	1,580e+04 kg	120 år
Timber cover			146,00 m³		7,300e+04 kg	
Overflade, Træmaling, udendørs, dækkende (t...	1	0	500,00 kg/m³	73000,00 kg	7,300e+04 kg	60 år
Wood studs			88,00 m³		4,400e+04 kg	
Konstruktionstræ, KVH-kvalitet (15% fugt / 13...	1	0	500,00 kg/m³	83,18 m³	4,400e+04 kg	60 år

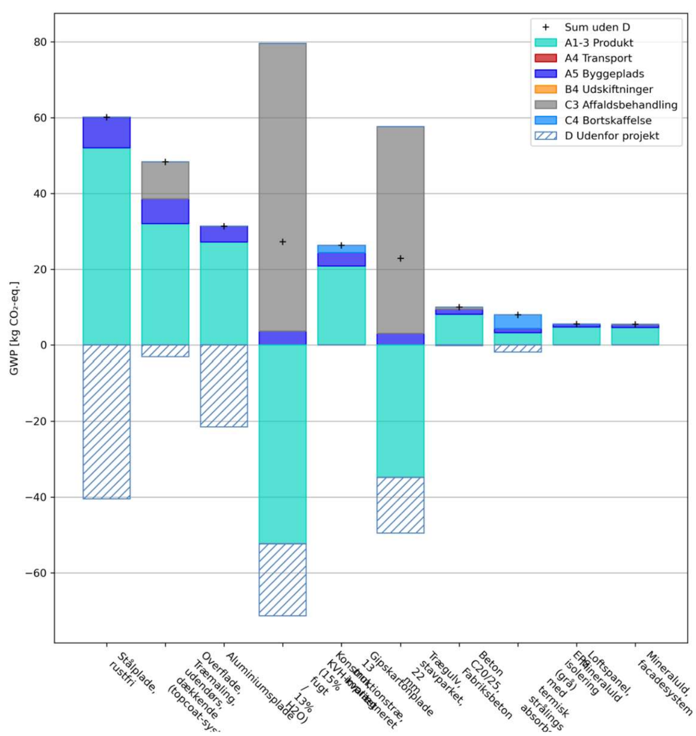
D.2.2 GWP for building stages and materials



Building stages GWP per m²



Building stages GWP per m²



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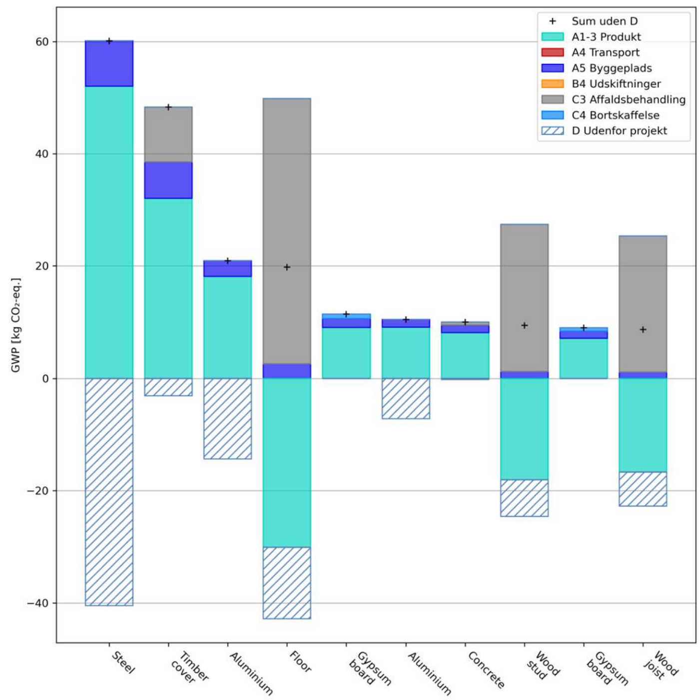
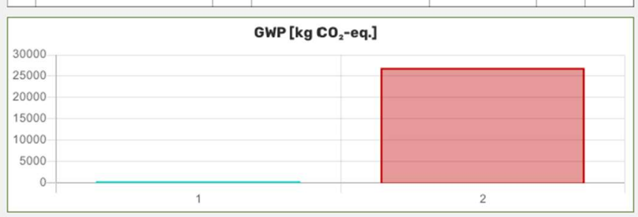
Building elements GWP per m²



Construction materials GWP per m²

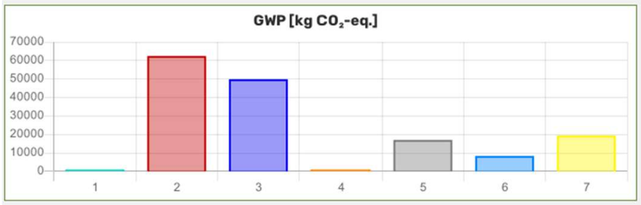
D.2.3 GWP for building elements

	Navn	Lag	Beskrivelse	Mængde	Gruppe	Kilde
1	Concrete	1		0,05 m³	Randfunda...	Bruger
2	Reinforcement	1		3 m³	Randfunda...	Bruger



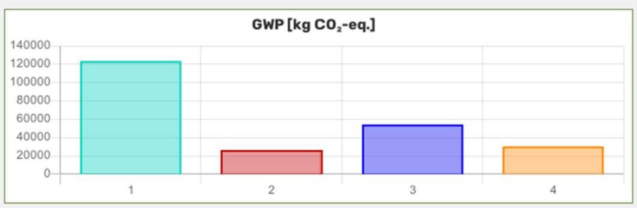
GWP for foundation

	Navn	Lag	Beskrivelse	Mængde	Gruppe	Kilde
1	DPM	1		2 m³	Andet	Bruger
2	Concrete	1		217 m³	Kælder dæk	Bruger
3	EPS insulation	1		453 m³	Kælder dæk	Bruger
4	Stone grit	1		270 m³	Kælder dæk	Bruger
5	Timber joist	1		54 m³	Kælder dæk	Bruger
6	Mineral wool	1		272 m³	Kælder dæk	Bruger
7	Floor	1		45 m³	Kælder dæk	Bruger



