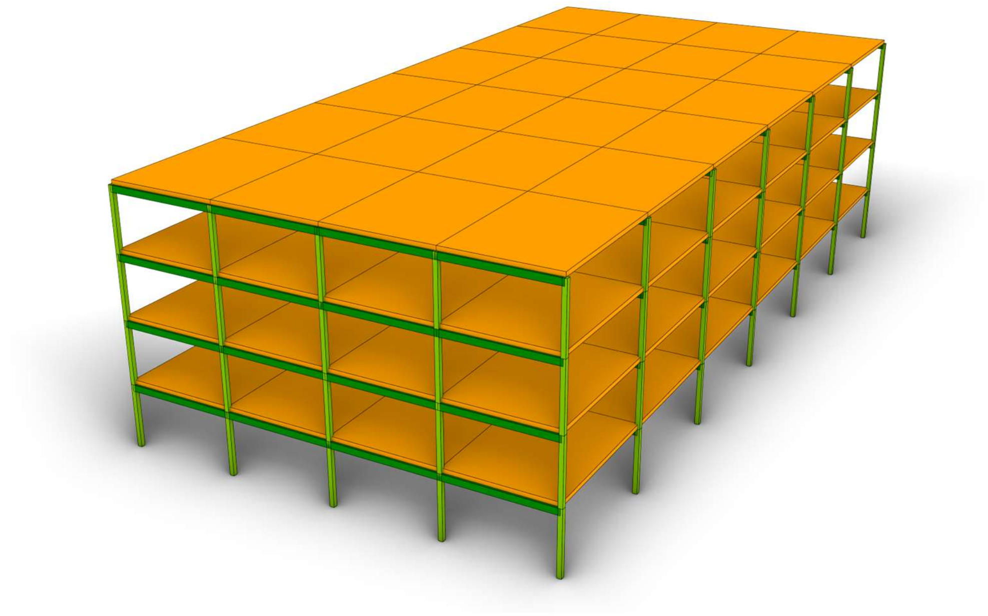

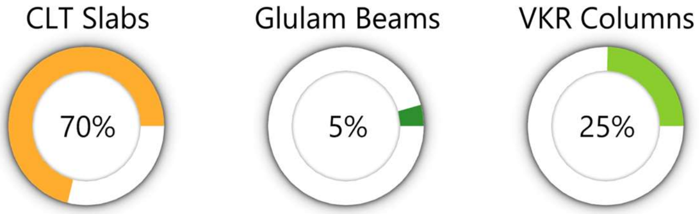

Predicting the Environmental Impact of Structural Systems with Parameterization

Development of a design tool for the early design stages

Master's Thesis in Structural Engineering and Building Technology

ROBIN FLYMAN

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024
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Master's thesis ACEX30

Predicting the Environmental Impact of Structural Systems with Parameterization

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Cover: Environmental impact assessment of a structural system generated by the tool.

Department of Architecture and Civil Engineering
Gothenburg, Sweden 2024

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Abstract

With the increasingly alarming threat from global warming, there is an urgent need to reduce the CO_2 emissions across all sectors. With 38% of the emissions globally and 21% in Sweden, there is a great potential to reduce the carbon footprint of the construction sector. The emissions from a building are split into embodied and operational carbon, where new laws and regulations in Sweden will start targeting the embodied carbon in buildings. In Sweden, the structural system accounts for half of the embodied carbon in a building on average.

The current procedure of conducting a life cycle assessment is often time-consuming and not suitable for early design stages, where there are many uncertainties. Designers need to have a holistic view when considering the emissions of a structural system, as optimising one part can increase the emissions from other parts of the system. In this thesis, a parametric tool was developed to address these points; uncertainties in the early stages, time constraints and limited knowledge regarding how the interplay is between the environmental impact and the parameters that controls the design of the structural system.

The parametric tool has an emphasis on structural design, where the aim is to generate structural systems and predict the environmental impact at early stages, where the most impact can be achieved to the lowest cost. This tool models a framed structural system with columns, beams, and slabs, then performs a load takedown. The modular design of the tool allows it to be modified or expanded in the future.

The parametric tool uses pre-calculated elements to design the structural system, after which it calculates and display the environmental impact to the user in a comprehensive way. Optimisation algorithms can be used to find some of the most optimised design alternatives for the given objectives.

A case study has been performed to verify the performance and accuracy of the tool. The results from the case study showed that the tool will select similar cross sections as a structural engineer in the preliminary design stages, resulting in comparable carbon emissions. It was challenging to compare the emissions for the structural system between the reference building and the system generated by the tool, as the reference building included load bearing walls, which is not included in the tool at this stage. The tool could be further developed by including load-bearing walls, foundation, and horizontal stabilisation.

Keywords: Structural systems, embodied carbon, decarbonize, simplified life cycle assessment, early stage design, topology optimisation, multi-objective optimisation, parametric design, Grasshopper.

Förutsägning av Miljöpåverkan från Stomsystem med Parametrisering
Utveckling av ett designverktyg för tidiga design skeden
ROBIN FLYMAN
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Sammanfattning

Med hotet från den globala uppvärmningen så finns ett brådskande behov av att minska koldioxidutsläppen inom alla sektorer. Med 38% av utsläppen globalt och 21% i Sverige så finns det en stor potential att minska byggsektorns koldioxidavtryck. Utsläppen från en byggnad delas upp i inbyggt- och operativt kol, där nya lagar och regleringar i Sverige kommer att rikta in sig på det inbyggda kolet i byggnader. I Sverige står stomsystemet i genomsnitt för hälften av det inbyggda kolet i en byggnad.

Det nuvarande proceduren för att genomföra en livscykelanalys är ofta tidskrävande och lämpar sig inte för tidiga design skeden, där det finns många osäkerheter. Konstruktörer måste ha en helhetssyn med hänsyn till utsläppen från ett stomsystem, eftersom att optimera en del kan öka utsläppen från andra delar av systemet. I detta examensarbete utvecklades ett parametriskt verktyg för att hantera dessa punkter; osäkerheter i tidiga skeden, tidsbegränsningar och begränsad kunskap kring hur samspelet ser ut mellan miljöpåverkan och de parametrar som styr utformningen av stomsystemet.

Det parametriska verktyget har ett fokus på designen av konstruktionen. Där syftet är att generera stomsystem och förutsäga miljöpåverkan i tidiga skeden, där störst påverkan kan uppnås till lägsta kostnad. Verktyget modellerar ett pelar-balksystem med bjälklag, balkar och pelare och utför en lastnedräkning. Verktygets modulära design gör det möjligt att modifiera eller bygga ut verktyget i framtiden.

Det parametriska verktyget använder sig av förhandsberäknade element för att designa stomsystemet, varefter det beräknar och ger användaren en heltäckande bild av miljöpåverkan. Optimeringsalgoritmer kan användas för att hitta några av de mest optimerade designalternativen för de angivna målen.

En fallstudie har genomförts för att verifiera verktygets prestanda och noggrannhet. Resultaten från fallstudien visade att verktyget kommer att välja liknande tvärsnitt som en konstruktör i de tidiga designskedena, vilket resulterar i jämförbara koldioxidutsläpp. Det var utmanande att jämföra utsläppen för stomsystemet mellan referensbyggnaden och det system som genererats av verktyget, eftersom referensbyggnaden hade bärande väggar som en del av stomsystemet, vilket inte ingår i verktyget i detta skede. Verktyget kan vidareutvecklas genom att inkludera bärande väggar, grund, samt inkludera horisontell stabilisering.

Nyckelord: Stomsystem, inbyggt kol, förenklad livscykelanalys, tidiga design skeden, topologioptimering, flermålsoptimering, parametrisk design, Grasshopper.

Acknowledgements

My work on this individual research project would not have been possible without the academic support of my supervisors, Daniel Jonsson and Jonathan Söderqvist, who never failed to encourage and provide me with valuable feedback. For that, I am forever grateful. Thank you, Daniel and Jonathan, it has been a great journey.

My supervisor at Chalmers University of Technology, Lic. Toivo Säwén, has helped me immensely with my report writing and provided valuable feedback on the tool I developed. I would like to thank you Toivo, for helping me raise the bar. A special thanks to my examiner, Senior Lecturer Mats Ander, for your commitment and all the support and encouragement I received.

At times, I consulted former coworkers at Buro Happold to gain feedback and insights from the industry. I would like to extend my thanks to them, and in particular Dr. Fraser Greenroyd, for dedicating time to advise me. And last but not least, I would like to extend my appreciation to the employees at VBK Konsulterande Ingenjörer AB for the help and joyful moments during these months.

Robin Flyman, Gothenburg, June 2024

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List of Abbreviations

CO_2	Carbon Dioxide
CO_2-eq	Carbon Dioxide Equivalent
BBR	Boverkets Byggregler
BF-BOF	Blast Furnace-Basic Oxygen Furnace
CLT	Cross-Laminated Timber
EAF	Electric Arc Furnace
EKS	Europeiska Konstruktionsstandarder
EPD	Environmental Product Declaration
EWP	Engineered Wooden Products
FLS	Fatigue Limit State
GBFS	Granulated Blast Furnace Slag
GWP	Global Warming Potential
LCA	Life Cycle Assessment
OOP	Object Oriented Programming
SLS	Serviceability Limit State
ULS	Ultimate Limit State

1

Introduction

This Master's thesis investigates the environmental impact of structural systems and explores innovative solutions to minimise the carbon emissions. By developing a parametric tool which focuses on global parameters in the early design stages, a wide range of design options can be investigated in a quick manner.

For the selected system, a simplified LCA is used to assess the environmental impact. A case study demonstrated that the tool selects structural elements comparable to those chosen by a structural engineer for the preliminary design. This allows the tool to model a structural system with comparable levels of emissions.

1.1 Background

One of the biggest challenges that humanity faces today is the global warming which is driven by the greenhouse gases produced by human activities. In 2015 the Paris Agreement was signed by 196 countries, which is an agreement that aims to restrict the temperature increase to 1.5°C compared to pre-industrial levels. In order to accomplish this, the world needs to become carbon neutral by 2050 (UNFCCC, n.d.).

The Swedish target is set to achieve net-zero emissions by 2045 (Sveriges Miljömål, 2023), which is in line with the Paris-agreement. Thus, there is a need to focus on all kinds of industries, including but not limited to the construction industry. The construction industry and built environment is a large contributor to global warming with a 38% share of the greenhouse gases globally (Broer et al., 2022) and 21% in Sweden (Boverket, 2024c).

Greenhouse gases is a collection of gases which all contributes to the global warming in different extent (Statistics Explained, n.d.). The two most recognised gases are *carbon dioxide* (CO_2) and methane. To calculate the *Global Warming Potential* (GWP) more easily, gases are converted to an equivalent amount of CO_2 that with the same GWP. This gives the unit *Carbon Dioxide Equivalent* (CO_2*-eq*), which will be referred to as carbon or CO_2 from here on.

There are two types of CO_2 emissions from buildings, embodied- and operational carbon (Jarrett, 2023). Embodied carbon refers to the CO_2 released from refining the raw materials into construction materials, in addition to the emissions from the construction and demolishing stages. This is set after finalising the building and can be seen as upfront carbon. Operational carbon refers to the CO_2 released from operating the building. This is dynamic and can change over time, for example by changing to a greener energy production, see Figure 1.1. Operational carbon typically includes heating, cooling, ventilation and overall power usage of the building (Jarrett, 2023).

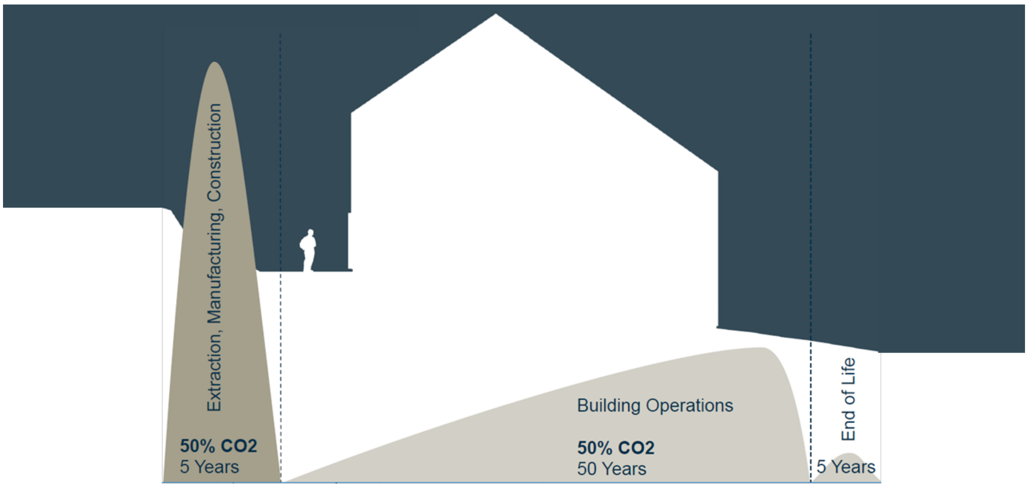


Figure 1.1: *Timeline of embodied- and operational carbon (Jarrett, 2023). Copyright 2024 by One Click LCA Ltd. Reprinted with permission.*

In Sweden, most of the reduction of greenhouse gases in the building industry have so far been tied to lowering the operational energy according to the government bill, Klimatdeklaration för byggnader (Prop. 2020/21:144). The bill also identifies that the embodied carbon currently stands for about 50% of the greenhouse gases emitted by the construction industry in Sweden, which the bill intends to target.

Climate declarations became mandatory in 2022 and require the developer to present the environmental impact when applying for a building permit (Boverket, 2024b). Boverket has since been assigned to establish emission limits for embodied carbon in new buildings, the limits are set to be introduced in 2025 at the earliest (Boverket, 2023b). The emission limits will be set tighter every few years and will thus regulate the amount of embodied carbon in new developments.

In a study conducted by Malmqvist et al. (2021), the environmental impact of various building elements was analysed. The elements were categorised into foundation, structural system, façades, and roof. The findings revealed that, on average, the structural system accounted for 50% of the embodied carbon across the 68 buildings studied in the report (Malmqvist et al., 2021).

A literature review focusing on *Life Cycle Assessment* (LCA) in the building design process, revealed that LCA is generally conducted at the end of the design process, when the design has been finalised (Roberts et al., 2020). Several studies suggested that integrating LCA into the early-stage designs could significantly influence the decision making process by allowing the designers to make informed decisions which would help reduce the environmental impact.

The literature review also stated that parametric design were one of the most prominent themes in the publications studied (Roberts et al., 2020). One of the big benefits of implementing a parametric design is that the designer could run through different designs in a quick manner. The study also discussed using pre-populated elements to conduct a simplified LCA which would be more suitable for early stages. There are already a few studies which have implemented the parametric tools for an early-stage LCA analysis, although only in a regional context. More work would be required in order to reach a wider userbase (Roberts et al., 2020).

1.2 Aim

The aim of the Master's thesis project is to create a functioning tool in Grasshopper which can model and iterate through different structural systems. This tool should design the structural system to comply with Eurocode. One of the basic functionalities of the tool should be to control the model by changing parameters, for example span lengths and material choice. The tool should prioritise user friendliness and enable the user to quickly iterate through different configurations of the structural system. The tool should output the preliminary dimensions of the structural system and environmental impact as the amount of embodied carbon in the system, which should be computed from from LCA module A1-A5, see Chapter 2.1.1. The tool should be developed in a scalable way so that other functionalities, such as additional structural systems and element types, can be added at a later date.

1.3 Objectives

To reach the aims specified in the thesis the following objectives should be met:

- Determine what structural systems are relevant to study.
- Determine what input parameters are most relevant.
- Decide how the workflow should look like and how the results should be presented.
- Investigate how to make sure that the structural system is reliable.
- Investigate if the tool will make similar choices as an engineer in early design stages.
- Evaluation of the tool with a case study.

1.4 Delimitations

The tool developed in this Master's thesis will be programmed in the Grasshopper plugin to Rhinoceros 3D by using Python as coding language.

Other limitations are necessary with regard to structural systems and material, as there is a large number of combinations. The materials investigated in this thesis will be the three most common structural materials in Sweden, concrete, steel and timber. The tool should in first hand be developed for a framed system, with the possibility to add other types of structural systems. The tool should comply with ultimate and serviceability limit state demands in Eurocode. A uniform grid should be generated by the tool, that is the same for all levels of the building. No transfer structures will be designed.

It is assumed that the slabs will be designed to comply with acoustic demands. This will not be checked in this thesis. Instead, an extra self-weight will be added to each slab to account for the weight of concrete screed, acoustic mats, or other materials that are typically needed to meet the acoustic demands. The additional self-weight will vary depending on the type of slab and project.

The environmental impact is limited to carbon emissions from the structural elements. The environmental data should be gathered from either Boverket, which supplies generic data, or from *Environmental Product Declaration* (EPD) from manufacturers, see Section 2.1.2. The relevant LCA modules, see Chapter 2.1.1, for this thesis is module A1-A5, as those are included in the climate declaration.

1.5 Research Questions

How should the tool be designed to be most useful in early-stage design?

How should the tool design a reliable structural system?

How should the tool be designed to integrate LCA calculations with the design process of structural systems?

2

Theory

This chapter addresses the environmental impact of the construction sector, current regulations, and a brief background for each construction material. It also discusses structural systems and what needs to be considered for early-stage design. Finally, digital tools are presented along with a brief background on optimisation.

2.1 Environmental Impact in the Construction Industry

The construction industry produces 38% of global CO_2 emissions (Broer et al., 2022). In Sweden, the share of CO_2 emissions is 21% according to Boverket (2024c). This is equally split between operational and embodied carbon, with the structural system accounting for roughly half of the embodied carbon Malmqvist et al. (2021).

Structural engineers have a good understanding of how structural systems function and can make a preliminary design relatively quickly based on their experience (Norman et al., 2020). However, structural engineers in general do not possess the same level of knowledge or experience concerning the environmental impact of said structural system (Anand & Amor, 2017). For the environmental impact there is a need to conduct LCA to get an accurate measure of the impact.

2.1.1 Life Cycle Assessment

A widely accepted way of evaluating the environmental impact of buildings is by conducting an LCA. The LCA includes, but is not limited to, CO_2 emissions, acidification, and ozone depletion. An LCA consists of four stages (Boverket, 2019):

- A - Production and construction stage, which includes raw material supply, transport, manufacturing, and construction or installation.
- B - Use stage, which includes use, maintenance, repair, and operational energy among others.
- C - End of life, which includes demolition, transport, waste processing and disposal.
- D - Benefits and loads beyond the system boundary, which accounts for the benefits of circular economy.

The different LCA stages and what are included in each step can be seen in Figure 2.1. The figure also shows the scope of embodied- and operational impact.

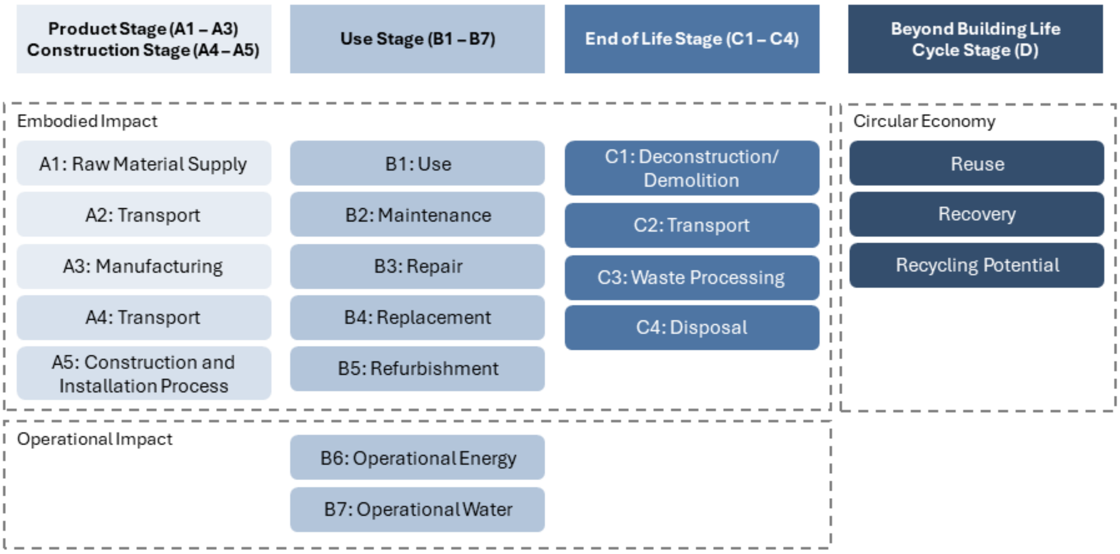


Figure 2.1: *The different stages of LCA according to EN 15978. Adapted from (Overbey, 2021).*

The LCA is often conducted towards the end of a project to aggregate the environmental impact which is needed to meet requirements for certifications or regulations (Säwén et al., 2024). However, this gives the designers very little room to make improvements, as can be seen in Figure 2.2. An LCA conducted in the early stages of a project could have a larger impact on the emissions with a lower cost attached to it (Roberts et al., 2020). In the literature study conducted by Roberts et al. (2020), they noted that the LCA would need to be simplified in order to fit the early design stages, where a lot of details are uncertain.

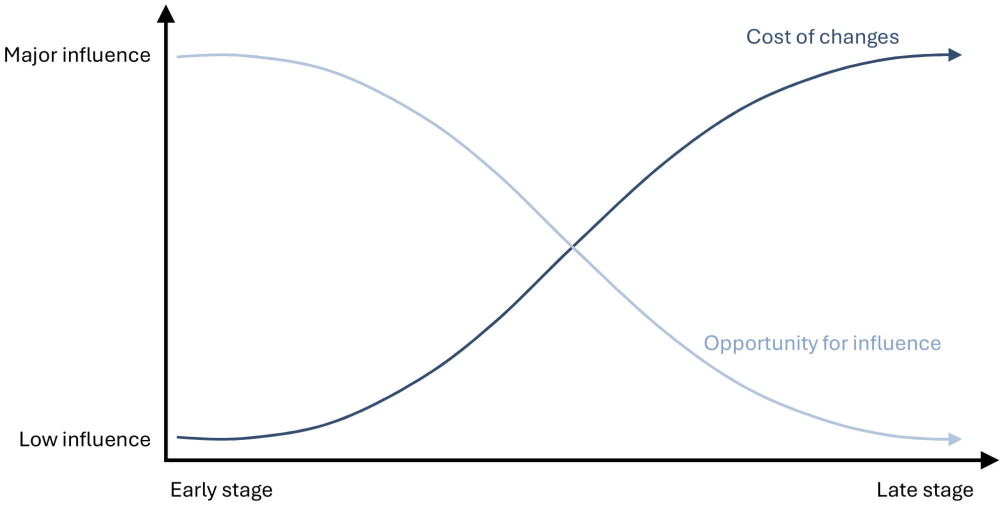


Figure 2.2: *The relationship between cost and influence during the project timeline. Adapted from (Cherry & Petronis, 2016)*

Roberts et al. (2020) discuss that a simplified LCA approach could be performed by attempting to predict the environmental impact or by attaching data to building elements in the model. Another way of simplifying the LCA is by cutting down on the number of aspects investigated, for example by focusing solely on the GWP of the elements.

2.1.2 Environmental Data

The data used for a climate declaration can either be from Boverket or from an EPD. Boverket supplies generic data with an additional 25% CO_2 emissions added to the industry average. This addition serves both as an encouragement for the use of more accurate EPDs, but also as a conservative measure (Boverket, 2023c).

The EPD data from manufactures are compiled according to standard EN 15804. An EPD need to cover A1-A3, C1-C4 and D stages in LCA, but some may include more stages (Stålbyggnadsinstitutet, 2020).

2.1.3 Driving Factors for Reducing Carbon Emissions

Several factors influence the decision-making process in the construction industry, including cost, time, and safety. However, there has not been a lot of incentives historically to consider the environmental impact when constructing new buildings, that is changing with new laws and more public awareness. Legal requirements and necessity to meet specific criteria to gain a sustainability certification are two things that can motivate developers to construct buildings with lower environmental impact.

2.1.3.1 Regulations

The European Union have implemented the *Emissions Trading System*, which is a system to limit how much CO_2 emissions the regulated sectors are allowed to produce. This is currently in the process of being expanded to include more sectors, including but not limited to the building sector. In 2023 *Fit for 55* was passed by European council which requires the emissions to decrease by 55% compared to 1990 level by 2030 in European Union (Boverket, 2023b). This law will use the emissions trading system to reach the goal (Council of the European Union, 2023).

In Sweden the recent addition of climate declaration will be regulating the CO_2 in the construction industry. Boverket is set to introduce limits on the embodied carbon in new developments by 2025, with the help of climate declaration (Boverket, 2023b). These emission limits are then planned to be revised every five years. The entire building, besides from fixtures, will be covered by the emission limits proposed by Boverket. The limits can be seen in Table 2.1.

Table 2.1: The proposed limit per building type in the climate declaration (Boverket, 2023b).

Design alternative	**Limit 2025** $[kgCO_2e/m^2]$	**Proposed limit 2030** $[kgCO_2e/m^2]$
Apartment building	375	285
Office building	385	290
School, not including kindergarten	380	285
Kindergarten	330	250
Single family home	180	155
Special housing	385	290
Other buildings	460	345

2.1.3.2 Certifications

There are many different certification schemes that will reward sustainable design practices, these systems often give credits for building with sustainable materials or reducing embodied or operational carbon. Some of the more well-known certification systems are *Leadership in Energy and Environmental Design* (LEED), *Building Research Establishment Environmental Assessment Methodology* (BREEAM) and Miljöbyggnad.

Miljöbyggnad is a Swedish certification scheme which covers a range of areas, including but not limited to the indoor environment, energy and circularity (Sweden Green Building Council, 2022). There are 15 metrics that give credits, one of which is climate impact. To qualify for bronze credit, a climate declaration has to be presented. The silver and gold credits require meeting a specific limit for the amount of embodied carbon in a building (Sweden Green Building Council, 2022), see Table 2.2.

Table 2.2: Limit per building type for silver and gold credit in Miljöbyggnad 4.0 (Sweden Green Building Council, 2022). Copyright 2022 by Sweden Green Building Council. Reprinted with permission.

Building type	**Limit silver credit** $[kgCO_2e/m^2]$	**Limit gold credit** $[kgCO_2e/m^2]$
Apartment building	290	260
Office building	280	250
School, not including kindergarten	270	240
Kindergarten	220	200
Single family home	120	110
Other buildings	370	330

2.1.4 Construction Materials and Climate Impact

Historically, timber and masonry, such as stone and bricks, were the most common construction materials in Europe until the 19th century. The industrial revolution reduced manufacturing cost and introduced new building typologies that required material with different properties, which paved the way for steel and concrete as modern construction materials (Tekniska museet, 2021).

Today there are three main materials for structural systems in Sweden, concrete, steel and timber, thanks to their material properties and availability (Elfors, 2019). Timber is generally seen as the green alternative but there is research being done on both steel and concrete to lower their emissions.

2.1.4.1 Timber

Timber has a long history as construction material, especially compared to the other main materials, concrete and steel (Al-Emrani et al., 2013). The good availability in Sweden and the material properties makes it a popular choice for constructing buildings. In recent years there is a growing trend to use timber for large construction projects as more research are conducted and more knowledge are gathered to solve the limitations of the material (Al-Emrani et al., 2013).

Engineered Wooden Products (EWP) has been developed over the years which utilises the material properties of timber more efficiently, or allowing for new application areas (Kliger et al., 2022). Some of the more well-known EWP includes plywood, *Laminated Veneer Lumber* (LVL), I-joist, *Cross-Laminated Timber* (CLT) and *glued laminated timber*, often called glulam. One advantage of EWP is that defects such as knots or parts with distortion are distributed more evenly and the end product will have a more reliable grading (Kliger et al., 2022).

Trees will absorb CO_2 while they grow, the absorbed carbon is called biogenic carbon (Masson, 2024). However, as there is uncertainties to what happens to the timber after end-of-life timber cannot be considered a carbon sink. In Sweden the disposed timber is usually used to produce energy (Elfors, 2019). Which is why the biogenic carbon are not accounted for in an LCA. Despite this, timber usually has lower CO_2 emissions compared to other materials in the structural system when designed for the same load (Elfors, 2019). See Table 2.3 for a summary of LCA stage A1-A5 for different timber products according to Boverket.

Table 2.3: CO_2 emissions from glulam and CLT according to Boverket's climate database (Boverket, 2024a).

Product	Density [kg/m3]	A1-A3 [$kgCO_2/kg$]	A4 [$kgCO_2/kg$]	A5 [$kgCO_2/kg$]
Glulam	434	0.133	0.0345	0.0084
CLT	465	0.120	0.0345	0.0077

2.1.4.2 Steel

Steel is essential for machinery and structures, making it one of the most widely used materials today (Hoffmann et al., 2020). In the construction industry, steel is used for load-bearing members, reinforcement, and various connection details, including those for timber or concrete members. Steel is a material that is strong in relation to its cross-sectional area, which is why it is commonly used to carry loads (Al-Emrani et al., 2013).

The beams and columns used in the construction industry comes in a wide range of shape and sizes, a few examples can be seen in Figure 2.3. A steel element can be made either as hot rolled or cold rolled, or it can be welded together (Al-Emrani et al., 2013).

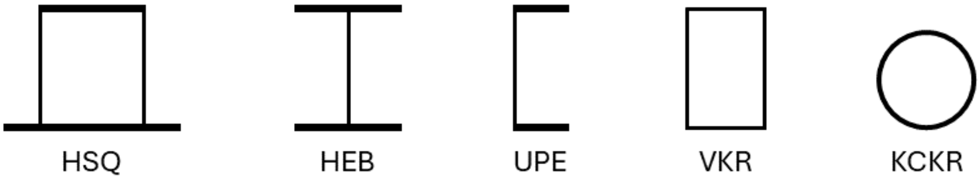


Figure 2.3: *Example of a few steel cross sections.*

The two main manufacturing methods for steel today are *Electric Arc Furnace* (EAF) and *Blast Furnace-Basic Oxygen Furnace* (BF-BOF) (EUROFER, 2020). The difference between them is that BF-BOF mainly uses virgin raw material to create new steel with a process called reduction that uses carbon to bind the oxygen in iron ore, leaving iron and carbon dioxide. While EAF melts recycled steel with an electric arc to produce steel (EUROFER, 2020). This leads to BF-BOF having significantly more carbon emissions due to its manufacturing method.

Research and testing are being conducted with the aim to produce fossil free steel. One production method that is used today is EAF with fossil-free electricity, this will produce steel with a fraction of the usual carbon emissions (SSAB, n.d.). Another method that is being developed is a process called *Direct Reduced Iron* to perform the reduction step with hydrogen, producing iron and water instead of iron and carbon dioxide (SSAB, n.d.).

The carbon emission from steel production accounts for 8% of humans total CO_2 emissions (Hoffmann et al., 2020). See Table 2.4 for a summary of LCA stage A1-A5 for different steel products according to Boverket.

Table 2.4: CO_2 emissions from different types of steel according to Boverket's climate database (Boverket, 2024a).

Product	Density [kg/m3]	A1-A3 [$kgCO_2/kg$]	A4 [$kgCO_2/kg$]	A5 [$kgCO_2/kg$]
Construction steel 80% virgin raw material	7850	3.15	0.0795	0.161
Construction steel 100% scrap based	7850	1.13	0.0795	0.0602
Reinforcement steel 100% scrap based	7850	0.745	0.0795	0.0742

2.1.4.3 Reinforced Concrete

Concrete is a common construction material due to its material properties and availability. It is very versatile as it can be made into any shape as long as there is a mould to support it during curing (Al-Emrani et al., 2013).

Concrete is made with a mix of cement, aggregates (e.g. sand and stone), water and other additives (MT Copeland, 2022). The ratio between these ingredients determines the material properties and workability of concrete; even a small change in the ratios can have a significant impact on the properties of the concrete. Some common types of concrete include plain concrete, lightweight concrete and self-compacting concrete (MT Copeland, 2022). The standard strength grades vary from C12/15 up to C90/105 (Al-Emrani et al., 2013).

Concrete contributes to approximately 7% of the global CO_2 emissions (Gregory & Logan, 2021). The high share of emissions is due to the energy intensive manufacturing method of one of the main ingredients, cement. The process of creating cement releases chemical bound CO_2 from the material, it also requires high temperatures which contributes to more CO_2 emissions as fossil fuels are needed (Gregory & Logan, 2021). See Table 2.5 for a summary of LCA stage A1-A5 for different concrete products according to Boverket.

Table 2.5: CO_2 emissions from different types of concrete according to Boverket's climate database (Boverket, 2024a)

Product	Density [kg/m3]	A1-A3 [kgCO2/kg]	A4 [kgCO2/kg]	A5 [kgCO2/kg]
Hollow core slab	1350	0.188	0.045	0.0
Hollow core slab Climate improved	1350	0.128	0.0324	0.0
Concrete C30/37	2350	0.145	0.0039	0.00447
Concrete C30/37 Climate improved	2350	0.108	0.0039	0.00337
Concrete C50/60	2350	0.204	0.0039	0.00623
Concrete C50/60 Climate improved	2350	0.153	0.0039	0.0047
Floor screed, <17% cement	1750	0.195	0.027	0.0111

Concrete undergoes a process known as carbonation during its lifetime which rebinds the CO_2 that was released from the manufacturing of cement (IVL Svenska Miljöinstitutet, 2021). This process takes many years, even decades. Carbonation is also very dependent on the surface to volume ratio, hence why carbonation is not accounted for when calculating the environmental impact of concrete.

The current process of making more environmentally friendly concrete replaces some of the cement with *Supplementary Cementitious Materials*, some common ones are fly ash and *Granulated Blast Furnace Slag* (GBFS) which are by-products from industrial processes (Gregory & Logan, 2021). But as those other processes are also changing to more sustainable options, the source of fly ash and GBFS are decreasing and other alternatives are needed (Schultz, 2024). Romans used volcanic ashes, known as pozzolan, in their concrete mixes. Pozzolan has potential for use in modern concrete mixes as well according to Schultz (2024).

The aggregates also have a potential to contribute to decarbonise concrete though the process of *Carbon Capture, Utilisation and Storage* (CCUS) (Hills et al., 2020). The CCUS is a process where CO_2 is captured from air, this CO_2 can react with certain minerals in a process called mineralisation. The mineralised products could then be used as aggregates in place of the typical aggregates, which would help reducing the overall carbon footprint of concrete.

2.1.5 Circular Economy

Looking at the principles of circular economy, reduce, reuse, recycle, there is good guidance for the construction sector to reduce its environmental impact. The Ellen MacArthur Foundation highlights four key strategies to achieve net-zero emission in the construction industry: build only what you need, use renewable materials, build efficiently and reuse (Arup, 2023).

- Build only what you need - no material is CO_2 negative, yet. Anything being built at all is contributing to the CO_2 emissions. If constructing the building can be avoided that would save the most amount of CO_2 emissions. The next strategy is to reevaluate if the entire building would need to be constructed, maybe the building can be downsized or some elements from the old building can be reused.

- Use renewable materials - the next measure is to look at environmental impact of the materials being used, which would have the lowest amount of embodied carbon with the same structural response.

- Build efficiently - make sure that each component is sufficiently utilised. An article in *The Structural Engineer* points out that the average utilisation rate for the structural system is about 60%, which means the structural system could be designed with less material (Poole, 2020). Another article from the same magazine explains that optimising the global structural system (i.e. grid spacing and material) can have a much larger effect on the environmental impact than optimising individual members (Gholam, 2020).

- Reuse - by reusing construction materials, no new CO_2 emissions are released to produce the materials. Another aspect of this is to design for disassembly, i.e. design in such a way that the materials can easily be reused. For example, to use members that has standard dimensions and simple connections that can easily be disassembled and reused after the end-of-life of the building. And also document in detail what have been used, what quality, what quantity, etc. to make it easier to plan and reuse it.

2.2 Structural Systems

The primary function of the structural system is to carry down vertical and horizontal loads to the foundation (Norman et al., 2020). The vertical loads are a result of the fixed loads such as structural elements and furniture combined with variable loads such as occupants and snow. The horizontal loads are primarily a result of wind pushing on the facade, but can also be a result of events such as accidents or earthquakes.

The structural system does also need to work with the intended use of the building, for example enabling long spans over a swimming pool. The choice of structural system and materials can depend on a number of different aspects, including but not limited to erection time, cost and complexity of connections (Norman et al., 2020).

The structural system in a typical building consists either of a framed system, see Figure 2.4, a system with load-bearing walls, see Figure 2.5, or a combination of both (Norman et al., 2020).

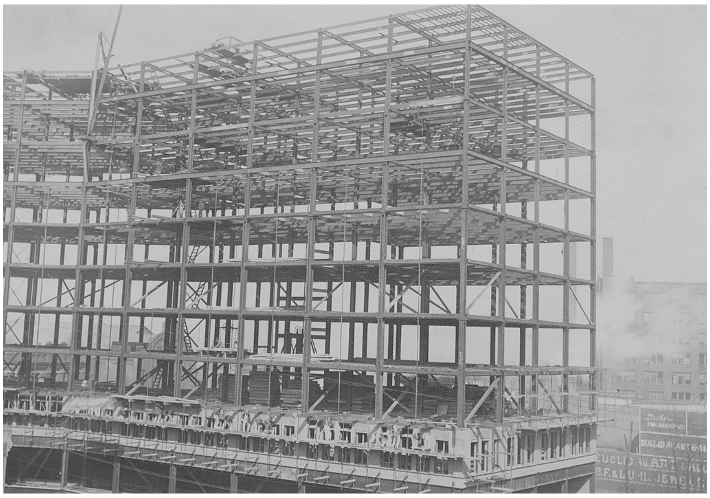


Figure 2.4: *Framed structural system (Cleveland Public Library Digital Gallery, 1895). In the public domain.*

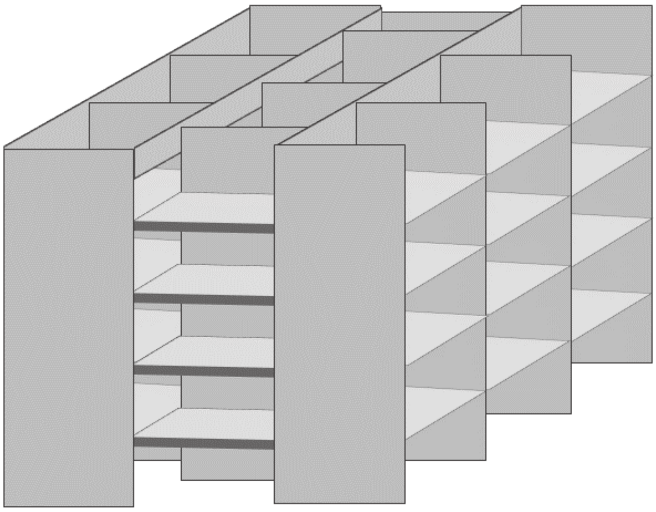


Figure 2.5: *Structural system with load bearing walls.*

2.2.1 Eurocode

The design of structural systems in Sweden must comply with the Eurocode, which is a set of standards that describes how to design the structural system in Europe. Each country has possibility to have local additions to Eurocode (Svenska Institutet för Standarder, 2023), *Europeiska Konstruktionsstandarder* (EKS) is the Swedish national annex. In this thesis, EKS 12 was used.

Eurocode are divided into 10 different sections, from EN 1990 to EN 1999, which covers different aspects or materials. For example, timber structures are designed against Eurocode 5, EN 1995 (Svenska Institutet för Standarder, 2023). When designing against Eurocode, it is common to consider ultimate- or serviceability limit state.

Ultimate Limit State (ULS) is in short defined in Eurocode as a state where human lives may be at risk or there is a risk of unacceptable economic or environmental damages as a cause of the collapse of a structural member or system (Svenska Institutet för Standarder, 2023).

Serviceability Limit State (SLS) is defined in Eurocode as a state where the performance of the structural system, the appearance or the comfort of the users is at risk during normal usage of the building (Svenska Institutet för Standarder, 2023).

Fatigue is also covered in the Eurocode standards with *Fatigue Limit State* (FLS). However, fatigue is more relevant to structures that are subjected to cyclic loading, such as bridges (Al-Emrani, 2023). For more static buildings FLS is often not relevant and will thus not be addressed in this thesis.

2.2.1.1 Permanent Loads

The permanent loads, denoted as G $[kN]$ or g $[kN/m^2]$, are a combination of loads that are expected to remain near constant over a long period of time. Some examples of permanent loads include self-weight of the element, fixtures, internal and external walls.

2.2.1.2 Variable Loads

Variable load, denoted as Q $[kN]$ or q $[kN/m^2]$, are a combination of loads that are expected vary over time. The load cycles vary depending on the load. For example, snow load is expected to have a cycle of one year, while traffic load can have a cycle of one day. Some examples of variable loads include snow load, wind load, traffic load and imposed loads.

2.2.1.3 Load Reduction Factor

The load reduction factor is based on the assumption that it is unlikely that the maximum variable loads will affect the structure all at once. Furthermore, it takes the load duration into account, as loads with long duration are more likely to have an overlap compared to loads with shorter duration (Al-Emrani et al., 2013). See Table 2.6 for the load reduction factors used for residential and office buildings.

Table 2.6: Table of load combination factors according to EKS 12.

Load Reduction Factor	ψ_0	ψ_1	ψ_2
Residential	0.7	0.5	0.3
Office	0.7	0.5	0.3

2.2.1.4 Reliability Class

Eurocode stipends that a reliability class are to be used when designing structures. This is decided by the risk of personal injuries or economic damage, see Table 2.7. In Sweden the value used is set by the national annex EKS 12 (Boverket, 2022).

Columns are normally designed for reliability class 3, while beams and floor slabs will in most cases be designed for class 2 (Boverket, 2022). For an explanation of the different classes used, see Table 2.7.

Table 2.7: Table of reliability classes according to EKS 12.

Reliability Class	γ_d	**Explanation**
Reliability Class 1	0.83	Low risk of serious personal injuries
Reliability Class 2	0.91	Some risk of serious personal injuries
Reliability Class 3	1.0	High risk of serious personal injuries

2.2.2 Ultimate Limit State

To ensure the safety of the building and the people inside, ULS covers the different failure modes that can happen to a structure. It also has safety factors incorporated to the equations to make sure that the structure can withstand the worst case scenario. These safety factors will depend on different variables, such as load duration and whether the loads are working against each other, favourable, or working with each other, unfavourable. There is also a need to check different load combinations to make sure the governing load combination is used. Equations according to EKS 12 (Boverket, 2022):

$$Q_d = \gamma_d \cdot 1.35 \cdot G_{k,j} \tag{2.1}$$

$$Q_d = \gamma_d \cdot (0.89 \cdot 1.35 \cdot G_{k,j} + 1.5 \cdot Q_{k,1} + 1.5 \cdot \psi_{0,i} \cdot Q_{k,i}) \tag{2.2}$$

Where:

Q_d	is the design load
G_k	is the permanent load, characteristic value
$Q_{k,1}$	is the main variable load, characteristic value
$Q_{k,i}$	is the other variable loads, characteristic value
γ_d	is the partial factor, which depends on the reliability class
ψ	is the load reduction factor

In equation 2.2 each variable load needs to be tested as the main load to find the governing load case.

2.2.3 Serviceability Limit State

Where ULS checks the collapse of the structural system, SLS mainly check the deformations and self-resonance of the structural members. Different load combinations will be used depending on the duration of the load. The load combinations are divided into characteristic (2.3), frequent (2.4) and permanent load combination (2.5). Equations according to EN 1990 (Svenska Institutet för Standarder, 2023):

$$Q_d = G_{k,i} + Q_{k,1} + \psi_{0,j} \cdot Q_{k,j} \tag{2.3}$$

$$Q_d = G_{k,i} + \psi_{1,1} \cdot Q_{k,1} + \psi_{2,j} \cdot Q_{k,j} \tag{2.4}$$

$$Q_d = G_{k,i} + \psi_{2,j} \cdot Q_{k,j} \tag{2.5}$$

Characteristic load combination is the maximum load that the building is expected to experience during normal usage and is only expected to occur a few times during the entire service life of the building (Al-Emrani et al., 2013). Frequent load combination is expected to occur more often than the characteristic load combination. And lastly, quasi-permanent load combination only considers the long-term load on the structure (Al-Emrani et al., 2013).

The characteristic load is usually set with the expectations that it will exceed the set value once in a 50-year period (Boverket, 2022). This is therefore the 98th-percentile value for loads that have a time period of one year, which includes snow load for example.

2.2.3.1 Vibration

Users do not like to feel the effects of vibration in the structure, which is why vibrations are included in the SLS requirements. Vibrations can be caused by mechanical equipment or by people walking, running or in other ways doing coordinated activities, such as exercising or dancing (Kliger et al., 2022). Sagging is another related problem that can make users feel uncomfortable as well (Gustafsson et al., 2017). Lightweight floors are more likely to experience sagging issues as the weight of the users is higher in proportion to the self-weight of the floor, compared to that of a heavy floor.

When designing a floor, it is recommended to aim for a fundamental frequency above 8 Hz according to Gustafsson et al. (2017), as humans are more sensitive to vibrations below 8 Hz. The fundamental frequency can be changed by modifying the stiffness, mass or the span of the element.

2.2.3.2 Deformation

Deformation is part of SLS demands and can often be a limiting design factor for slabs or beams. The deflection limit can vary depending on the application (Svenska Institutet för Standarder, 2023) but there are general limits. According to Gustafsson et al. (2017) the deflection limit for a beam can be set to L/500 for instantaneous deflection or L/300 for the final deflection, where L is the length of the beam. Similar limits have been specified for floors where the final limit is around L/200 - L/250 Gustafsson et al. (2017).

2.2.3.3 Acoustics

The acoustic performance of a building can have a great influence on the overall wellbeing of the user and is often regulated by national building codes (Kliger et al., 2022). In Sweden, the acoustic demands are regulated by *Boverkets Byggregler* (BBR) (Boverket, 2023a). According to Gustafsson et al. (2017) there are five main aspects that are measured when it comes to acoustics in a building:

- Airborne sound insulation
- Impact sound insulation
- Traffic noise and other external sources
- Reverberation time
- Service equipment noise

For a framed structural system with floor slabs the airborne- and impact-sound insulation are the most relevant aspects to investigate (Gustafsson et al., 2017).

The acoustic performance are divided into four different sound classes (Boverket, 2023a), see Table 2.8. Where class C is considered to be the minimum acceptable level in new developments.

Table 2.8: A short explanation of each sound class according to (Gustafsson et al., 2017).