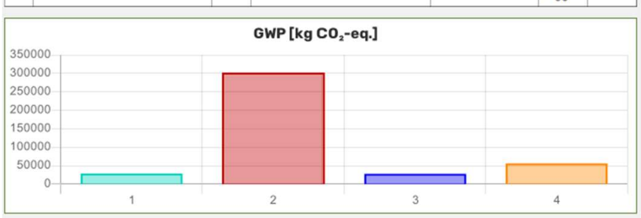
GWP for ground floor deck

	Navn	Lag	Beskrivelse	Mængde	Gruppe	Kilde
1	Floor	1		287 m³	Etagedæk	Bruger
2	Mineral wool	1		863 m³	Etagedæk	Bruger
3	Wood joist	2		172 m³	Etagedæk	Bruger
4	Gypsum board	3		164 m³	Etagedæk	Bruger



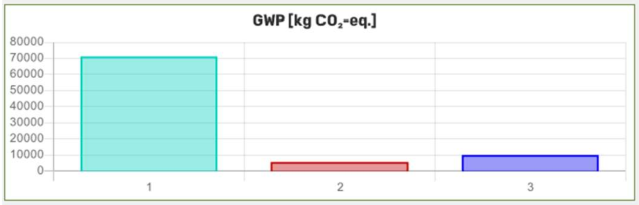
GWP for floor deck

	Navn	Lag	Beskrivelse	Mængde	Gruppe	Kilde
1	Mineral wool	2		878 m³	Ydervægge	Bruger
2	Timber cover	1		146 m³	Ydervægge	Bruger
3	Wood studs	2		88 m³	Ydervægge	Bruger
4	Gypsum board	4		304 m³	Ydervægge	Bruger



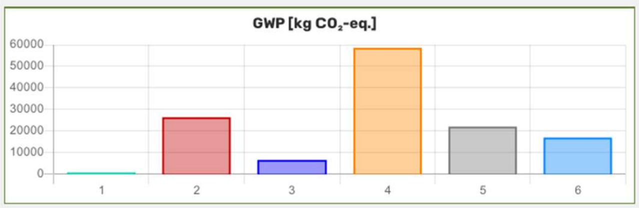
GWP for external wall

	Navn	Lag	Beskrivelse	Mængde	Gruppe	Kilde
1	Gypsum board	4		386 m³	Ikke-bær…	Bruger
2	Mineral wool	3		176 m³	Ikke-bær…	Bruger
3	Wooden studs	3		32 m³	Ikke-bær…	Bruger



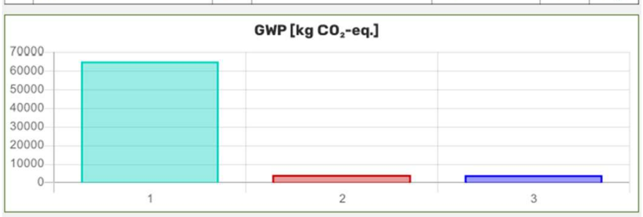
GWP for internal wall

	Navn	Lag	Beskrivelse	Mængde	Gruppe	Kilde
1	DPM	1		1 m³	Tage	Bruger
2	Bitumen	2		14 m³	Tage	Bruger
3	Gypsum board	1		36 m³	Tage	Bruger
4	Wood stud	4		186 m³	Tage	Bruger
5	Mineral wool	3		713 m³	Tage	Bruger
6	Wood plate	1		36 m³	Tage	Bruger



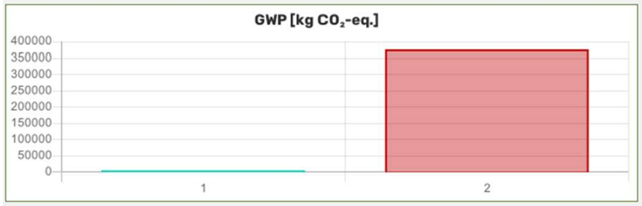
GWP for roof

	Navn	Lag	Beskrivelse	Mængde	Gruppe	Kilde
1	Aluminium	1		2 m³	Døre	Bruger
2	Timber	1		4 m³	Døre	Bruger
3	Glass	3		1 m³	Døre	Bruger



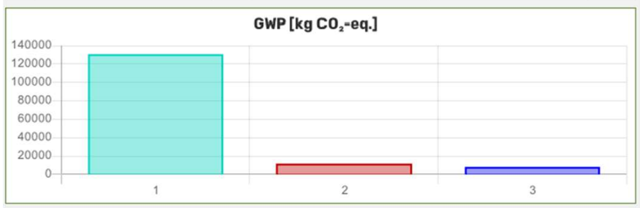
GWP for external door

	Navn	Lag	Beskrivelse	Mængde	Gruppe	Kilde
1	Timber	1		8 m³	Døre	Bruger
2	Steel	1		12 m³	Døre	Bruger



GWP for internal door

	Navn	Lag	Beskrivelse	Mængde	Gruppe	Kilde
1	Aluminium	1		4 m³	Vinduer	Bruger
2	Timber	1		11 m³	Vinduer	Bruger
3	Glass	3		2 m³	Vinduer	Bruger



GWP for window