Sound class	**Explanation**
A	Highest class, used when high quality sound environment is important.
B	Good sound environment. Common to aim for in residential buildings.
C	The minimum level according to BBR.
D	Only used in exceptional cases, when sound class C is hard to achieve.

2.2.4 Construction Materials and Structural Systems

The three main materials: timber, steel, and concrete, have very different material properties. These can complement each other but may be hard to combine when considering other aspects, such as creep. Material properties that are often looked at are density, Young's modulus, fire resistance, compressive and tensile strength, to mention a few. It is also important to know if the material behaves differently in different directions (orthotropic) or if it behaves the same in all directions (isotropic). Timber is an example of an orthotropic material and steel is an example of a isotropic material.

See Table 2.9 for typical values of the strength and stiffness of the three main construction materials (Norman et al., 2020).

Table 2.9: Typical values for material properties for timber, steel and reinforced concrete.

Material	**Timber**	**Steel**	**Reinforced concrete**
Young's modulus [MPa]	8,000-13,700	210,000	15,000-30,000 **
Characteristic compressive strength [MPa]	17-29 (parallel to grain) *	275-355 (typical value) ***	12-90
Characteristic tensile strength [MPa]	10-22.5 (parallel to grain) *	275-355 (typical value)	Assumed to be zero
Characteristic bending strength [MPa]	16-32 (parallel to grain) *	275-355 (typical value) ***	Depends on the amount of steel reinforcement

* Mean value for C16 timber and GL32 glulam for the lower and upper bound respectively

** Long-term to short-term for the lower and upper bound respectively

*** Less if flexural or lateral torsional buckling occurs for compression and bending respectively

2.2.4.1 Timber

Timber structures are designed according to Eurocode 5 (EN 1995) in Sweden. The most common EWP's used for structural systems are CLT and glulam elements (Jelly, 2019). The properties of timber depend on the type of wood used, with spruce and pine being the most common species for structural timber in Sweden (Svenskt Trä, n.d.-a).

The strength of timber is dependent on the fibre direction; it is generally much stronger parallel to the fibres compared to loading perpendicular to the fibres, see Figure 2.6. The compressive and tensile strengths are similar, the main difference is that a tensile failure is more brittle compared to compressive failure (Kliger et al., 2022). Timber is graded by machines, to sort it into different characteristic strength classes. The characteristic strength is defined by the fifth percentile, meaning that 5% of the samples fall below the specified grade(Kliger et al., 2022).

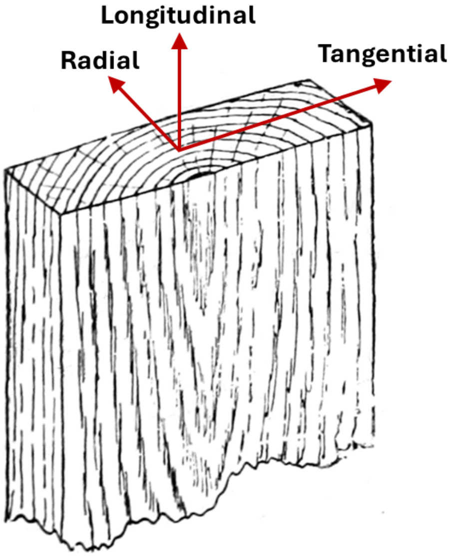


Figure 2.6: *The fibre directions in a wooden plank. Adapted from (Boxall & Loasby, 1907). In the public domain.*

The CLT element are one of the most popular EWP products. An odd number of layers are used to produce a CLT panel, often three to nine layers. Each layer is arranged with the grains perpendicular to the previous layer, see Figure 2.7 (Kliger et al., 2022). This creates an element with strength in two directions, similar to a reinforced concrete slab. The CLT elements are normally used as slabs or as wall elements, to utilise the two-way action most efficiently (Kliger et al., 2022). The element size is usually governed by transport limitations, in Sweden the maximum transport length and height without special permit is 24 m and 4.5 m respectively (Gustafsson et al., 2017).

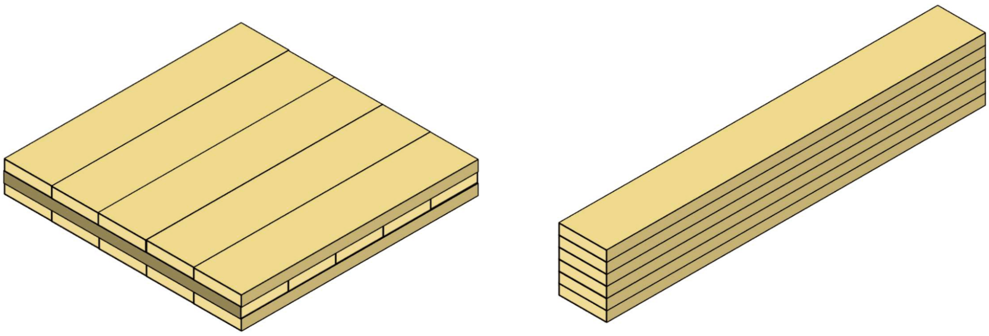


Figure 2.7: *The plank directions of a CLT slab and a glulam beam.*

Glue laminated timber or glulam, as it is often referred to, is another popular EWP, which are produced in the form of beams, columns or arches. Glulam is produced by gluing timber laminations together in the same fibre direction, see Figure 2.7. There are a number of default cross sections that are either stocked or can be manufactured. Glulam members can be made as straight or curved.

An important advantage of glulam is the high strength-to-weight ratio, which makes it competitive to steel or concrete element for use in structural systems (Gross, 2016). Another advantage of glulam elements is that they have less variation in strength across different elements. Gross (2016) notes that this is due to the fact that defects are less likely to occur in the same place across multiple layers.

For glulam beams the compression perpendicular to the fibres can cause a crushing failure in the member, as timber is significantly weaker perpendicular to the fibres (Gross, 2016). This can in many circumstances be the limiting factor, especially for taller buildings.

2.2.4.2 Steel

Steel structures are designed according to Eurocode 3 (EN 1993). In structural systems, steel is commonly used for beams, columns, reinforcement, and connection details. Steel is crucial to the modern construction industry, as it enabled the first skyscrapers in the late 19th century (Bellis, 2020).

Steel has equal yield limit for both compressive and tensile stresses. However, when it comes to compressive stresses, buckling is often the limiting factor for steel members. The slenderness and support conditions have a strong influence on the buckling capacity of the steel member (Al-Emrani et al., 2014). Another failure mode that is relevant for steel structures is fatigue failure. Fatigue failure is caused by repeated cyclic loading that creates microcracks and makes them propagate to full cracks (Al-Emrani, 2023).

Steel members can have a ductile or brittle failure depending on the circumstances. For example, during normal conditions steel is expected to have a ductile failure while temperature decrease or fatigue could lead to a brittle failure (Al-Emrani, 2023).

2.2.4.3 Structural Concrete

Concrete structures are designed according to Eurocode 2 (EN 1992). Structural concrete is often divided into three main groups, plain-, reinforced- and prestressed concrete (Al-Emrani et al., 2013). Plain concrete has a high compressive capacity but a low tensile capacity.

Tensile capacity can be increased by adding reinforcement. The designer will have a large influence on the properties by deciding the amount and placement of the reinforcement (Al-Emrani et al., 2013). The reinforcement will give the concrete element a more ductile failure, which gives more time to discover the failure before it happens (Gothia Armering, n.d.).

Prestressing introduces compressive stresses in the element, often at the bottom where tensile stresses are normally anticipated, see Figure 2.8. The element demonstrates different behaviour compared to a similar reinforced element, until the load is sufficiently large to overcome the prestressing force (Al-Emrani et al., 2013). The prestressed concrete elements show an increased SLS capacity due to fewer cracks and lower deformation compared to equivalent reinforced concrete elements under the same load condition. However, prestressing will not affect its ULS capacity, the failure load is thus the same as for an equivalent reinforced concrete element. Similar effects can be achieved by post-tensioning, which requires tensioning the steel wires on site (Al-Emrani et al., 2013).

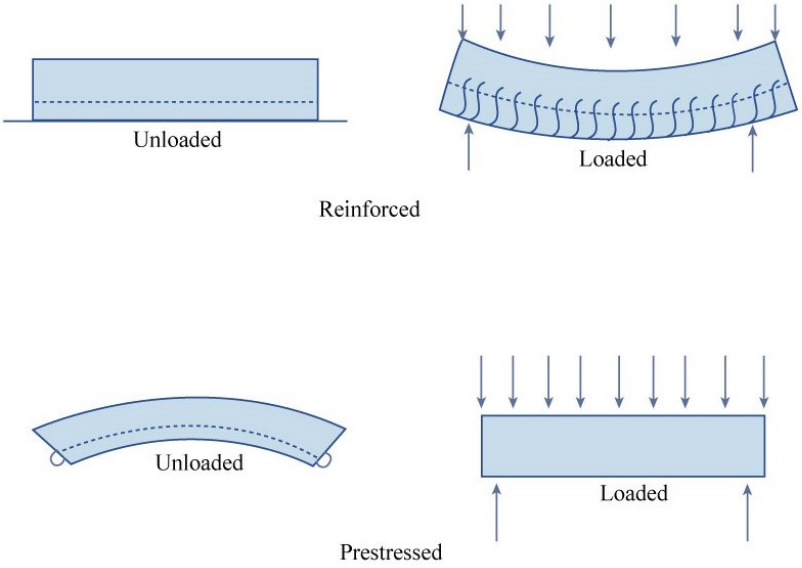


Figure 2.8: *Behaviour of a reinforced concrete beam compared to a prestressed concrete beam (MIT OpenCourseWare, 2008). CC BY-NC-SA.*

There are a few different concrete slab types available, including but not limited to hollow core slab and waffle slab (Prasad, n.d.). The different slabs are designed for different application areas, many of these slabs are designed to be more material efficient.

A hollow core slab is a prefabricated concrete element that is mainly used as a floor or roof element (Al-Shaarbaf et al., 2018). The slabs are prestressed and designed with several holes, usually four to six holes per element, that runs the entire length of the element, see Figure 2.9. The self-weight is reduced with the hollow cores, which also makes the element more material efficient (Al-Shaarbaf et al., 2018). Hollow core slabs are able to clear long spans, which makes them suitable for a wide range of building typologies, residential and office buildings among others (Al-Shaarbaf et al., 2018).

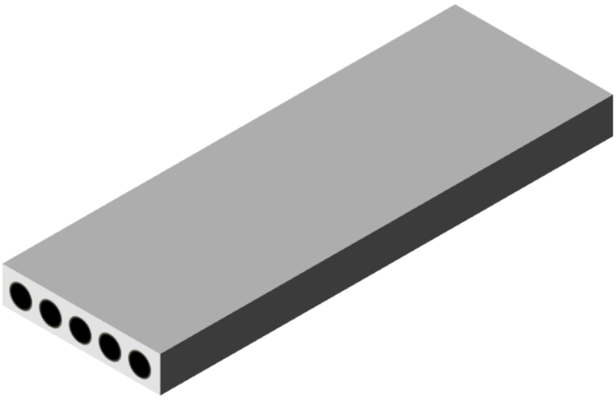


Figure 2.9: *Example of a hollow core slab.*

2.2.5 Structural Grid

The purpose of a structural grid is to help the cooperation between architects and engineers, the architects can plan the layout from the grid lines and the structural engineer can plan the structural system from the same lines (Varawalla, 2018). The columns are usually placed where the lines intersect and the beams or load bearing walls are typically placed along the lines in either direction, see Figure 2.10.

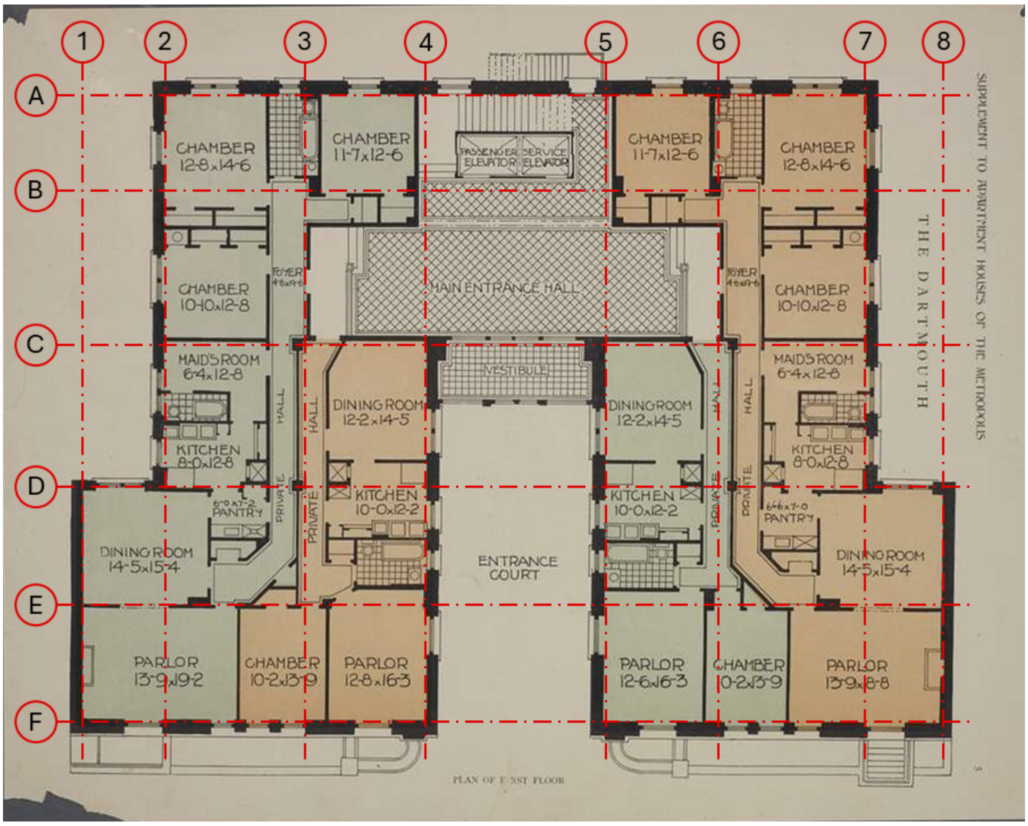


Figure 2.10: *Example of a structural grid. Adapted from (The New York Public Library, 1909). In the public domain.*

Structural engineers will often work with a structural grid along with material selection in the early design stages. Both can be seen as global parameters which affects the entire system and would be hard to change later (Gholam, 2020).

In a case study, Buro Happold found that the dimensions of the structural grid is one of the most important parameters when it comes to the amount of embodied carbon for a structural system, almost as important as material choice itself (Roynon, 2020).

2.2.6 Design Life

A structure is often designed to last for a certain amount of years, this is called the design life. Some typical figures for the design life can be 10 years for a temporary building, 50 years for normal buildings, and up to 120 years for bridges (Designing Buildings, 2022).

Concrete structures typically have a long design life, up to 75 years, but can be extended with proper maintenance. This can be comparable with steel which have a life expectancy of over 100 years. Timber structures have an expected design life of 30-50 years (Buro Happold, 2021).

2.2.7 Preliminary Sizing

Designers typically use rules of thumb to decide the preliminary sizing for an early-stage design. This allows designers to get a close estimate of the final sizing and also a close estimate of the final loads acting on the structure. Nowadays the designer can look at tables with preliminary sizing from manufacturers or trade associations. Preliminary sizing tables are usually more refined than rules of thumb and will give a closer estimate (Norman et al., 2020).

2.3 Rhinoceros 3D and Grasshopper

Rhinoceros 3D, often called Rhino, is a 3D modelling program that uses NURBS (Non-Uniform Rational Basis Spline) for modelling. This allows the user to create complex geometry more easily (McNeel, n.d.).

A digital model can be created in two different ways, by direct- or parametric modelling. Direct modelling requires the user to define the geometry, which could allow the user to create a quick model, like a sketch. While in parametric modelling, the model has a set of constraints, or parameters, that needs to be defined. Parametric modelling takes more time to set up but allows the user to automate their workflow, which can result in time saving for an iterative process (Jabi, 2013).

There are a number of plugins that are compatible with Rhino, one of them is Grasshopper. Which utilises visual scripting to create a model, see Figure 2.11. Visual scripting uses similar logic as conventional scripting, but each action is performed by blocks, or components, that can be connected to create a form of script, or algorithm. This is suitable for parametric modelling, which can be a way to quickly change or generate new models.

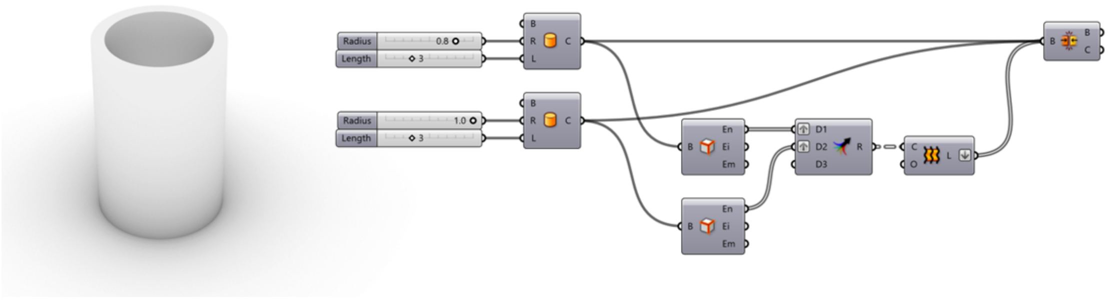


Figure 2.11: *A hollow cylinder created with a Grasshopper script by defining the height, inner and outer radii.*

Grasshopper contains default components which every user has access to, users can also download plugins to Grasshopper or script their own components. The plugins are often specialised to perform more advanced tasks, for example to run a simulation or read data from Excel sheets. Users can also resort to scripting their own components if the standard components or plugins are unable to perform a certain task. The custom components are scripted in either C# or Python.

2.3.1 LCA Plugins

There are a few plugins to grasshopper that are focused towards conducting an LCA, either simplified where CO_2 emissions are the main focus, or a more detailed LCA. The ones that were investigated in this thesis are:

- BHoM LCA Toolkit
- Bombyx 2
- CardinalLCA
- One Click LCA

See Chapter 3.2.2 for more details of the tool study, which included these plugins.

2.3.2 PancakeSpreadsheet

The plugin PancakeSpreadsheet is used to read or save data from Excel directly in Grasshopper. Unlike similar plugins, PancakeSpreadsheet does not need to have the Excel sheet open, nor does it even need to have Excel installed, the plugin simply requires an Excel file to read. The user can specify which sheet to read and what cell range to import. To efficiently gather data from Excel sheets, a good and predictable structure is beneficial, as then the same script can be used for several projects without much modification.

2.3.3 UI+

UI+ is a plugin that enables the user to create an interface or dashboard that can be populated with different controllers or information. This would allow the user to control parameters of the script without having Grasshopper open, and thus letting the user to focus on the Rhino viewport and the dashboard.

2.3.4 Wallacei

Wallacei is designed to run multi-objective optimisation, this plugin uses an evolutionary solver for the optimisation procedure. The user can select which objectives to optimise against and also select which results to view. Wallacei can also reconstruct what settings the inputs had for that particular solution after the run has been completed, which means that it is not necessary to record any parameters.

The evolutionary solver is a well established algorithm in the computational field and is explained briefly in Chapter 2.5. An evolutionary algorithm can typically be quite slow to run and while it continuously produces answers it does not guarantee a solution (Rutten, 2010). Which is why a runtime limit can be set, or a solution limit. It can also be stopped early if the user desires. If the user chooses to end the solver early, the answers that has already been generated will be available.

2.4 Scripting

Python is one of the most popular programming languages today, which is much thanks to its syntax. A programming language's syntax relates to how abstract the language is, a low-level language are more closely related to the binary language of computers, whereas a high-level language is more abstract and are written more similar to how humans talk. A high-level language like Python is therefore more easy to understand and accessible for programmers (Safarowic, 2024). Python utilises libraries to access commonly used classes, functions, or other essential functionalities. The libraries are often tailored for a specific purpose, NumPy for example is a popular Python library which focuses on scientific computing.

Object Oriented Programming (OOP) is a programming paradigm which is used by many programming languages, Python among others. The developer can define classes, which is a template that is used to create instances of objects. These objects can be assigned properties which is information that is unique to that object. Classes can also define methods that will execute a set of actions or operations when called upon (Codecademy, 2023).

If the class Shape is defined, it could create multiple instances of objects, Cylinder and Cube for example. The class can have properties assigned to it, baseArea, height, etc. It can also have methods, computeVolume, which would calculate the volume by multiplying the base area by the height. This allows the programmer to construct more general scripts.

2.5 Optimisation

In mathematics, optimisation is the procedure of minimising or maximising the results of a function (Rockafellar, 1997). In many engineering problems the aim is to optimise a solution in order to help out the decision -making process (Savic, 2002). The problem can be optimised against the cost, material usage, emissions or some other parameter.

In the optimisation field, evolutionary algorithm is well established and popular. Evolutionary algorithms start with an initial set of solutions, often called population, to select from. Individuals in this population are evaluated based on their fitness value, and those who are ranked higher are more likely to be selected as parents. These parents can then be exposed to crossover and mutation (Bartz-Beielstein et al., 2014).

Crossover is when the algorithm combines parts of the genes (design variables) of the parents to create a new offspring (individual). This is done in the hope of finding a better solution based on two fit parents.

Mutation is when a random change is introduced to the genes of the parent to create a new offspring. This is done to expand the search range, and to avoid local minima or maxima.

The crossover will explore the space defined by the boundaries of the current population, while mutation can expand the search range by introducing new traits. Different algorithms will perform crossover and mutation in different extent, some have a chance to use one after the other, while others might separate them entirely.

2.5.1 Optimisation for Structural Systems

In terms of structural optimisation there are three different kinds of optimisations that can be made:

- Sizing optimisation
- Shape optimisation
- Topology optimisation

Sizing optimisation is considered to be the simplest of these three. It involves optimising the size of elements, such as thickness, width, or height, for a given set of constraints (Srivastava et al., 2017). The second option, shape optimisation, focuses on the geometry of the element, using the boundary of the element as the design parameter. In this type of optimisation, the cost or amount of material is often of great interest. And lastly, the topology optimisation, which is considered to be the most complex one of these three, involves determining the best material layout within a given boundary. There are a great number of parameters involved, as Srivastava et al., 2017 notes:

"*Applying topology optimisation to structural design typically involves considering quantities such as weight, stresses, stiffness, displacements, buckling loads and resonant frequencies, with some measure of these defining the objective function and others constraining the system.*"

Topology optimisation can generally be seen as selecting the optimal structural grid, material, and structural elements for an efficient system. This approach can lead to significant material reduction (Srivastava et al., 2017).

2.5.2 Single and Multi-Objective Optimisation

Optimisation algorithms can either focus on optimising against a single objective or against multiple objectives. Single objective optimisation is deemed considerably easier, as a single answer can be obtained (Savic, 2002). However, one of the drawbacks is that there are few problems where a true single objective can be defined.

Often in real-world problems there are multiple objectives that needs to be optimised, hence not a single best solution exists for those problems, and a trade-off is required (Savic, 2002). During multi-objective optimisation, the set of potential solutions can become very large. Using Pareto optimal set is a common way to limit the number of solutions to include in the decision-making process. The solutions in the Pareto set are not dominated by any other solution, which means that each solution included in Pareto set has at least one objective where it is better than other solutions (Savic, 2002). If a solution is worse in every aspect compared to another solution, it will not be included in the set.

2.5.3 Rationalisation

Rationalisation is one form of optimisation that focuses on lowering the number of options. One example can be the cross sections of stocked elements, they usually come in standard sizes, which is a form of rationalisation.

Rationalisation is also used on construction sites, to reduce the number of different cross sections for columns for example. This would have the benefit of simplifying the design process, reducing the construction time and could even lower the material cost, but it comes with the cost of increasing the material usage and thus embodied carbon in the structure (Poole, 2020).

3

Methodology

The different steps of the methodology of this thesis work is presented in Figure 3.1.

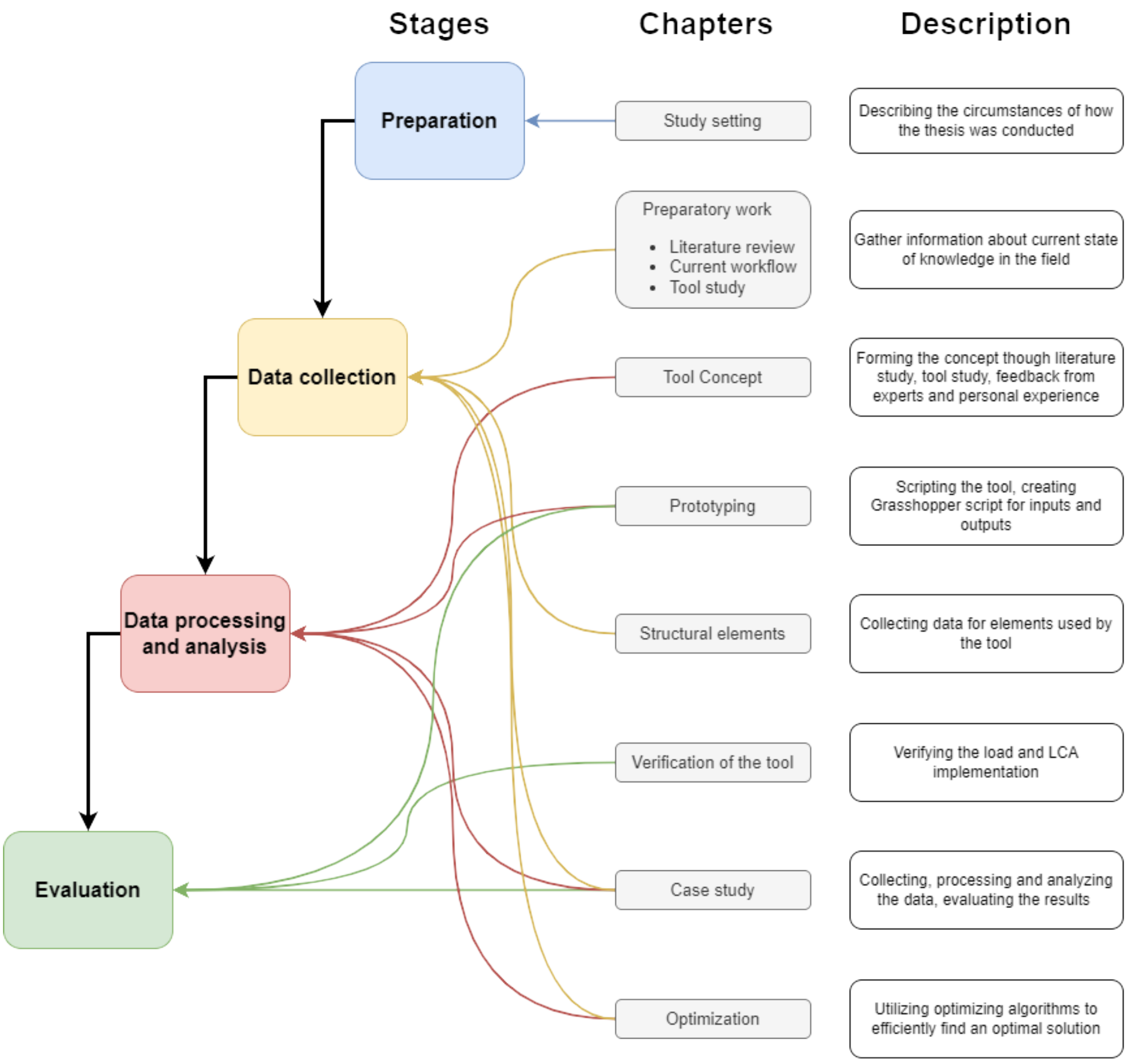


Figure 3.1: *Flowchart to present an overview of the methodology.*

3.1 Study Setting

This Master's thesis was conducted primarily at the engineering company VBK Konsulterande Ingenjörer AB in Gothenburg, between January and June 2024. The supervisors were from VBK and Chalmers University of Technology. Additionally, other employees at VBK contributed to the research on various occasions. Their expertise included structural engineering, LCA, and programming among others. Many of the people involved have experience working with and providing work for architects as well.

Literature review and data collection was conducted through Google Scholar, online search engines and library resources. Other tools used in this thesis included OneClick LCA, Rhinoceros 3D, Grasshopper and several plugins to Grasshopper, which are described in Chapter 2.3.

3.2 Preparatory Work

As preparatory work the current workflow for conducting LCA in preliminary design stages at VBK was investigated. A tool study was also conducted to gather an overview of relevant tools and plugins that are currently in use. Together with the supervisors the outline of the tool was brainstormed, to figure out what limitations, functionality, input and output the tool should have.

3.2.1 Current Workflow

An interview was conducted to investigate the current workflow at VBK and explore what the thoughts and expectations are for an early stage LCA analysis tool. In total 12 questions were asked about the current process of early stage LCA analysis, about the clients, and what the thoughts and expectations are for this kind of tool. The questions and answers can be found in Chapter 5.1.

3.2.2 Tool Study

The tool study aims to investigate different plugins, web-tools or programs that can be used for conducting LCA. Tools that can also automatically determine a suitable sizing for structural elements are of particular interest.

A few different plugins, web-tools or programs that conduct LCA at various design stages have been investigated in the tool study to identify the usability and development potential. In a meta review conducted by Säwén et al. (2024) some of the main themes when reviewing LCA and building performance tools are usability, the performance of the tools, how compatible the tool is with other software and what cost is associated with the tool. What functionalities the tool offer and for what purpose they were designed are also actively discussed subjects. The following evaluation criteria have been noted for each tool:

- Purpose
- Functionality
- Usability
- Compatibility
- Performance
- Cost
- Availability of support
- Tool transparency
- Confidence level
- Overall impression of the tool

The full table, including a list of questions that were used to assess the tools for each criterion can be found in Appendix A.

3.3 Tool Concept

It is beneficial to have an end product in mind when developing a tool. To define the requirements a holistic approach was used.

The initial requirements were defined from looking at findings from the literature review and identifying factors that would have a significant impact on the end result. The tool study provided some valuable insights by highlighting the strengths and weaknesses of existing tools. Also, VBK had a few requests on what to include in the functionality of the tool.

After the initial requirements were set there was a brainstorming process where the requirements evolved mostly through discussions with supervisors. These discussions were important to explore the potential and limitations of the tool, to set realistic expectations. The tool development itself helped adjust the requirements and expectations with the new insights that emerged during the development.

The final considerations were of a more subjective nature, such as desired functionalities identified from the tool study analysis. Also, personal experience will play a role in forming the tool concept.

3.4 Prototyping

With the initial requirements from the tool concept the tool development could get started. The initial scripting phase consisted of getting familiar with python syntax and planning how to develop the prototype in an efficient way. The development was broken down into smaller, more manageable milestones that could be tested and verified. The goal was to make the tool scalable, which means that new functionalities can be added over time without compromising the functionalities already added. Which fits well together with the milestone-approach.

When implementing a new feature in the tool, the aim was to get it working on a simple scenario. After the proof of concept had been verified the next step was to make it work on more general cases. And finally, the aim was to make the code more efficient and understandable.

For example, recognising which slabs are connected to which beams and then making sure that the load transfer was working had a few iterations. At first, influence areas were used which would be used to add the permanent and variable load to each element independently from each other. However, that would not add the dead load from each slab to the beams, hence a more general case needed to be added. In the first proof of concept a fixed structural grid was used to check that the load transfer would work properly, this used lists to keep track of the load. In the next step a for-loop was constructed that would work on any size of the grid. However, it would only work on an orthogonal grid, which is why OOP was implemented. With OOP a method was implemented to allow the objects to recognise if they shared nodes with each other, and automatically transfer the load between the element if they shared nodes.

3.5 Structural Elements

The main idea behind the tool is that it should automatically select the cross section and provide the user with the environmental data. To instil confidence for the tool it needs to have verifiable data of each element, what the environmental impact is and what load bearing capacity each element has. Such data can sometimes be gathered from manufactures directly, other times trade organisations can provide the data for general elements and the third option is to calculate the capacity by hand calculations or with help of tools. For this thesis a combination of all three sources has been used. The environmental data can either be found in the EPD which manufacturers provide, or at Boverkets climate database, which contains generic data for a number of construction materials.

3.6 Verification of the Tool

The verification was conducted by checking the load computed by the tool against hand calculations for a simple structural system. A small system was chosen to ensure that the hand calculations were straightforward and easy to perform.

A load takedown was conducted by assuming imposed loads and calculating one ULS and one SLS load case to compare against the tool. The elements were then selected manually from the Excel sheet to verify that the tool had selected the same elements. The load was first calculated for the slab after which the slab element was selected. The load was then assumed to be transferred to the beams, with half the load to each beam, including the self-weight of the slab. This process was repeated for beams and columns. For columns, an additional step was involved, where the load from the column above is transferred down. This was also verified through hand calculations and making sure the same elements was selected.

The embodied carbon output was verified against data from a commercial software. This was done by ensuring that the same volume and density was used by both tools. This verification was performed for a slab element and an element that represented both beams and columns, as they use the same method for calculating the embodied carbon. To simplify the process, elements that were present in both the case study and the tool was selected.

3.7 Case Study

The reference building in the case study is a kindergarten. The building footprint of the kindergarten has an angular shape with a corridor in the middle. Seven different design alternatives were made for this kindergarten to evaluate the embodied carbon. For a detailed list of materials and elements for each proposal, see Appendix B.2. Almost all design alternatives have load bearing walls with floor slabs that spans from the exterior wall to the corridor. This created a building with two long and one short span, see Figure 3.2 and 3.3.

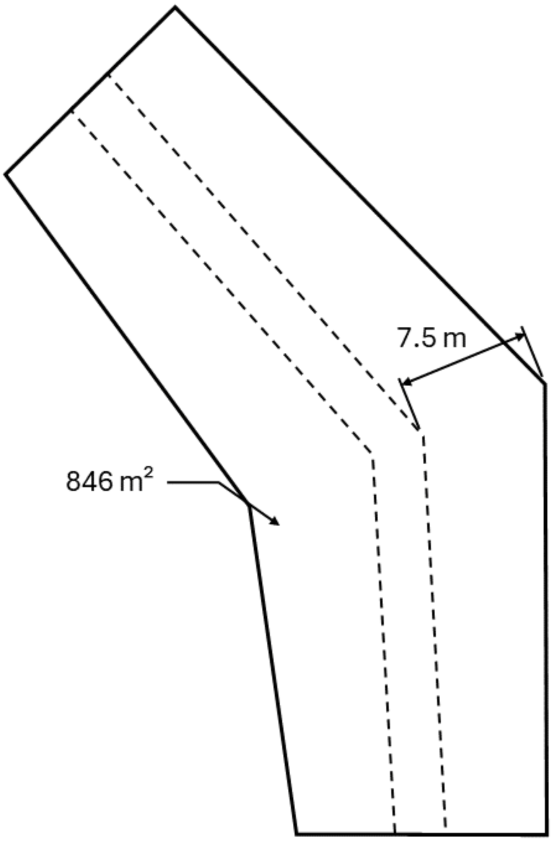


Figure 3.2: *Plan view of the reference building with the hallway in the middle.*

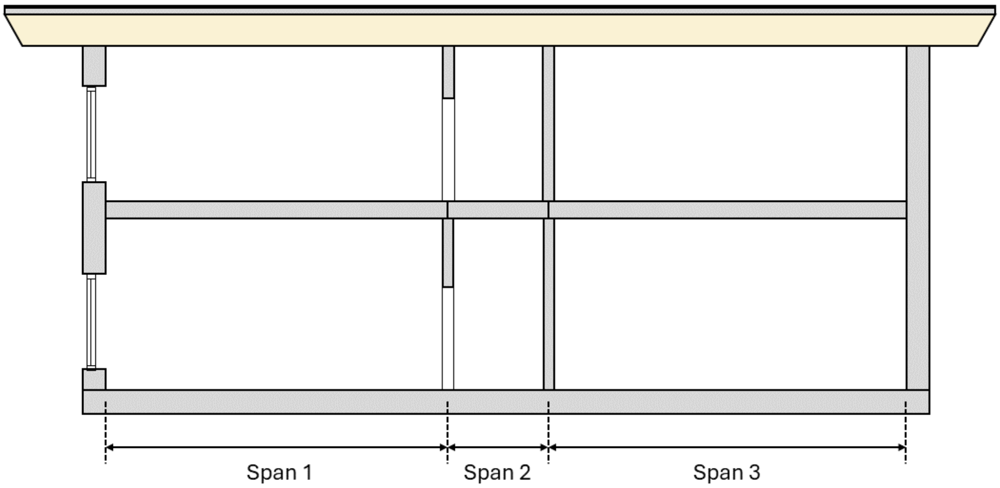


Figure 3.3: *A typical section of the reference building.*

The building footprint of the reference building are not suitable for the current version of the tool, as it works best with a rectangular footprint. The parametric model will thus need to approximate a new footprint which should keep the main characteristics from the reference building to make a fair comparison. The main characteristics includes number of spans, span lengths, and floor area, see Chapter 5.4.1 for the approximated geometry.

The reference building was selected as it was one of few available that was designed after the climate declaration became mandatory. It was not optimal for the tool, with the shape of the building footprint and the load bearing walls. However, the project had a high target for environmental impact, which meant that several alternatives were made to find one with low amount of embodied carbon. The requirements from climate declaration also meant that the embodied carbon had been calculated and documented for each design alternative.

The case study aims to compare the structural systems between the reference building and the parametric model. For this part the tool needs to produce a similar structural system compared to the case study alternatives, in terms of load cases, building footprint, span lengths and material selection. The outcome of this part is to compare:

- If similar elements have been selected, where applicable.
- The emissions from different parts of the structural system.
- The emissions from the structural systems as whole.

And finally, the case study aims to utilise optimisation algorithms to investigate if a solution with lower amount of embodied carbon can be found compared to any of the design alternatives of the reference building.

3.8 Optimisation

In an attempt to find the most optimal solution for a given building footprint an optimisation solver was used. A multi-objective optimisation plugin, Wallacei, was tested to perform a topology optimisation to compare against the case study.

The carbon emission was selected as the first objective to optimise against, the second objective to minimise would in most cases be the cost. However, since cost is not included in the tool, span lengths were chosen as objectives instead. In floors plans there are certain span lengths that fits some plans better than others. To optimise against these specific span lengths, a residual was constructed that reached its lowest value at the desired span lengths.

3.9 Risk Analysis

The tool is only considered for preliminary design and is still under development which means that it has not gone through full testing. The tool is dependent on the quality of the input data, poor data will lead to unreliable results.

3.10 Societal, Ethical and Ecological Aspects

There are no societal or ethical aspects identified with this subject. This thesis aims to help guide designers towards more environmentally friendly options and should be a net positive.

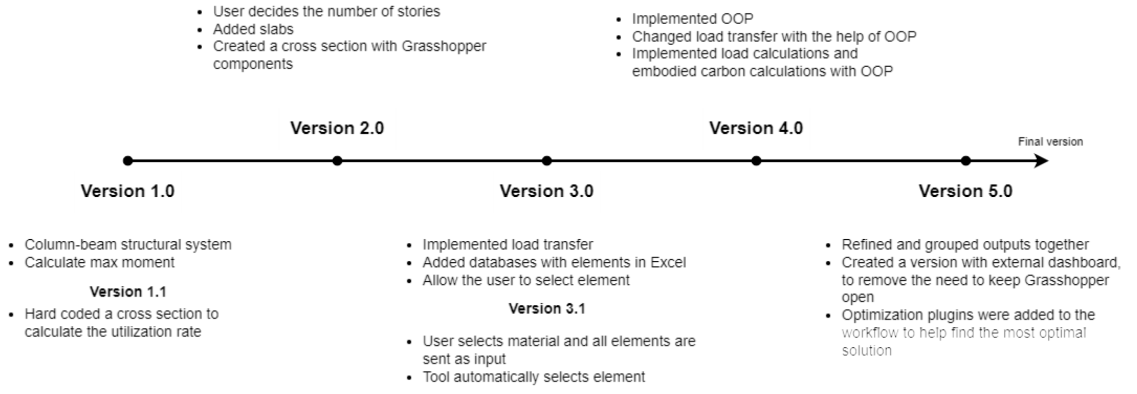
4

Tool Development

This chapter provides a comprehensive overview of the development process of the parametric tool. It begins with a detailed explanation of the iterative process when developing the tool, followed by a quick overview of the Grasshopper script and the algorithm of the tool. After which the inputs and outputs of the tool is explained, and the data gathering process of structural elements is discussed followed by a brief discussion regarding the environmental data. Finally, the results of verification and user testing is presented.

4.1 Scripting

The scripting has been an iterative process, where the focus has first been to implement a proof-of-concept and then refine it to more general situations and finally to make the code more readable by others. The major milestones in the tool development can be seen in Figure 4.1.



Version 1.0
- Column-beam structural system
- Calculate max moment

Version 1.1
- Hard coded a cross section to calculate the utilization rate

Version 2.0
- User decides the number of stories
- Added slabs
- Created a cross section with Grasshopper components

Version 3.0
- Implemented load transfer
- Added databases with elements in Excel
- Allow the user to select element

Version 3.1
- User selects material and all elements are sent as input
- Tool automatically selects element

Version 4.0
- Implemented OOP
- Changed load transfer with the help of OOP
- Implemented load calculations and embodied carbon calculations with OOP

Version 5.0
- Refined and grouped outputs together
- Created a version with external dashboard, to remove the need to keep Grasshopper open
- Optimization plugins were added to the workflow to help find the most optimal solution

Figure 4.1: *Short description of each milestone during the tool development.*

Version 1.0

Firstly, with the help of standard Grasshopper components a structural grid was created by dividing a surface by a number of spans in x- and y-direction. From this structural grid the columns and beams were created to represent a simple structural system. In the first version the system was only one story high. This system gave a list of columns and beams to use as inputs to the tool. A number was added as an input to represent the imposed load, from this the maximum moment for each beam was calculated. This was done as a way to explore possible ways to decide the cross sections of the elements.

Version 1.1

The next step was to create a mock up cross section for calculation. The outputs were investigated as well, how they should be presented to the user. At this point the output consisted of the utilisation rate of each cross-section. With the help of standard Grasshopper components, the results were displayed on each element in the 3D model.

Version 2.0

The tool was adopted from handling a single story to letting the user decide how many stories the model should have. This also changed the input from a list structure to a Grasshopper tree structure, which required some rewriting of the code. In this version, slabs were added as an input as well. Slabs were added in a similar manner as the beams and columns, but by using surfaces instead of curves.

After getting the basic geometry working for a structural system the focus was shifted back to cross sections and elements. An attempt was made to model cross sections with standard Grasshopper components, calculate the section modulus and the height to use when computing the cross section. It was quickly apparent that this was a very time-consuming process for the user and the idea of using prepopulated elements was a better option.

Version 3.0

At this point a load transfer was being implemented in the tool, to transfer the loads all the way down to the last set of columns. The load transfer was implemented for this specific kind of system as a proof-of-concept at this stage. The ability to visualise the results on the 3D model was beneficial when implementing the load transfer, as the verification became easier.

After gathering the data for elements, a dataset for each type of element was constructed in Excel. This included the cross-sectional area, the density, embodied carbon according to stage A1-A5, and the load bearing capacity. The plugin PancakeSpreadsheet was used to grab the data from the Excel sheets, and allowed the user to select an element from a list to use in the tool.

Version 3.1

The material input was changed from letting the user select an element in a list to sending in all data for a given material at once, e.g. all HEB beams. This allowed the tool to automatically select the best cross section for the load and to make sure that the utilisation rate never exceeds 100%. At this point the data needed to be organised in the same way for all materials.

Version 4.0

After getting familiar with OOP, a proof-of-concept system was implemented where different elements could recognise if they were sharing nodes. This was used to replace the existing load transfer method. The benefit of using a method which could recognise if the elements share a node is that irregular grids would also work, which has potential for future development of the tool.

Load calculations and embodied carbon calculations was also implemented in this stage with OOP. The reliability class and utilisation rate were added as inputs to use with the load calculations.

Version 5.0

To investigate how the tool could become more user-friendly, the plugin UI+ was added to the script. A dashboard can be created with the help of this plugin, to allow users to control certain Grasshopper components, such as number sliders or a drop-down list, outside of the Grasshopper window. This can help create a more user-friendly workflow by focusing on the input and output parameters.

The outputs were also refined and grouped together in either environmental output or load output. The outputs have a Grasshopper tree structure, the same structure as the input slabs, beams or columns. This made it easier to display the correct data on the correct element.

An optimisation plugin was investigated, Wallacei, to see if it could help optimise the structure. The user needs to decide which parameters to use as genes, and what objectives to optimise against. A workflow was created to present the result in a more efficient way.

A summary of the geometry and the output of the embodied carbon was compiled and shown next to the 3D model with the help of standard Grasshopper components.

4.2 Grasshopper Script

The Grasshopper script created for this thesis can be seen in Figure 4.2, where it has been separated into several sections. The first section is the most important to the user as that is where they can change the input parameters and also decide what kind of results should be displayed on the 3D model itself.

4.3 Tool Algorithm

A simplified version of the tool algorithm is presented in Figure 4.3. The tool will first calculate the slabs, then beams, and finally the columns. For each element it will perform a load and embodied carbon calculation and add it to the output together with the selected cross sections. If a slab, beam, or column does not have cross sections with sufficient capacity the tool will stop the calculations and display an error message.

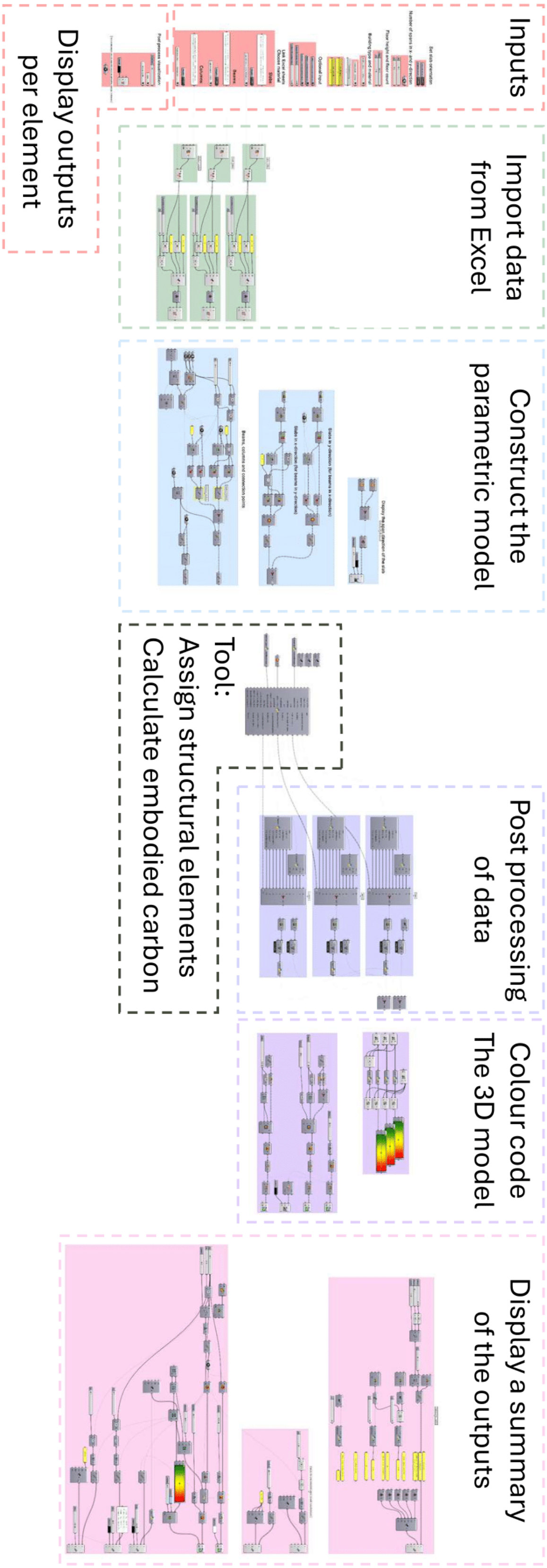


Figure 4.2: *An overview of the Grasshopper script created for this thesis.*

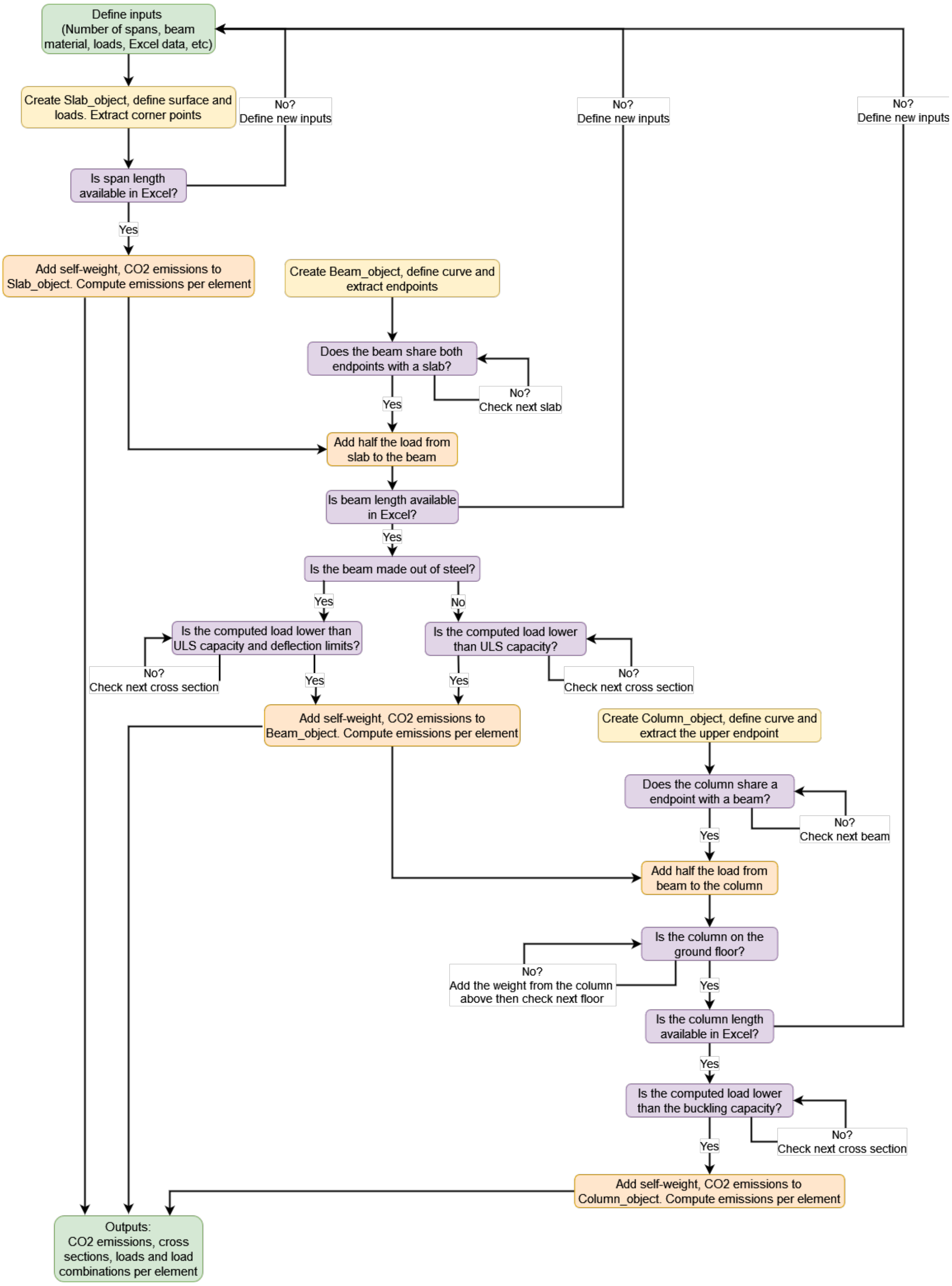


Figure 4.3: *A flowchart to present the algorithm of the tool.*

4.4 Input and Output

The number of inputs required to design a building and conducting a detailed LCA analysis can be extensive. There are studies that recommend simplifying the scope by reducing the number of inputs to ensure an efficient design process by focusing on the aspects with highest impact (Kjær Zimmermann et al., 2019). It is also assumed that fewer input parameters would ensure a smoother and less overwhelming experience for users who are inexperienced with Grasshopper or LCA.

The footprint of the building is the foundation to the parametric model, it will set the boundary for the structural system and is thus an important input. There are many numerical input parameters, such as span length, number of floors or floor height. Other input parameters include selecting values from a list. For example material selection, where there are predefined and limited choices available. And lastly there are also optional parameters, that will in most cases work with the default value, such as reliability class.

The output parameters should be informative and relevant, the most relevant output in this thesis is the environmental impact of an element or the entire system. Other output that was deemed to be relevant for the designer was load calculations, this should also help to make the tool feel transparent and verifiable. And lastly the cross section chosen by the tool are also highly relevant, as those will need to be checked when the design becomes more and more detailed. For the full input and output list, see Figure 4.4.

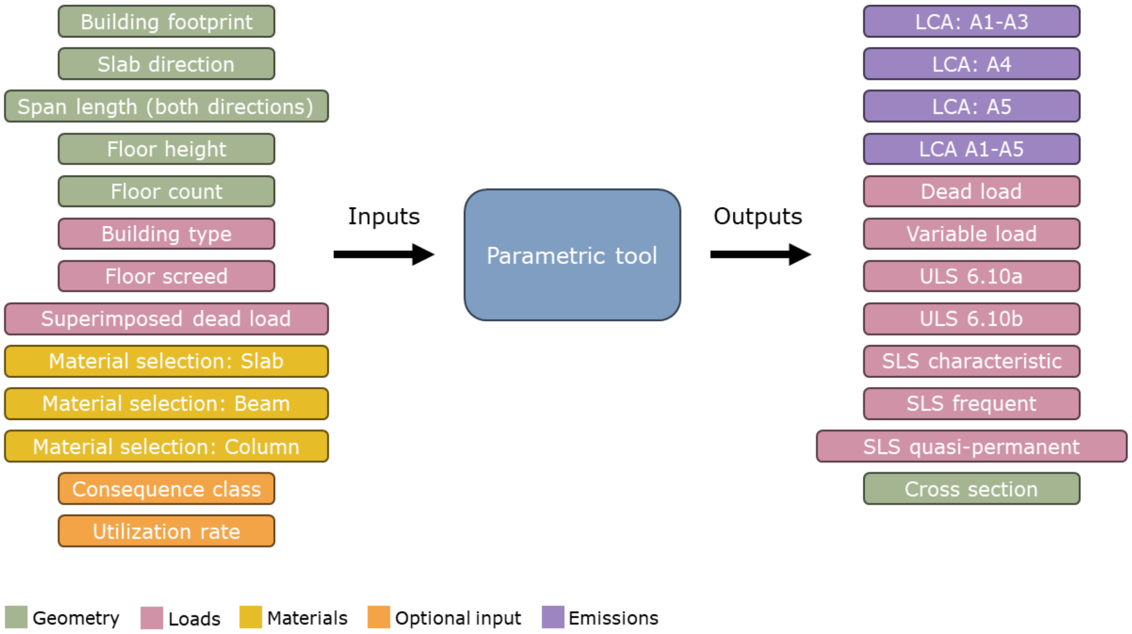


Figure 4.4: *A schematic view of the inputs and outputs to the tool.*

An explanation to the geometry-based inputs can be found in Table 4.1, the load based inputs can be found in Table 4.2, the material based inputs can be found in Table 4.3, and the explanation to the optional inputs can be found in Table 4.4.

Table 4.1: Explanation of geometry-based inputs for the tool.

Parameter	Type	Explanation
Building footprint	Surface	An rectangular surface in the xy-plane which defines the boundary of the structural system.
Slab direction	Boolean	A toggle to determine whether one-way slabs span in the x- or y-direction.
No. of span in x-dir No. of span in y-dir	Number slider	Forms the structural grid by dividing the building footprint by the number of spans in each direction.
Floor height	Number slider	Determines the height from floor to floor.
Floor count	Number slider	Determines the number of floors.

Table 4.2: Explanation of loads-based inputs for the tool.

Parameter	Type	Explanation
Building type	Value list	Determines the imposed load based on what type of building is selected.
Floor screed	Number slider	Computes extra CO_2-emissions from the floor screed.
Superimposed dead load	Number	Extra dead load from floor screed, fixtures, internal walls, etc.

Table 4.3: Explanation of material-based inputs for the tool.

Parameter	Type	Explanation
Material selection: Slab	Value list	Imports cross sections, self weight and CO_2-emissions of the selected material from Excel.
Material selection: Beam	Value list	Imports cross sections, self weight, CO_2-emissions and capacity of the selected material from Excel.
Material selection: Column	Value list	Imports cross sections, self weight, CO_2-emissions and capacity of the selected material from Excel.

Table 4.4: Explanation of optional inputs for the tool.

Parameter	**Type**	**Explanation**
Reliability class	Value list	Decides the reliability class for slabs, beams and columns. Class 2 is default for slabs and beams. Class 3 is default for columns.
Utilisation rate	Number slider	Decides the maximum utilisation rate for each element, default value is 100%.

An explanation to the emission based outputs can be found in Table 4.5, load related outputs can be found in Table 4.6, and the geometry related output are explained in Table 4.7.

Table 4.5: Explanation of emission related outputs from the tool.

Parameter	**Type**	**Explanation**
LCA: A1-A3	Number	The emissions per element [$kgCO_2$] according to LCA scope A1-A3, production stage
LCA: A4	Number	The emissions per element [$kgCO_2$] according to LCA scope A4, transport from production site to construction site
LCA: A5	Number	The emissions per element [$kgCO_2$] according to LCA scope A5, site energy usage and waste
LCA: A1-A5	Number	The emissions per element [$kgCO_2$] according to LCA scope A1-A5, embodied carbon

Table 4.6: Explanation of load related outputs from the tool.

Parameter	**Type**	**Explanation**
Dead load	Number	Characteristic value of all permanent loads acting on the element, including the self-weight of the object
Variable load	Number	Characteristic value of all variable loads acting on the element
ULS 6.10a	Number	6.10a load combination calculated according to (2.1)
ULS 6.10b	Number	6.10b load combination calculated according to (2.2)
SLS characteristic	Number	Characteristic load combination calculated according to (2.3)
SLS frequent	Number	Frequent load combination calculated according to (2.4)
SLS quasi-permanent	Number	Quasi-permanent load combination calculated according to (2.5)

Table 4.7: Explanation of geometry related output from the tool.

Parameter	**Type**	**Explanation**
Cross section	Text	The chosen cross section for each element.

4.5 Structural Elements

The structural elements needed for a framed system are slabs, beams, and columns. The data gathering process resulted in data for hollow core slabs, CLT slabs, glulam beams, glulam columns, steel beams and columns. To complement it with more elements, a couple of in-house tools were used to calculate more glulam beam cross sections and reinforced concrete columns.

The design life of all structural elements is assumed to be 50 years. Each element is affected by permanent load and variable load. The permanent load consists of the dead load of the element itself, a superimposed dead load (internal walls, floor screed, HVAC systems, light fixtures, etc) which have a standard load defined in the industry. The variable load is assumed to only consist of the imposed load which is supplied by EKS 12.

The floor screed can range from 30 to 70 mm in normal circumstances (Betongelementföreningen, 2013), for load circumstances a typical value in the industry is 0.25 kN/m^2 per 10 mm concrete screed. The standard load of interior walls is 0.5 kN/m^2 in the industry. Fixed installations, such as HVAC, light fixtures and similar, have a collective standard load of 0.2 kN/m^2 in the industry.

4.5.1 Slabs

The slabs used in this tool for the preliminary design are either hollow core concrete elements or CLT slabs as they are both common slab elements.

The data from hollow core slab was gathered from an archived version of the trade organisation Svensk Betongs website (Svensk Betong, 2017). This contained information of spans for hollow core slab elements for preliminary design which has taken both ULS and SLS into consideration, see Appendix C.1. This table has been cross referenced against similar tables from "Bygga med prefab" which is a handbook for prefabricated concrete elements (Betongelementföreningen, 2013). The load cases investigated were firstly one for an office building with 2.5 kN/m^2 variable load and an extra 1.5 kN/m^2 superimposed dead load. The second load case were one for a residential building with 2.0 kN/m^2 variable load and an extra 2.0 kN/m^2 superimposed dead load. The superimposed dead load uses weight from assumptions which are common in the industry: 30mm of concrete screed, installations and interior walls.

It should be noted that a couple of the cross sections in Bygga med prefab displayed a maximum span width that were around 1.5m less than the tables from Svensk Betong when considering SLS demands. The SLS performance is dependent on the degree of pretensioning, thus the tables might assume a lower degree of pretensioning than the graphs from Bygga med prefab.

Timber floors is light in comparison to concrete and does often need to be designed for acoustics demands. Usually this involves adding insulation, concrete or special acoustics mats. The CLT-Handbook presents a few example designs that work in terms of acoustics. Floor structure type 8 in the CLT-handbook was selected to represent a typical office building and floor structure type 9 was selected to represent a typical residential building (Gustafsson et al., 2017).

An approximate extra weight can be concluded from these examples by subtracting the weight of the CLT from the total weight. This gives the office example (floor structure type 8) an extra 45 kg/m^2 (≈ 0.5 kN/m^2), and the residential example (floor structure type 9) an extra 135 kg/m^2 (≈ 1.4 kN/m^2). For the full load assumptions, see Table 4.8

Table 4.8: Load assumptions of a CLT slab for an office building and residential building.

CLT Slab		
	Office $[kN/m^2]$	**Residential** $[kN/m^2]$
Extra weight	0.5	1.4
Interior walls	0.5	0.5
Fixed installations	0.2	0.2
$\sum$ superimposed dead load	1.2	2.1

The office building should be designed for a variable load of 2.5 kN/m^2 and residential building for a variable load of 2.0 kN/m^2 (Boverket, 2022)

The CLT slabs were obtained from Setra, a manufacturer of EWP. Setra have compiled a table containing span lengths for different load cases where both ULS and SLS have been accounted for according to Setra (2021). The slabs were selected assuming the load case for residential and office buildings.

4.5.2 Beams

The steel beams which were used in the tool were selected from a brochure from the steel manufacturer Tibnor. The beams are assumed to be simply supported with a distributed load, the beams are also assumed to be supported against lateral torsional buckling (Tibnor, 2023). The tables have listed the capacity of the beams according to (2.1)-(2.2), excluding the self-weight of the beam. The manufacturer has also listed the deflection for the corresponding frequent SLS load combination (2.4). The deflection was however not limited to L/300 and thus the capacity was recalculated to have a limiting deflection of L/300. See Appendix C.2 for an example of a dataset which contains both ULS and SLS capacity.

The data used for glulam beams have been gathered from the trade organisation Svenskt Trä's tables for preliminary design (Svenskt Trä, n.d.-b). The tables were intended to be used for timber joists, which means that the beams would sit with a narrow spacing, consequently the elements listed in the table has a relatively low load bearing capacity. An in-house tool from VBK was used for calculating and adding more cross-sections to the list.

The extra cross-sections would make it easier for the tool to find cross sections with a sufficient load bearing capacity. In both cases ULS and the deflection in SLS have been accounted for. Furthermore, both Svenskt Trä and the calculated glulam beams are assumed to be supported against lateral torsional buckling. The calculated beams are also assumed to have sufficient capacity for compression perpendicular to the fibres. It is unknown what assumptions Svenskt Trä has made for compression perpendicular to the fibres. All glulam elements are designed with climate class 1 and a strength class of GL30c.

4.5.3 Columns

Another in-house tool from VBK was used for calculating the buckling capacity of concrete columns. This assumed only an axial load on the column. The columns were designed with either 4x12mm or 4x16mm reinforcement, see Appendix C.3 for the calculated capacity. When calculating the CO_2 emissions for the columns an extra 8% were added to the concrete emissions for columns with 4x12mm reinforcement and 12.5% for columns with 4x16mm reinforcement. This were done as a simplification, as the spreadsheet format and the code of the tool does not allow adding emission data for two materials separately to create a composite material. See Appendix D for the CO_2 calculations.

The steel columns were selected from the same brochure from Tibnor as the steel beams. These tables listed the buckling capacity in the strong and weak direction. As a conservative measure and for simplicity, the capacity in the weak direction were chosen to be used in the datasets. The columns are assumed to be loaded with an axial force and have a pinned connection in both ends.

The glulam columns were also selected from Svenskt Trä. The preliminary design tables contained the load bearing capacity with regard to buckling in the strong and weak direction. Also here the weak direction were chosen to be used in the datasets. Svenskt Trä assumed that the columns would be loaded with an axial force and have a pinned connection in both ends. The glulam columns were designed with a strength class of GL30c and a climate class of 1 or 2.

4.6 Environmental Data

The environmental data used in the datasets has been gathered from climate database supplied by Boverket, which contains generic data. This data has an extra 25% CO_2 added to the mean value, as a conservative measure. The user can easily use specific data from EPD, which are supplied by manufacturers, to avoid the extra CO_2 emissions.

The emissions are calculated as $kgCO_2/kg$ material, this needs to be multiplied by the density to get $kgCO_2/m^3$, which is the unit the tool has been programmed for. The volume is computed inside the tool by multiplying the cross-sectional area by the length of the element for beams and columns. For slabs, the cross-sectional area is set per metre slab, which means it needs to be multiplied by the span length and width of the element (the surface area) to get the volume.

Once the tool has both carbon emission per cubic meter and the volume it can calculate and present the emissions per element, for LCA scope A1-A3, A4, A5 and A1-A5. As the climate declaration has a limit per square metre gross floor area, the output has been adapted with standard components to display $kgCO_2/m^2$ next to the model, see Figure 4.5.

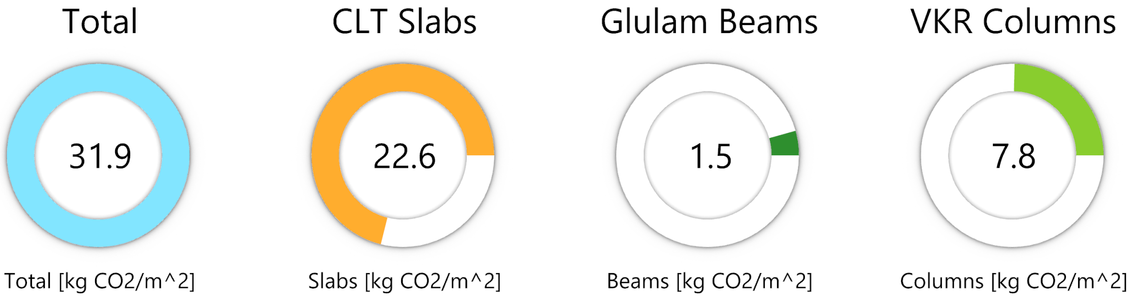


Figure 4.5: *How the CO_2 emissions are presented by the tool.*

4.7 Verification

To be sure that the load transfer calculations have been implemented correctly, it was necessary to verify the calculations by comparing them to hand calculations. The embodied carbon calculation has also been verified by comparing with data from OneClick LCA.

4.7.1 Carbon Emission Verification

This investigation aims to see if the GWP calculated by the tool is the same as the GWP from a commercial software, in this case OneClick LCA. From the list of elements used in the different design alternatives, see Appendix B.1, three elements were identified to be suitable for a comparison, VKR columns, CLT slab with floor screed and CLT slab with climate improved concrete as floor screed. The GWP from OneClick LCA was compared against the GWP calculated by the parametric tool, the results can be seen in Table 4.9.

Table 4.9: Comparison between the CO_2 emissions calculated by OneClick LCA and the emissions calculated by the tool for a few structural elements.

Element	VKR 100x100x6,3	CLT slab 280 mm Floor screed 30 mm	CLT slab 280 mm Concrete 30/37 30 mm Climate improved
Functional unit	181.25 m	838.8 m^2	838.8 m^2
OneClick LCA A1-A5	11,216 $kgCO_2$	27,680 $kgCO_2$	24,325 $kgCO_2$
Parametric tool A1-A5	11,191 $kgCO_2$	27,982 $kgCO_2$	24,533$kgCO_2$
Difference	0.2%	1.1%	0.9%

As can be seen in Table 4.9, the difference is very small between the elements. It is caused by a rounding error when extracting the data from OneClick LCA.

4.7.2 Load Takedown Verification

A simple model was used for calculating the loads by hand and then compare against the loads computed by the parametric tool, as verification. The model had a building footprint of 10x10m. The structure was designed with two spans in both directions. The elements chosen for the verification were a hollow core concrete slab, steel HEB beams, and glulam columns. The loads assumed for the verification was an imposed variable load of 2.5 kN/m^2 (office building) and a superimposed dead load of 2.0 kN/m^2.

A summary of the verification can be found in Table 4.10, see Appendix E for the full hand calculations and the result obtained from the parametric tool.

Table 4.10: Verification of the load takedown in the tool with hand calculations.

	Hand calculations		Parametric tool	
Element	**ULS 6.10b**	**SLS frequent**	**ULS 6.10b**	**SLS frequent**
Slab	8.52 kN/m2	5.92 kN/m2	8.52 kN/m2	5.92 kN/m2
Beam (central)	43.59 kN/m	30.51 kN/m	43.6 kN/m	30.52 kN/m
Beam (edge)	22.19 kN/m	15.62 kN/m	22.19 kN/m	15.62 kN/m
Column (central)	240.00 kN	152.97 kN	240.10 kN	153.06 kN
Column (edge)	122.16 kN	78.28 kN	122.17 kN	78.30 kN
Column (corner)	61.02 kN	39.09 kN	61.15 kN	39.20 kN

The table shows a small differences between the hand calculations and the parametric tool, this is due to rounding error in the hand calculations.

4.8 User Testing

To gather feedback, a beta version of the tool was sent to the supervisors for testing and one additional employee at VBK. Two of the testers are experienced with Grasshopper, while the other two has moderate to low experience with Grasshopper. The testers had full freedom when testing the tool, some aid were provided to the testers with less Grasshopper experience. Some of the comments that were provided are presented below:

- It is difficult to find the results on the canvas.
- It is not obvious at first what the different numbers shown in the 3D model are.
- You do not want to feed in the file-path manually every time.
- Specify what the different parts of the script does.
- Directing the user with a "Start here" and some instructions would be helpful.
- The analysis runs immediately after adding the building footprint as input, a boolean toggle would have been nice.
- It would have been nice to be able to display the utilisation rate.
- It would have been nice to be able to print the entire result by clicking a button.
- When you get familiar with the script it becomes quite handy.
- It is much faster compared to the current process of conducting LCA in early stages.

Some comments have been added to the script to let the user know what each part does. Units have also been added to the numbers that are displayed in the 3D model, which should make it clearer what they are representing. However, the majority of these issues are to be considered for further development of the tool.

5

Results

In this chapter the results that has been gathered from the interview, tool study, tool concept and the case study are presented.

5.1 Interview

A summary of the interview conducted with Jonathan Söderqvist, VBK, are presented below, the full interview can be found in Appendix F

When conducting an early stage LCA he is trying to target the element with largest carbon footprint as they could offer large reduction with few changes. He also said that it takes a long time to compile the alternatives, and since it is not billed, LCA does not get allocated a lot of time in the projects. The main tool for him is currently either Excel or OneClick LCA. The clients are either interested in getting the verification for the climate declaration or passing the demands set by Miljöbyggnad.

The desired functionality includes being able to get an early approximation, to compare different options and also a low entry barrier to allow more people to conduct an early stage LCA themselves. The outputs that should be included are amount of emissions and amount of materials, but a cost estimate would also be highly desirable. According to Jonathan an acceptable margin of error might be in the 10-15% range. He estimated that span lengths, number of stories and the material have the largest influence on the amount of embodied carbon in a building.

5.2 Tool Study

The results of the tool study are presented as a summary in Table 5.1, and the detailed results from the tool study can be found in Appendix A.

Table 5.1: Summary of the tool study.

Tool name	**Purpose**	**Usability**	**Tool format**	**Overall impression**
OneClick LCA Carbon Designer 3D	Early stage LCA	Quick and easy to use	Web tool	Mid
OneClick LCA Grasshopper plugin	Late stage LCA	Long setup time. Easy to use*	Grasshopper plugin	Mid-High
PANDA	Early stage structural design and LCA	Quick and easy to use	Computer program	High
Cardinal LCA	Late stage LCA	Long setup time. Easy to use*	Grasshopper plugin	Mid
Bombyx	Early and late stage LCA	Long setup time. Easy to use*	Grasshopper plugin	Low
BHoM LCA Toolkit	Late stage LCA	Rquires high knowledge	Grasshopper plugin	Low-Mid

* Assuming the user is familiar with Grasshopper already

General comments about each tool:

One Click LCA Carbon designer 3D - The tool is quick and easy to use but the user cannot be certain that the tool generate a structurally sound system. It is also somewhat limited when it comes to changing materials as the user can not add their own environmental data from the manufacturers EPD. On the other hand, it handles the material as percentage so it can be quick to check different configurations of a system which uses composite materials.

One Click LCA Grasshopper plugin - The tool is quick to use but requires the user to provide their own 3D model which may or may not be quick to modify. The tool also requires a license to use, which may be expensive for the Grasshopper tool alone. The Grasshopper tool can push the data to the website which is a handy feature. The data from the tool is displayed on the 3D model itself which allows for quicker and more intuitive understanding.

PANDA - The tool creates hundreds of possible structural systems and verify them against Eurocode, with the national annex of United Kingdom. The tool is very comprehensive and still easy to use, there are a lot of settings that an experienced user can configure. One downside is that it is difficult to force the program to obey a certain column spacing or force it to create a system with a certain material. The user can view the data used for the GWP and change if needed. The user can also view and verify the structural calculations that were done for Eurocode.

PANDA displays the environmental impact of the system against the cost of the system on a graph for all configurations. The tool should help making an informed decision in the early design stages and could also help speed up the early-stage design overall, which could justify the subscription cost.

Cardinal LCA - The tool is simple to use, the user provides a 3D model and select materials from a database, the user can also provide their own material data. The plugin has two databases, one from United Kingdom and one from United States. However, the database from United States seems to be unavailable. The tool can be fairly quick to set up if selecting data from the databases. The results can be presented as a short report, as a graph or by colour coding the 3D model according to the GWP of each element.

Bombyx 2 - The tool is in general simpler to use, the user needs to provide the geometry and select material from a list. The tool uses data from Switzerland, despite efforts, the databases have not been found which leaves some uncertainties regarding the environmental data. The tool can also estimate the GWP of the elements of a building in the schematic stage. The results are displayed as a list only. It is overall a quick tool, but the confidence level is uncertain.

BHoM LCA Toolkit - The tool requires a lot of custom components to set up the workflow properly, which can be difficult for an inexperienced user. The tool can be integrated with other programs in the AEC-industry, such as Revit. The tool has several datasets to choose from and the option to use custom environmental data. The tool is part of the open-source project BHoM, which Buro Happold is in charge of.

5.2.1 Input Analysis

A majority of the Grasshopper plugins tested required the user to provide a model with defined volumes, this is less feasible during early stages where the volumes are not fully defined yet. It also causes a problem with testing different materials, as the cross sections would be different for a steel beam compared to a glulam beam. Many of the plugins had a list of materials and their environmental data, which made it quick and easy to apply a material to the model. There were also some plugins that let the user add their own material data, this would increase the time to set up the analysis but is a handy feature that increases the functionality of the tool. Overall, it seems like the plugins are more suitable for the later design stages when the final design have been achieved.

Both PANDA and One Click Carbon designer 3D requires the user to define the volume directly in their interface with a few simple parameters and then generate the structural system automatically, Carbon designer 3D generate one at a time while PANDA will generate a wide range of possible systems at once. The carbon designer 3D has no transparency how the structural elements are selected or if they have the capacity to handle the loads, PANDA on the other hand has an extensive list of design parameters that the user can configure, which it will use to design systems that comply with Eurocode.

5.2.2 Results Presentation and Analysis

The output can vary between the plugins and the programs, some compile a small text report of the current system, others display graphs, while some display the data in the model, either by colour or by writing it out. The data can be compiled for the entire system at once or divided into the different elements, it differs between the tools how the data is displayed.

In general when it comes to displaying the results it should be clear, informative and relevant. According to Hollberg et al. (2021) the most popular types of visualisation are pie- and bar charts, although colour coding 3D models are gaining popularity but they are so far mostly only used in experimental tools. When it comes to presenting results with little information, a pie chart or colour-coded 3D model would be more suitable, to present more information or to compare different options a bar chart or some other type of chart would be more suitable. Hollberg et al. (2021) also noted that very few tools had visualisations that targeted decision makers, most tool focus on the designers.

5.3 Tool Concept

Forming the tool concept was an iterative process that began with the literature study. While end date is hard to define, as improvements can always be made. The requirements included in this section was defined before the case study began.

One of the most important goals of the tool was that it should be used in an early-stage design, this is when the largest impact can be made at the lowest cost.

At first, there was an ambition to check the design against Eurocode. However, it was soon apparent that the number of checks, exceptions and verification required would be difficult to fit in the time given for the Master's thesis. The speed could also be affected in a negative way if the list of checks is extensive. As a consequence, it was decided to use tables with pre-calculated elements.

Being able to pick any of the main materials was another ambition which was highly prioritised. Inspiration was taken from the tool study, where a few tools had list of materials to select from. A similar list with structural element and relevant data could be created in a similar fashion, that would allow the user to quickly select and change between different elements. Given that the elements have predetermined capacity this could be a promising alternative to computing the cross section according to Eurocode with a given load.

As studies have shown, the global parameters of a structural system, span length or material for example, could have a much larger impact compared to optimising a cross section for a given load. This led to the desire to focus on the span and material selection for the structural system, which is also more suitable in an early-stage design where the final load is not yet known. This would also gain benefit from being developed in a parametric environment as it could allow the user to generate different structural systems by adjusting only a few parameters.

Another aspiration for the tool was to make it easy to use to allow greater benefit with a wide userbase. As many in the industry are not familiar with Grasshopper, the interface, number of settings and type of setting requires careful consideration. Gathering feedback from users who are inexperienced with Grasshopper during a beta test of the tool would likely be beneficial.

5.4 Case Study

The case study aimed to investigate three main topics:

- To see if the embodied carbon differed for comparable elements between the commercial software and the tool developed in this thesis.
- To attempt to match the elements used in the structural system of the reference building and compare the embodied carbon against the system modelled by the parametric tool.
- To use optimisation plugins to find an alternative design with lower amount of embodied carbon compared to the reference building or parametric model.

Seven different alternatives were designed to evaluate the embodied carbon, one of which was chosen as design proposal. For a detailed list of materials and elements for each proposal, see Appendix B.2.

Some limitations that were made for this case study was to assume that all elements have a design life of 50 years. Horizontal stability is not considered and only the structural system itself is analysed, which does not include the foundation.

5.4.1 Parametric Model

The reference building in the case study has an angular shape, see Figure 3.2. This geometry would not work in the current version of the tool, and thus a rectangular bottom area was approximated for the case study.

Span lengths have a significant impact on the final result of the environmental impact, which is why the span length was chosen as primary focus when determining the dimensions for the parametric model. In the reference building, the longest span length was 7.5 meters, which was approximated to 6.8 meters in the parametric model, as shown in Figure 5.1. This adjustment was necessary because the maximum span length in the preliminary design tables for CLT slabs were 7 metres. The new approximated building had roughly the same footprint area, 845 m^2, compared to the original 846 m^2. The parametric model was designed with three spans in the short direction and eight spans in the long direction, see figure 5.1.

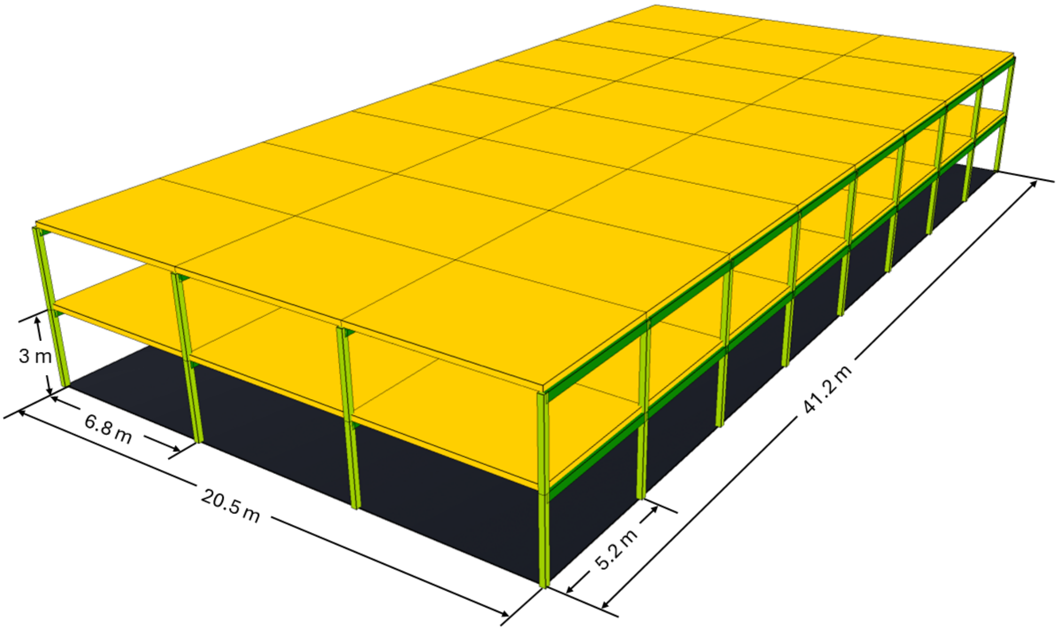


Figure 5.1: *The dimensions used in the parametric model.*

5.4.2 Comparing Structural Systems

In this section the focus will be to try to replicate the structural system in the reference building as close as possible, in terms of material, spans, cross sections and emissions.

There are three sub goals in this investigation, to see if the tool selects similar cross sections when applicable, to compare the emissions from different part of the structural system, e.g. comparing slabs against slabs, and to compare the embodied carbon emissions between the entire structural systems.

5.4.2.1 Selecting Similar Elements

The results of the comparison between the elements chosen by an engineer for a preliminary design compared to the elements selected by the parametric tool, can be seen in Table 5.2.

Table 5.2: Comparison between the choice of an experienced engineer and the selection of a parametric tool for early-stage design.

Engineer's choice	**Tool's selection**	**Comments**
CLT slab 280 mm	CLT slab 300 mm	Uncertain of the exact span length.
Concrete slab 260 mm	Hollow core slab 200 mm	The elements got different properties and are used in different circumstances.
HEA200 beam	HEA260 beam	It is uncertain what span or load the HEA200 beam was designed for. HEA260 is the smallest cross section that is available for 5.2m long spans (the span in the parametric model) according to Tibnor's tables.
VKR column 100x100x6,3	VKR column 100x100x6,3	Some uncertainties regarding the load and buckling length of the columns

The elements selected by the engineer and the tool had similar cross sections, especially for the VKR columns and CLT slabs. The two other elements, concrete slabs and HEA beams showed a greater difference, which is partly explained by lack of material data and the uncertainties of the reference model.

5.4.2.2 Comparing Emissions From a Group of Elements

The second part compares the embodied carbon from a commercial software, OneClick LCA, against the embodied carbon computed by the tool for the different load bearing categories, i.e. slabs, beams or columns. Six different elements were identified as either directly comparable or indirectly comparable, see Table 5.3 and Figure 5.2. The criterion was that the tool had to pick the element and the quantity itself, with one exception, the steel beams which had vastly different lengths, 101.5m in the reference building compared to 330m in the parametric model. It is assumed that the steel beams were only used in a certain part of the reference building, not the entire system. The embodied carbon from the steel beams were recalculated as if the beams were 101.5m long.

Table 5.3: Embodied carbon comparison for all elements of a category between the reference building and the system generated by the tool, using the reference building as baseline.

	Reference building	**Parametric tool**	**Difference**
Element	CLT slab 280 mm, part of roof structure	CLT slab 300 mm	
CO_2 emissions	21,168 $kgCO_2$	22,812 $kgCO_2$	+8%
Element	CLT slab 280 mm Climate improved concrete 30 mm	CLT slab 300 mm Climate improved concrete 30 mm	
CO_2 emissions	24,325 $kgCO_2$	25,978 $kgCO_2$	+7%
Element	CLT slab 280 mm Floor screed 30 mm	CLT slab 300 mm Floor screed 30 mm	
CO_2 emissions	27,680 $kgCO_2$	29,450 $kgCO_2$	+6%
Element	VKR100x100x6,3 Unknown amount	12 x VKR120x120x6,3 52 x VKR100x100x6,3	
CO_2 emissions	11,216 $kgCO_2$	12,335 $kgCO_2$	+10%
Element	HSQ-beam Total length: 101.5m	HEB240 + HEB260 Recalculated to 101.5m	
CO_2 emissions	34,517 $kgCO_2$	30,274 $kgCO_2$	-12%
Element	Concrete floor slab 260 mm	Hollow core slab 200 mm Floor screed 30mm	
CO_2 emissions	142,596 $kgCO_2$	43,279 $kgCO_2$	-70%

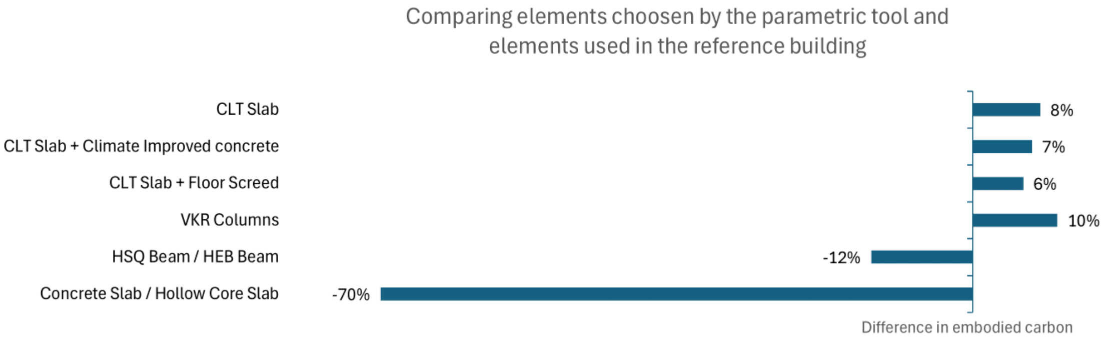


Figure 5.2: *Difference in embodied carbon between elements in the reference building and elements in the system generated by the tool.*

The results obtained from the comparison between the reference building and the parametric model showed that the emissions from the elements are within 12% of their counterpart. With concrete slabs being the exception, which had a difference of 70% in the amount of emissions. The parametric tool showed a tendency to overestimate the embodied carbon, which can be seen in Table 5.3. However, since the selection were done for a preliminary design stage, no definite conclusion can be drawn regarding the emissions in the final design.

The large difference for the carbon emissions of the concrete slabs can be mainly explained by the fact that hollow core slabs are by design a more material efficient slab. While a massive concrete slab needs to carry more of its self-weight.

5.4.2.3 Comparing Emissions From the Entire Structural System

The final part is to compare the entire structural systems for each of the seven alternatives. The following limitations have been made:

- Elements should be selected by the parametric tool itself, given the geometry and material inputs.
- The embodied carbon calculations for the parametric model only included one floor of slab, the second floor would be the roof equivalent in the reference building which were designed with beams in every design alternative. Hence the assumption was made that the systems would be more comparable if the second slab floor was excluded.
- The timber slabs are paired with timber beams and hollow core slabs with steel beams in the parametric model. This would be common combinations in the industry, it also resembles the reference building, which paired timber slabs with timber walls and concrete slabs with concrete walls.

A summary of the comparison can be seen in Table 5.4 and Figure 5.3, and the full comparison can be seen in Appendix B.2.

Table 5.4: Comparison between embodied carbon in different parts of the structural system and the total sum, for the reference building and the parametric tool.

Design alternative	**1**	**2**	**3**	**4**	**5**	**6**	**7**
			Reference building - emissions [tCO2]				
Slab	28	145	28	28	145	114	28
Beam	15	38.6	3.4	4.6	68	38.4	3.4
Load bearing wall	5.8	89	5.8	5.8		71	5.8
Column	11	11			47	11	
Total	59.8	283.6	37.2	38.4	260	234.6	37.2
			Parametric tool - emissions [tCO2]				
Slab	29.5	43.3	29.5	29.5	43.3	43.3	29.5
Beam	3	98.4	3	3	98.4	98.4	3
Column	13.3	13.3	0.5	0.5	13.3	13.3	0.5
Total	45.8	155	33	33	155	155	33
				Difference			
Total	**-23%**	**-45%**	**-11%**	**-14%**	**-40%**	**-34%**	**-11%**

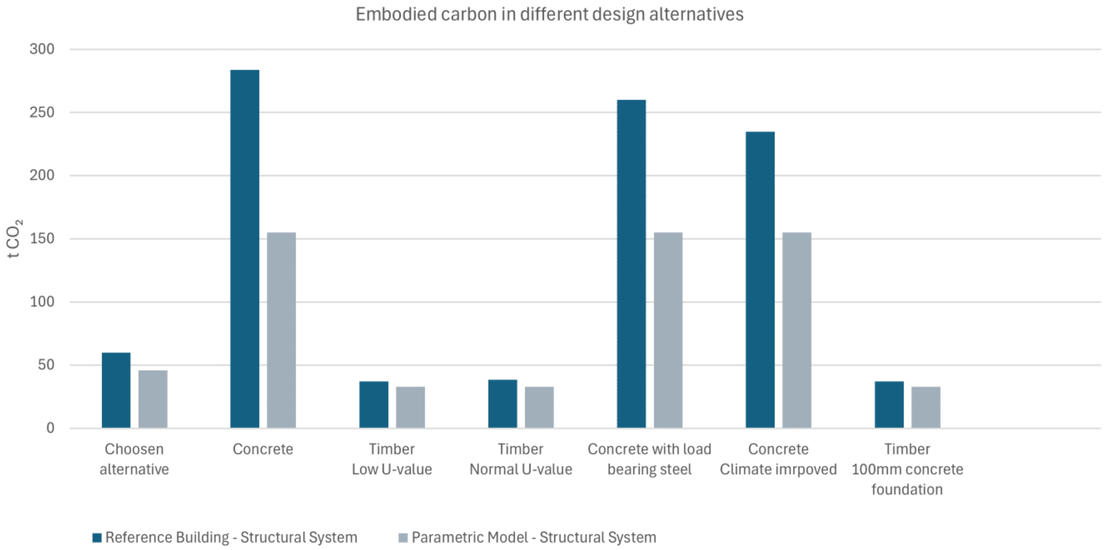


Figure 5.3: *Embodied carbon for each design alternative, in order 1 to 7, as presented in Table 5.4.*

As the table shows, design alternative 3 and 7 has the lowest amount of embodied carbon for the structural system, with 37.2 tCO_2 for the reference building and 33 tCO_2 for the parametric model. Which equals to a difference of 11% embodied carbon between the systems.

The results indicates that the load bearing walls makes it difficult to make a fair comparison, which is reasonable when considering the difference in volume between load bearing walls or beam and columns. However, design alternatives with lower amount of embodied carbon from load bearing walls, such as alternative 1, 3, 4 and 7, have less difference between the structural systems compared to the other alternatives. This can be explained by the fact that the load bearing walls make up a smaller portion of the overall emissions.

Alternative 5 have high amount of embodied carbon from the columns, which might be because that alternative had no load bearing walls. Another outlier is the beams. The steel beams used in the alternatives are designed to be 101.5 metres or 202 metres, which does not line up with the parametric tool which has 330 metres of beams in total. It is assumed that the steel beams are only used in a specific part of the building. And as mentioned earlier, the concrete slab is an unfair comparison against the hollow core slabs which further increases the difference between the alternatives with a high share of emissions.

5.4.3 Optimising the Structural System

Wallacei was used for running a multi-objective topology optimisation with respect to total CO_2/m^2 emissions and the residual, see Section 3.8, for both slab and beam span length. The equations used for calculating the residual was:

$$residualSlab = |(7 - X)|^{1.5} \tag{5.1}$$

$$residualBeam = |(5 - Y)|^{1.5} \tag{5.2}$$

Where X denotes the slab length, and Y denotes the beam length. The lowest value of the residuals can thus be expected at seven and five metres for the slab and beam respectively.

The input parameters that were used as genes are listed below:

- Slab direction
- No. of spans in x-dir
- No. of spans in y-dir
- Floor count
- Material selection: Slab
- Material selection: Beam
- Material selection: Column

And the other input parameters that were fixed can be seen below together with the selected value for each:

Other input parameters that were fixed:

- Floor height: 3 m
- Floor screed: 30 mm
- Superimposed dead load: 2.0 kN/m^2
- Building type: Office
- Utilisation rate: Default value - 100% for all members
- Reliability class: Default values - class 3 for columns and class 2 for beams and slabs

A multi-objective optimisation was conducted with a generation size of 20 and 10 generations, which gave a population size of 200, out of ~4500 possible combinations. The simulation took approximately 10 minutes to run.

From the simulation the top two solutions for each fitness objective was selected, the model together with the CO_2/m^2-output can be seen in Figure 5.4, and the genes for each solution can be seen in Table 5.5, 5.6 and 5.7.

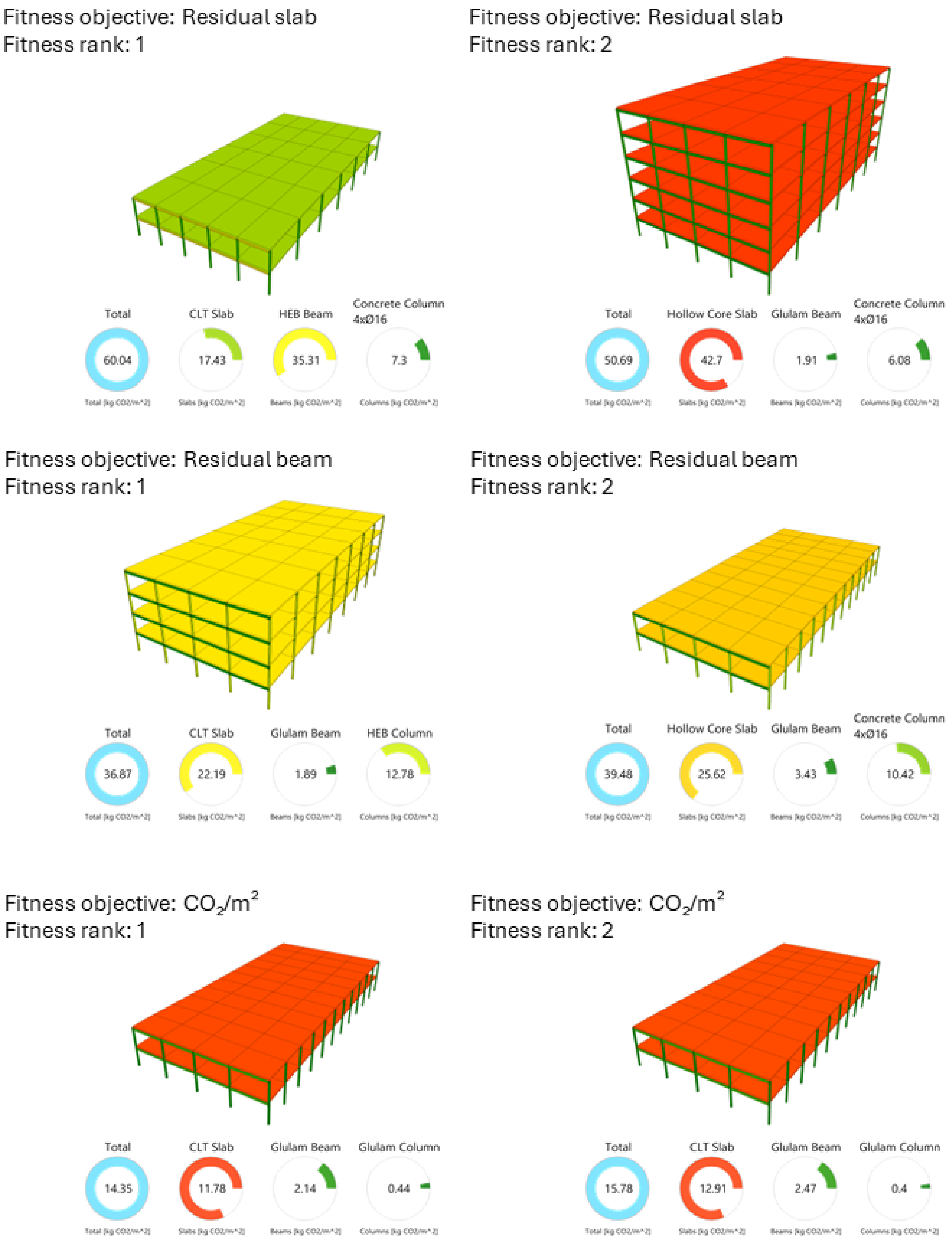


Figure 5.4: *The model and the CO_2/m^2-output for the two highest ranked solutions for each fitness objective.*

The colours in each model show the share of emissions that each element type has, with a red-green colour scale for high- to low share of the emissions. This is also indicated by the circles below each structural system.

Table 5.5: Multi-objective optimisation, with the genes shown for rank 1 and 2 slab residual.

Fitness objective	Residual slab	Residual slab
Fitness rank	1	2
Slab direction	Y-direction (long side)	Y-direction (long side)
Slab span length	6.9 m	6.9 m
Beam span length	4.1 m	5.1 m
Floor count	2 floors	6 floors
Slab material	CLT Slab	Hollow Core Slab
Beam material	HEB Beam	Glulam Beam
Column material	Concrete column 4xØ16 reinforcement	Concrete column 4xØ16 reinforcement

In Table 5.5 it can be seen that the span length for slabs is close to the desired seven metres. However, no other conclusions can be drawn as this only show fitness against the residual slab-objective.

Table 5.6: Multi-objective optimisation, with the genes shown for rank 1 and 2 beam residual.

Fitness objective	Residual beam	Residual beam
Fitness rank	1	2
Slab direction	Y-direction (long side)	Y-direction (long side)
Slab span length	5.9 m	3.7 m
Beam span length	5.1 m	5.1 m
Floor count	4 floors	2 floors
Slab material	CLT Slab	Hollow Core Slab
Beam material	Glulam Beam	Glulam Beam
Column material	HEB Column	Concrete column 4xØ16 reinforcement

In Table 5.6 it can be seen that the span length for beams is close to the desired five metres. However, no other conclusions can be drawn as this only show fitness against the residual beam-objective.

Table 5.7: Multi-objective optimisation, with the genes shown for rank 1 and 2 CO_2/m^2.

Fitness objective	Total CO_2/m^2	Total CO_2/m^2
Fitness rank	1	2
Slab direction	Y-direction (long side)	Y-direction (long side)
Slab span length	3.7 m	4.1 m
Beam span length	5.1 m	5.1 m
Floor count	2 floors	2 floors
Slab material	CLT Slab	CLT Slab
Beam material	Glulam Beam	Glulam Beam
Column material	Glulam Column	Glulam Column

Figure 5.4 and Table 5.7 shows that both options are similar to the other, in terms of carbon emissions, geometry and material choices, which was expected. The optimisation procedure found that the timber alternatives were most efficient and that a short span length were desirable. The short span length allows the tool to select smaller cross sections and thus get a lower amount of embodied carbon due to the smaller volume.

The best alternative from the optimisation is used to compare against the design alternative with the lowest amount of embodied carbon for the reference building and the parametric model. The results can be seen in Table 5.8 and a graph is presented in Figure 5.5.

Table 5.8: Comparison between the best design alternatives.

Model	$kgCO_2/m^2$	Reduction from optimised model
Reference building	22.0	35%
Parametric model	19.5	26%
Optimised model	14.4	-

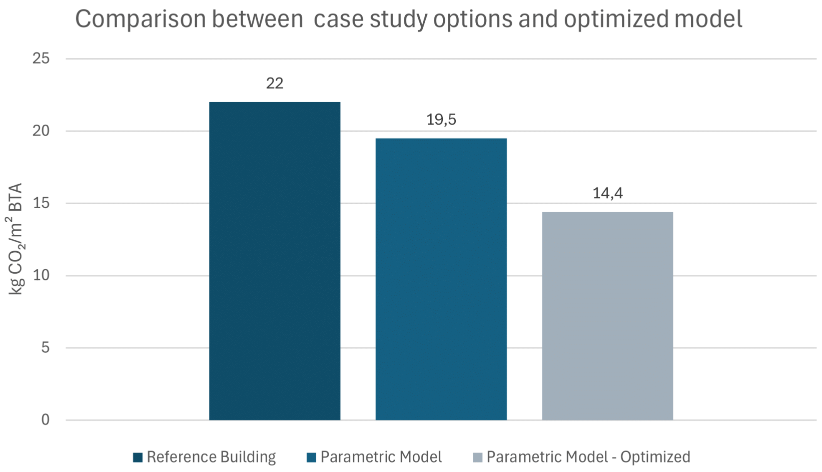


Figure 5.5: *Comparison between the structural system with lowest embodied carbon compared to the automatically generated system.*

The results from the optimisation procedure showed that the emissions could be lowered another 26% compared to the parametric model used for design alternative 3, 4 and 7. When comparing against the best option from the reference building the optimisation could reduce the emissions by 35% compared to alternative 3 or 7.

6

Discussion

The construction industry stands before major changes in the coming years and decades with new laws and regulations being passed to limit the emissions in the construction industry. The sooner companies start to adapt the better off are they to pass the coming emission limits. Already now we can see a lot of companies starting to adapt for the coming changes to the climate declaration, which will place a limit on the embodied carbon in a structure.

6.1 Literature Study

One interesting aspect is that steel and concrete, which used to be seen as very harmful to the environment could in fact become net zero, or close to it, in the future. This means that the materials that we are now trying to avoid could end up being the better choice. And if successful, this alone could lead to substantial savings of the embodied carbon in the structural system.

This thesis chose to not include any climate improved options for steel or concrete when conducting the case study, as most options in the case study did not have the climate improved variants. However, in hindsight it would be interesting to see if the climate improved options of concrete and steel would stand a better chance against a timber building. After all, changing to a more environmentally friendly option is a simple change and will allow the dimensions of the structure can remain the same. This is likely one of the first thing designers look at.

Another important aspect to consider in the fight against global warming is circular economy. This is not properly addressed in this thesis. A synergy could be achieved between the tool and circular economy if databases with recycled material are set up which would include their load bearing capacity and other necessary data for each element. If so, the data structure could perhaps be adapted to allow the user to quickly add recycled elements.

6.2 Interview

From the interview it became clear that the current process takes a long time with very few options tested. The knowledge level of conducting LCA seems to be quite low, as it is left to a handful of people to conduct these and report back their findings. Which is also reinforced later in the interview when the functionality was discussed. The desire was to have a low entry barrier to allow more people in the company to work with LCA.

6.3 Tool Review

The tool study revealed that there are a great number of tools available on the market to conduct LCA, in different stages. Many of these required a model as input, which limits the usability for structural systems in early stages as the user would either spend time making sure the system is robust, or quickly testing alternatives without knowing the structural capacity of the system.

PANDA seemed to do a good job modelling structural systems and evaluating their environmental impact. However, it was limited to the national annex in United Kingdom. It was not always that the simulation showed design alternatives with timber for example, it seemed to favour concrete and steel designs.

OneClick LCA have developed several LCA tools, the two of interest are: Carbon Designer 3D and their online OneClick LCA platform. Carbon Designer 3D is supposed to generate structural systems and assess their environmental impact. However, as noted in the interview and the tool study the results can be questionable and hard to understand. Their online platform can be tedious and slow, which makes it less suitable for early-stage assessments.

The other Grasshopper plugins do seem like decent alternatives to OneClick LCA but not to properly assess a structural system. Then a comprehensive workflow would be needed.

6.4 Tool Development

A parametric work environment is very suitable for this kind of tool, as it can automate parts of the workflow. Grasshopper has a good reputation as a parametric tool which is why it was chosen as the main tool for this thesis. Also, with the combination of Rhino and Grasshopper the user can modify the model and get feedback in real time.

The development of the tool itself was an iterative process, where implementing a functionality usually involved making a simpler version as a proof of concept and then refining it, either to work in a more general way or to make it work faster. Part of the development process also consisted of gathering feedback, inspiration and searching for solutions to the problems.

Some of the more complicated things that were encountered during the coding was the Grasshopper tree structure and OOP. Working with a tree structure as an input could be figured out relatively fast with decent documentation available. However, how to create a tree structure in the code was more complicated as the documentation available was poor. Fortunately, there was employees at VBK who had the knowledge of how to create the tree structures. Another thing that was challenging at first was the concept of OOP, but after getting used to it, it quickly became a powerful way of scripting.

The tool was scripted with Python in grasshopper. This was a choice that largely depended on the syntax. However, as C# is a compiled language, it will usually have a faster run time compared to Python. But for a relatively small tool like this one, it is expected that the difference is negligible.

The tool can model a system and perform the calculations relatively fast, between half a second up to two seconds in most cases. This caused a small delay when trying to drag the number slider , while testing different span lengths for example. This would partly feel annoying to use but it was also a accuracy problem, as it would be difficult to pinpoint exactly when the slider would hop to the next integer. To solve this, the slider was replaced with a dropdown menu, this also made the delay feel less of a problem. But still, the tool would gain a lot from being quicker and more responsive, as it would feel better to use when collaborating with someone or using it in real-time, in a meeting.

6.4.1 Choice of System

To get the most benefit of the tool, a common structural system would need to be selected. A column-beam structural system was selected as it is common in both office and industrial buildings, and also used in residential buildings. The tool can be modified in the future to accommodate a system with load bearing walls for example or to take horizontal stabilisation into consideration.

The workflow does currently only work for a rectangular building footprint. However, the tool itself can handle any shape, as long as the elements share nodes with each other. As a workaround multiple scripts can run in parallel, to form a L- or U-shaped building footprint for example. The input surface needs to be aligned to the global xy-axis, as certain calculations in the tool uses the length in x- and y-direction.

6.4.2 Elements Used by the Tool

The tool does not take into account how the connection will be designed, or which elements works with each other. For example, a HSQ-beam is popular to use with a hollow core slab as they have a design that works well together. However, there is no indication of that in the tool. An output with various types of information would probably be a good addition to the tool. This could contain information of what has or has not been checked for each member, what the typical design practice is or other limitations.

This tool needs to reduce all failure modes to one metric to compare against the model. For slabs the length is used, for beams and columns the ULS load capacity is used. Except for steel beams, where the SLS capacity are also checked. These metrics were chosen based on the design data found for each element. It would be preferable to use the same metric for all elements, to keep the Excel sheets and the tool simple. Exceptions for certain elements leads to a more complicated code, a tool that runs slower and more complicated Excel sheets. The single metric approach ensures that the tool runs fast and provides results that are suitable for preliminary design stages.

Another thing to note is that the tool is heavily reliant on accurate material data. If poor data are used then the cross-sections of an element might need to scale up significantly, which could affect other parts of the structure or the overall design.

If one of the elements has poor data then a lot of changes might be necessary later in the design process, which could affect the other elements as well. The data found for steel elements had a high detail level which instilled confidence. The data for timber elements was not as detailed but was still considered reliable to use. The capacity of concrete elements depends on the amount of reinforcement, which are typically not included in preliminary design tables or graphs.

The hollow core elements included was found at an archived web page of Svensk Betong. The fact that it was withdrawn raised some questions about the reliability of the table. However, after cross referencing against another graph for preliminary design the decision was made to include the data from the table.

A few timber beams were verified against an in-house tool for calculating the capacity of timber elements, which instilled more confidence in both the tool and the data that were collected. The difficulty of finding standard concrete elements resorted to the use of another in-house tool for calculating the capacity of concrete columns to be included in the tool. In general, the data for all kinds of elements, except steel, was much more difficult to find than what was expected.

6.4.3 Inputs and Outputs

One of the aims with the tool was to ensure that it would be usable by a wide range of users. One of the problems is that there are relatively few people in the industry that uses Grasshopper, which means that the tool would need to cater to those people as well. The goal was then to make a simple and easy to use tool, without too complicated inputs or outputs.

The inputs were selected based on the fact that the tool is intended to be used in early stages, where there are a lot of uncertainties and low level of detail. The inputs cover the basic geometry, imposed loads, material selection and optional input for max utilisation rate and reliability classes. This was deemed sufficient for the system currently being modelled. However, if a roof, horizontal stability or the foundation were to be added, the number of inputs would need to increase.

Another thing that was tested was to use UI+ to create a dashboard, which would let the user control the Grasshopper script from the Rhino viewport. This was more a proof of concept and was not shown in this thesis. It would require some time to get the dashboard to look professional enough, and thus the decision was made to focus on the tool development and Grasshopper script instead. However, if implemented it could help users who are not familiar to Grasshopper and find it overwhelming, it would also most likely give a more professional appearance when presenting in a meeting.

The output from the tool is the environmental impact, the loads, and the cross section for each element. However, for large systems, displaying information on each element can be quite overwhelming and thus the environmental impact was grouped together to be displayed as a global metric, see Figure 4.5. This allows the user to get a quick overview of the impact while at the same time being able to get that detailed information, which is a good compromise.

6.5 Case Study

The reference building which was used for the case study had seven different design alternatives to evaluate the environmental impact. Most design alternatives had load bearing walls which made it difficult to compare against the system modelled by the parametric tool. The difference in volume between a system of beams and columns and a solid load bearing wall are significant. In addition, there was no information of the actual structural system, utilisation rates or how it looked like, just the volume or mass of each component. This was particularly difficult when it came to the steel beams, as they were too short to have been used in the entire building, with no information on where or how they were used.

The case study was divided into three parts, firstly to see if similar elements are selected and to see if the environmental impact of different parts of the structural system is similar. The second part was, to see if the emissions are comparable when the tool models a similar structural system as the reference building. The third and last part was to see if optimisation algorithms can be used to automatically find a low impact structural system.

The first part of the case study did not run into many problems. The second part was more difficult as the systems were not comparable. However, the results from the first part indicates that the entire systems should end up within a reasonable difference from each other, given they use the same type of elements.

The reference building had a couple of systems with timber elements, those ended up with quite close in terms of embodied carbon compared to the timber alternative in the parametric model. Which indicates, together with the results from the first part, that given the same type of elements the structural system should end up within a reasonable difference from each other.

The results from the optimisation showed that, even while using the same material, it might still be possible to lower the embodied carbon by tweaking the inputs, such as span lengths and slab direction. However, the design with the lowest embodied carbon might not be feasible option based on the floor plan. This stage is a good time and opportunity for the architect and engineer to have a discussion about possible trade-offs.

6.6 Further Development

This tool can be improved further by adding load bearing walls for a starter. This would make the tool more general and allow it to design more building typologies. However, there would be almost no incentive to use load bearing walls in the design unless horizontal load and stability is also added. Load bearing walls would help take both vertical and horizontal loads. Horizontal loads would also almost certainly require a core to be added in the design.

To make more complete design alternatives, a roof should be included in the tool. This would also need to consider wind, snow and other external loads.

Foundation and piling could also be integrated into the tool, as piling is highly relevant in Gothenburg. It would be interesting to explore whether heavier structural systems would increase the CO_2 emissions from the foundation by requiring more piling.

As this tool uses pre-calculated elements there could be some uncertainties regarding the capacity of the system. To instil more confidence in the tool a FEM analysis could be included in the workflow. This would allow the user to see if there is any assumptions that would not work. The tool already uses centrelines and surfaces, which could be imported to a FEM program to perform the analysis.

Many decisions are taken based on the cost. If an estimation of the cost could be included in the tool, the designer could make better informed choices earlier on.

A summary of the potential areas that could be considered for further improvement of the cool:

- Adding more types of structural systems
- Adding horizontal stability together with core and bracing
- Adding a roof, snow and wind loads
- Adding foundation
- Adding a FEM analysis to the workflow
- Adding a cost metric to each element

These functionalities would allow the tool to model more building typologies. It would model more accurate structural systems and give the designer more information to make more informed choices.

7

Conclusion

A parametric tool was developed in this Master's thesis which predicts the embodied carbon emissions from structural systems in early design stages. When tested against a reference building with comparable elements, the system showed similar amount of emissions, within 14% from each other. An evolutionary optimiser was also used as part of the case study, the optimiser found a solution with 35% less carbon emission compared to the reference building.

In the early design stages, engineers must explore a wide range of design options to increase the likelihood of finding the optimal solution. The tool developed in this thesis focuses on exactly that: to investigate a wide range of options in a quick manner and displaying relevant information to guide the engineer toward the best choices. Optimisation plugins further enhances the workflow, by automatically identifying low carbon options to investigate further.

Another problem investigated during the thesis was how the tool should design a reliable structural system. The tool utilises pre-calculated elements, where the load-bearing capacity has already been calculated and verified. An element can then quickly be selected without running extensive Eurocode checks. This is one benefit of conducting a preliminary design, it is sufficient to get a rough estimate of the cross sections needed for further considerations.

Pre-calculated elements were also used to integrate the LCA calculations in the tool. They contain a large part of the necessary information to calculate the environmental impact. The other part that is necessary comes from the parametric model, where the element is selected and the overall geometry is decided. The tool will assess the environmental impact by a simplified LCA, which only considers the CO_2 emission from LCA stage A1-A5, as those needs to be presented in the climate declaration.

By focusing on relevant parameters, such as span lengths, applied loads and material selection, the tool is quick to use and requires few inputs. The outputs are then presented in real-time, which allows the user to understand what impact each design choice has. A summary of the environmental impact and the geometry is presented to the user. The user can also choose to display any of the load combinations or environmental impact calculated per element.

The relationship between design parameters and embodied carbon is complex. The designer needs to have a holistic view and test many different configurations to achieve the best solution. This tool helps the designer to do just that.

Bibliography

Al-Emrani, M. (2023, August). *Steel structures.* Division of Structural Engineering.

Al-Emrani, M., Engström, B., Johansson, M., & Johansson, P. (2013). *Bärande konstruktioner Del 1* (2013:1). Avdelningen för konstruktionsteknik.

Al-Emrani, M., Engström, B., Johansson, M., & Johansson, P. (2014). *Bärande konstruktioner Del 2* (2011:1). Avdelningen för konstruktionsteknik.

Al-Shaarbaf, I. A., Al-Azzawi, A. A., & Abdulsattar, R. (2018). A STATE OF THE ART REVIEW ON HOLLOW CORE SLABS. *13*(9). Retrieved April 16, 2024, from https://www.researchgate.net/publication/325554859_A_state_of_the_art_review_on_hollow_core_slabs

Anand, C. K., & Amor, B. (2017). Recent developments, future challenges and new research directions in LCA of buildings: A critical review. *Renewable and Sustainable Energy Reviews*, *67*, 408–416. https://doi.org/10.1016/j.rser.2016.09.058

Arup. (2023, June 9). *Circular economy principles for achieving net zero in the built environment.* Youtube. Retrieved January 30, 2024, from https://www.youtube.com/watch?v=rWFkLa-QI0s

Bartz-Beielstein, T., Branke, J., Mehnen, J., & Mersmann, O. (2014, April 24). *Evolutionary algorithms.* Retrieved May 27, 2024, from https://onlinelibrary.wiley.com/doi/abs/10.1002/widm.1124

Bellis, M. (2020, January 10). *The first skyscrapers* [ThoughtCo] [Section: ThoughtCo]. Retrieved February 16, 2024, from https://www.thoughtco.com/how-skyscrapers-became-possible-1991649

Betongelementföreningen. (2013, September 24). *Bygga med prefab : En handbok i teknik, estetik, kvalitet, ekonomi, miljö.* Retrieved May 11, 2024, from https://www.yumpu.com/sv/document/view/20431133/ladda-ner-prefabsystem

Boverket. (2019, February 20). *Introduktion till livscykelanalys (LCA) - boverket.* Retrieved January 23, 2024, from https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/livscykelanalys/introduktion-till-livscykelanalys-lca/

Boverket. (2022). *Application of the european construction standards, EKS 12* [Boverket]. Retrieved June 24, 2024, from https://www.boverket.se/en/start/publications/publications/2023/application-of-the-european-construction-standards-eks-12/

Boverket. (2023a, May 30). *Bättre ljudklass än BBR* [Boverket]. Retrieved April 19, 2024, from https://www.boverket.se/sv/PBL-kunskapsbanken/regler-om-byggande/boverkets-byggregler/bullerskydd/ljudklassning/

Boverket. (2023b). *Gränsvärde för byggnaders klimatpåverkan och en utökad klimatdeklaration.* Retrieved May 23, 2024, from https://www.boverket.se/sv/om-boverket/publicerat-av-boverket/publikationer/2023/gransvarde-klimatpaverkan/

Boverket. (2023c, October 10). *Om Boverkets klimatdatabas* [Boverket]. Retrieved May 6, 2024, from https://www.boverket.se/sv/klimatdeklaration/klimatdatabas/om-klimatdatabas/

Boverket. (2024a, March 11). *Boverkets klimatdatabas* [Boverket]. Retrieved June 20, 2024, from https://www.boverket.se/sv/klimatdeklaration/klimatdatabas/

Boverket. (2024b, January 30). *Om klimatdeklaration* [Boverket]. Retrieved April 4, 2024, from https://www.boverket.se/sv/klimatdeklaration/om-klimatdeklaration/

Boverket. (2024c, January 23). *Utsläpp av växthusgaser från bygg- och fastighetssektorn* [Boverket]. Retrieved March 11, 2024, from https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/miljoindikatorer---aktuell-status/vaxthusgaser/

Boxall, C. W. D., & Loasby, H. A., F. W. (1907). *Plank cut to show figure.* Retrieved June 14, 2024, from https://commons.wikimedia.org/wiki/File:Cassells_Carpentry.146_Plank_Cut_to_show_Figure.png

Broer, R., Simjanovic, J., & Toth, Z. (2022, January 24). *IMPLEMENTING THE PARIS AGREEMENT AND REDUCING GREENHOUSE GAS EMISSIONS THROUGHOUT THE LIFE CYCLE OF BUILDINGS:* BPIE. Retrieved March 11, 2024, from https://www.bpie.eu/wp-content/uploads/2022/01/SPIPA-LCA-2022FINAL.pdf

Buro Happold. (2021, March 26). *Could the next london bridge be carbon zero?* [Buro happold]. Retrieved February 9, 2024, from https://www.burohappold.com/articles/could-the-next-london-bridge-be-carbon-zero/

Cherry, E., & Petronis, J. (2016, November 2). *Architectural programming | WBDG - whole building design guide.* Retrieved June 18, 2024, from https://www.wbdg.org/design-disciplines/architectural-programming

Cleveland Public Library Digital Gallery. (1895). *New england building 1895 CP01037 construction.* Retrieved June 14, 2024, from https://cplorg.contentdm.oclc.org/digital/collection/p4014coll18/id/1950

Codecademy. (2023, September 28). *What is object-oriented programming?* [Codecademy blog]. Retrieved May 23, 2024, from https://www.codecademy.com/resources/blog/object-oriented-programming/

Council of the European Union. (2023, December 13). *Fit for 55.* Retrieved February 16, 2024, from https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/

Designing Buildings. (2022, April 27). *Design life.* Retrieved February 9, 2024, from https://www.designingbuildings.co.uk/wiki/Design_life

Elfors, S. (2019, February 2). *Byggnadsstommens klimatpåverkan.* Sveriges Kommuner och Landsting. Retrieved March 11, 2024, from https://skr.se/download/18.3c9f9e1e17db3f33e522cc1/1639428539774/7585-350-5.pdf

EUROFER. (2020, March 30). *What is steel and how is steel made?* Retrieved June 24, 2024, from https://www.eurofer.eu/about-steel/learn-about-steel/what-is-steel-and-how-is-steel-made

Gholam, B. (2020). What do we mean by efficiency? a holistic approach to reducing embodied carbon. *The Structural Engineer*, *Volume 98*, 4. Retrieved February 1, 2024, from https://www.istructe.org/journal/volumes/volume-98-(2020)/issue-10/a-holistic-approach-to-reducing-embodied-carbon/

Gothia Armering. (n.d.). *Armering betong* [Gothia Armering]. Retrieved February 28, 2024, from https://gothiaarmering.se/produkter/armering/

Gregory, J., & Logan, A. (2021, January 8). *Concrete | MIT climate portal*. Retrieved January 29, 2024, from https://climate.mit.edu/explainers/concrete

Gross, H. (2016, March). *Limträhandbok Del 1* (5th ed.). Skogsindustrierna. https://www.svenskttra.se/siteassets/5-publikationer/pdfer/limtrahandbok-del-1-svenska-2018.pdf

Gustafsson, A., Crocetti, R., Just, A., Landel, P., Olsson, J., Pousette, A., Silfverhielm, M., & Östman, B. (2017). *KL-trähandbok* (First). Skogsindustrierna. Retrieved April 19, 2024, from https://www.svenskttra.se/siteassets/5-publikationer/pdfer/svt-kl-trahandbok-2017.pdf

Hills, C. D., Tripathi, N., & Carey, P. J. (2020). Mineralization technology for carbon capture, utilization, and storage [Publisher: Frontiers]. *Frontiers in Energy Research*, *8*. https://doi.org/10.3389/fenrg.2020.00142

Hoffmann, C., Hoey, M. V., & Zeumer, B. (2020, June 3). *Decarbonization challenge for steel*. Retrieved June 24, 2024, from https://www.mckinsey.com/industries/metals-and-mining/our-insights/decarbonization-challenge-for-steel

Hollberg, A., Kiss, B., Röck, M., Soust-Verdaguer, B., Wiberg, A. H., Lasvaux, S., Galimshina, A., & Habert, G. (2021). Review of visualising LCA results in the design process of buildings. *Building and Environment*, *190*, 107530. https://doi.org/10.1016/j.buildenv.2020.107530

IVL Svenska Miljöinstitutet. (2021, June 29). *Carbonation of concrete*. Retrieved January 29, 2024, from https://www.ivl.se/projektwebbar/co2-concrete-uptake/carbonation-of-concrete.html

Jabi, W. (2013). *Parametric design for architecture* (´). Laurence King Student & Professional.

Jarrett, S. (2023, August). *Embodied carbon vs operational carbon*. Retrieved January 22, 2024, from https://www.oneclicklca.com/embodied-carbon-vs-operational-carbon/

Jelly. (2019, July 30). *WHAT ARE THE KEY DIFFERENCES BETWEEN CLT AND GLULAM?* [Seagate mass timber]. Retrieved April 18, 2024, from https://seagatemasstimber.com/what-are-the-key-differences-between-clt-and-glulam/

Kjær Zimmermann, R., Kanafani, K., Nygaard Rasmussen, F., & Birgisdóttir, H. (2019). Early design stage building LCA using the LCAbyg tool: Comparing cases for early stage and detailed LCA approaches. *IOP Conference Series: Earth and Environmental Science*, *323*(1), 012118. https://doi.org/10.1088/1755-1315/323/1/012118

Kliger, R., Johansson, M., Crocetti, R., Mårtensson, A., Lidelöw, H., Norlin, B., Crocetti, R., & Pousette, A. (2022, April). *Design of timber structures volume 1* (3rd ed.). Swedish Forest Industries Federation. Retrieved April 18, 2024, from https://www.swedishwood.com/siteassets/5-publikationer/pdfer/sw-design-of-timber-structures-vol1-2022.pdf

Malmqvist, T., Borgström, S., Brismark, J., & Erlandsson, M. (2021). *Referensvärden för klimatpåverkan vid uppförande av byggnader*. KTH Skolan för Arkitektur och Samhällsbyggnad. Retrieved April 16, 2024, from https://www.boverket.se/contentassets/5c704bbb2b2f4bd1a31beecf355efaa4/referensvarden-for-klimatpaverkan-vid-uppforande-av-byggnader_kth-2021.pdf

Masson, S. (2024, February 5). *Biogenic carbon* [One click LCA]. Retrieved February 18, 2024, from https://oneclicklca.zendesk.com/hc/en-us/articles/360015036640-Biogenic-Carbon

McNeel. (n.d.). *What are NURBS?* [What are NURBS?]. Retrieved June 26, 2024, from https://www.rhino3d.com/features/nurbs/

MIT OpenCourseWare. (2008, November 21). *Reinforced and prestressed concrete*. Retrieved June 14, 2024, from https://www.flickr.com/photos/mitopencourseware/3048302726/

MT Copeland. (2022, February 2). *16 types of concrete & how they're used* [MT copeland]. Retrieved January 29, 2024, from https://mtcopeland.com/blog/16-types-of-concrete/

Norman, J., Broadbent, O., Carr, J., De'Ath, R., Harpin, R., Knowles, G., & Lloyd, I. (2020, April 8). *Conceptual design of buildings* (First edition). The Institution of Structural Engineers.

Overbey, D. (2021, January 29). *LCA stages matter when tracking embodied carbon*. Retrieved June 26, 2024, from https://www.buildingenclosureonline.com/blogs/14-the-be-blog/post/89547-lca-stages-matter-when-tracking-embodied-carbon

Poole, I. (2020). Rationalisation versus optimisation – getting the balance right in changing times. *The Structural Engineer*, *Volume 98*, 4. https://www.istructe.org/IStructE/media/Public/TSE-Archive/2020/Rationalisation-versus-optimisation-getting-the-balance-right-in-changing-times.pdf

Prasad, B. (n.d.). *Slab types - deep review on types, design and construction* [Structural guide]. Retrieved February 28, 2024, from https://www.structuralguide.com/slab-types/

Prop. 2020/21:144. Klimatdeklaration för byggnader. Retrieved January 22, 2024, from https://www.regeringen.se/contentassets/8012373f173e44b19b96d9c7c314ffd9/klimatdeklaration-for-byggnader-prop.-202021144.pdf

Roberts, M., Allen, S., & Coley, D. (2020). Life cycle assessment in the building design process – a systematic literature review. *Building and Environment*, *185*. https://doi.org/https://doi.org/10.1016/j.buildenv.2020.107274

Rockafellar, R. T. (1997). *FUNDAMENTALS OF OPTIMIZATION*. Retrieved May 27, 2024, from https://sites.math.washington.edu/~burke/crs/515/

Roynon, J. (2020, April 2). *Embodied carbon: Structural sensitivity study* (Case Study). Buro Happold. https://www.istructe.org/resources/case-study/embodied-carbon-structural-sensitivity-study/

Rutten, D. (2010, September 25). *Evolutionary principles applied to problem solving.* Retrieved June 27, 2024, from https://www.grasshopper3d.com/profiles/blogs/evolutionary-principles

Safarowic, S. (2024, March 13). *Why is python considered a high-level programming language?* Retrieved May 13, 2024, from https://www.xccelerate.co/blog/why-python-a-high-level-programming-language

Savic, D. (2002). Single-objective vs. multiobjective optimisation for integrated decision support.

Säwén, T., Sasic Kalagasidis, A., & Hollberg, A. (2024). Critical perspectives on life cycle building performance assessment tool reviews. *Renewable and Sustainable Energy Reviews*, *197*, 114407. https://doi.org/10.1016/j.rser.2024.114407

Schultz, C. v. (2024, January 19). *Svenska cementfabriken testar klassisk metod från romarriket* [Section: hållbar industri]. Retrieved January 29, 2024, from https://www.nyteknik.se/hallbar-industri/svenska-cementfabriken-testar-metod-fran-romarriket/4228872

Setra. (2021, October 1). *KL-trä bjälklag i, II & inner- & yttervägg.* Retrieved April 25, 2024, from https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf

Srivastava, P. K., Simant, & Shukla, S. (2017). Structural optimization methods: A general review. *6*(9). Retrieved May 27, 2024, from https://1library.net/document/zw3o11gy-structural-optimization-methods-a-general-review.html

SSAB. (n.d.). *Fossil free steel* [SSAB]. Retrieved January 26, 2024, from https://www.ssab.com/en/fossil-free-steel

Stålbyggnadsinstitutet. (2020, December). *Introduktion till miljövarudeklarationer, EPD* (No. 268). Stålbyggnadsinstitutet. Stockholm, Sweden. https://media.sbi.se/securepdfs/2020/11/Miljovarudeklarationer_bilaga_201124.pdf

Statistics Explained. (n.d.). *Glossary:carbon dioxide equivalent.* Retrieved April 18, 2024, from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Carbon_dioxide_equivalent

Svensk Betong. (2017, January 22). *Dimensionering av håldäck* [Svensk betong]. Retrieved April 10, 2024, from https://web.archive.org/web/20170122003902/http://www.svenskbetong.se/bygga-med-betong/bygga-med-prefab/statik/haldack/dimensionering-av-haldack

Svenska Institutet för Standarder. (2023). *Basis of structural and geotechnical design (SS-EN 1990:2023)* (2nd ed.). https://www.sis.se/

Svenskt Trä. (n.d.-a). *Egenskaper hos barrträ* [Svenskt Trä]. Retrieved February 6, 2024, from https://www.svenskttra.se/trafakta/allmant-om-tra/fran-timmer-till-planka/egenskaper-hos-barrtra/

Svenskt Trä. (n.d.-b). *Hjälp med dimensionering* [Svenskt Trä]. Retrieved June 30, 2024, from https://www.svenskttra.se/bygg-med-tra/om-limtra/dimensioneringshjalp/

Sveriges Miljömål. (2023, April 13). *Utsläpp av växthusgaser till år 2045.* Retrieved May 28, 2024, from https://www.sverigesmiljomal.se/etappmalen/utslapp-av-vaxthusgaser-till-ar-2045/

Sweden Green Building Council. (2022). *Miljöbyggnad 4.0* (Certification). Sweden Green Building Council. Retrieved May 25, 2024, from https://www.sgbc.se/app/uploads/2022/12/Manual_MB_4.0_1.pdf

Tekniska museet. (2021, December 7). *Byggnadskonsten* [Tekniska museet]. Retrieved March 11, 2024, from https://www.tekniskamuseet.se/lar-dig-mer/100-innovationer/byggnadskonsten/

The New York Public Library. (1909). *The dartmouth. plan of first floor.* Retrieved June 14, 2024, from https://picryl.com/media/the-dartmouth-plan-of-first-floor-577e23

Tibnor. (2023). *Tibnors konstruktionstabeller.* Retrieved May 10, 2024, from https://www.tibnor.se/medias/konstruktionstabellerSWE-2023.pdf?context=bWFzdGVyfHJvb3R8MzE0ODU1NnxhcHBsaWNhdGlvbi9wZGZ8YURGaEwyZ3daaTg1TVRFd05ETTFPREl6TmpRMkwydHZibk4wY25WcmRHbHZibk4wWVdKbGJHeGxjbE5YUlMweU1ESXpMbkJrWmd8ZGY5ZTdhNjMwYzhiMjkwYTQ5MmE0OWRiMGNjYmE5ZTMwMTY3YjdlZmVmYWRmNzExYmZkYzAwZDE3ZWJmNTQ0MQ

UNFCCC. (n.d.). *The paris agreement.* Retrieved March 11, 2024, from https://unfccc.int/process-and-meetings/the-paris-agreement

Varawalla, H. (2018, September 4). *The planning grid: Creating a framework for design* [Healthcare architecture]. Retrieved April 15, 2024, from https://healthcarearchitecture.in/the-planning-grid-creating-a-framework-for-design/

A

Tool Study

The results from the tool study are presented in this appendix.

Tool:	**One Click LCA Carbon designer 3D**	**One Click LCA Grasshopper plugin**
Purpose of the tool? What task or goal is the tool aiming to achieve? When is the tool supposed to be used in a project?	The tool performs a LCA analysis at an early stage. The tool seem to be useful as an early stage design tool.	The tool performs LCA analysis at any stage, as long as the geometry and material is defined. It seems to be more useful in later stages, when the 3D model have been fully developed.
Functionality What features does the tool offer? Does it fulfil the requirements, or are there any gaps in functionality?	Quickly generate a system and display embodied carbon results based on early stage parameters. It is quick, however the results are a rough estimate. The structural systems are not guaranteed to be structurally sound.	Computes LCA based on input geometry and material selection. Displays the results with the 3D model. Can select materials from a large number of databases, however the license determines what database is available. Also some uncertainties regarding which LCA modules are computed.
Usability How intuitive is the tool's interface? Is it easy to learn and navigate? Does it require extensive training or documentation?	Easy to use, can quickly change the design of the structural system. Changing the generated materials might take some time.	Easy to use, assuming the user is comfortable with Grasshopper. Takes time to set up each material, and change them.
Compatibility and integration What type of tool is it? Does the tool integrate with existing software or systems used in the industry?	Web browser tool, no installations required.	Grasshopper plugin, also integrated with One Click LCA website to push the results there.
Performance and stability How fast is the tool to set up? How does the tool perform in terms of speed and responsiveness? Is the tool stable and reliable, or does it crash frequently?	Quick to use and stable.	Can be slow to set up as the user need to login to verify the license every time.
Cost What is the cost for using the tool? Does the cost justify the value it provides?	Subscription ~3500 SEK/month The tool provides value by verifying LCA data for the user, which will be a demand in the future.	Subscription ~3500 SEK/month. The tool provides value by allowing the user to verify LCA data.
Support and documentation What support options are available for the tool? Is there comprehensive documentation or user guides available?	Support available with paid plan. Documentation available.	Support available with paid plan. Documentation available.
Tool transparency / Verification of data How transparent is the tool regarding the sources of data it utilizes? Are there ways to cross-reference or validate the data through external sources or methods?	Low transparency. The tool gets data from similar projects, unsure from where that data is gathered and how it is used.	Mid transparency. Uses a number of databases to get data, Boverket among others. The material data can not be read by the user.
Confidence of the data Can users/testers have confidence that the results produced by the tool are accurate and reliable? Clear documentation provides transparency and allows users/testers to understand how the results were obtained and verify the correctness of the outcomes.	Medium level of confidence. As the data produced is not obtained in a way the user can verify or understand.	High level of confidence. The tool have a medium level of transparency, the databases are easy to find which makes verification easier.
Overall impression	Mid	Mid-High

Tool:	**PANDA**	**Cardinal LCA**
Purpose of the tool? What task or goal is the tool aiming to achieve? When is the tool supposed to be used in a project?	Early stage structural system design with emission and cost data. The tool provides info regarding the emissions (module A1-A3) at an early conceptual stage. It seems to be very useful in early stages ad it can help the designer to make informed choices.	The tool performs LCA analysis at any stage, as long as the geometry and material is defined. It seems to be more useful in later stages, when the 3D model have been fully developed.
Functionality What features does the tool offer? Does it fulfil the requirements, or are there any gaps in	Generate and displays structural solutions, their cost and their embodied carbon at an early stage from a simple model. The tool is quick to use and displays a large amount of options.	Computes LCA module A1-A3 based on input geometry and material selection. Displays the results with the 3D model and as a report. The tool works well but is somewhat basic.
Usability How intuitive is the tool's interface? Is it easy to learn and navigate? Does it require extensive training or documentation?	Easy to set up, however there is a lot of customisation that can be done, which requires some experience. The tool has default values for most things except the geometry. Got tutorial videos.	Easy to use, assuming the user is comfortable with Grasshopper. Takes time to set up each material, and change them.
Compatibility and integration What type of tool is it? Does the tool integrate with existing software or systems used in the industry?	Standalone program. Not compatible with any other program.	Grasshopper plugin.
Performance and stability How fast is the tool to set up? How does the tool perform in terms of speed and responsiveness? Is the tool stable and reliable, or does it crash frequently?	Quick to use but the program crashes sometimes.	Slow to set up but stable.
Cost What is the cost for using the tool? Does the cost justify the value it provides?	Subscription ~3750 SEK/month. The tool provides value by allowing the user to take a informed choice at an early design stage.	Free The tool provides value by allowing the user to calculate/estimate LCA module A1-A3.
Support and documentation What support options are available for the tool? Is there comprehensive documentation or user guides available?	Support available with paid plan. Tutorial videos available.	No support.
Tool transparency / Verification of data How transparent is the tool regarding the sources of data it utilizes? Are there ways to cross-reference or validate the data through external sources or methods?	High transparency. Uses data from ICE- or IstructE-databases (UK based) which can be read by the user. The values can be changed by the user to fit another database or EPD. The structural calculations are available for the user.	High transparency. Uses data from ICE- or EC3-databases (United Kingdom respectively United States based), this data can be read by the user. The user can also type in the info themselves from an EPD or database.
Confidence of the data Can users/testers have confidence that the results produced by the tool are accurate and reliable? Clear documentation provides transparency and allows users/testers to understand how the results were obtained and verify the correctness of the outcomes.	High level of confidence. The tool is very transparent, the user can see both environmental data and structural calculations.	High level of confidence. The tool has a high level of transparency and the data/results can be verified by the user.
Overall impression	High	Mid

Tool:	**Bombyx 2**	**BHoM LCA Toolkit**
Purpose of the tool? What task or goal is the tool aiming to achieve? When is the tool supposed to be used in a project?	The tool estimates the emissions based of a few parameters. It can also perform a more accurate LCA analysis, given geometry and material. It has uses both in the early and later stages of the design.	The tool performs LCA analysis at any stage, as long as the geometry and material is defined. It seems to be more useful in later stages, when the 3D model have been fully developed.
Functionality What features does the tool offer? Does it fulfil the requirements, or are there any gaps in functionality?	Computes LCA module A1-A3 based on input geometry and material selection. Compiles the results as a list. Can also estimate the embodied carbon based on some general assumptions for a early stage study. It is not as transparent as it could be, uncertainties regarding the estimated results as well.	Computes LCA module A1-A3
Usability How intuitive is the tool's interface? Is it easy to learn and navigate? Does it require extensive training or documentation?	More unintuitive, but fairly easy to learn. A bit quicker than other Grasshopper plugins but also less control.	Requires more advanced knowledge to use. A lot of custom components and poor documentation.
Compatibility and integration What type of tool is it? Does the tool integrate with existing software or systems used in the industry?	Grasshopper plugin.	Grasshopper plugin, can be connected to most other software in the AEC-industry via BHoM.
Performance and stability How fast is the tool to set up? How does the tool perform in terms of speed and responsiveness? Is the tool stable and reliable, or does it crash frequently?	Quick to use and stable.	Slow to set up but stable.
Cost What is the cost for using the tool? Does the cost justify the value it provides?	Free The tool provides value by allowing the user to quickly estimate the emission a certain project might have.	Free (open source) The tool provides value by allowing the user to calculate LCA module A1-A3, and having the possibility to push/pull information from other software in the industry.
Support and documentation What support options are available for the tool? Is there comprehensive documentation or user guides available?	No support.	Some support. Some documentation.
Tool transparency / Verification of data How transparent is the tool regarding the sources of data it utilizes? Are there ways to cross-reference or validate the data through external sources or methods?	Mid transparency. Uses Swiss data but have not been able to verify the numbers. The material data can be read by the user.	High transparency. Uses databases to get data, Boverket among others. The material data can be read by the user.
Confidence of the data Can users/testers have confidence that the results produced by the tool are accurate and reliable? Clear documentation provides transparency and allows users/testers to understand how the results were obtained and verify the correctness of the outcomes.	Medium level of confidence. The tool has medium level of transparency. The databases are difficult to find, which makes verification harder.	High level of confidence. The tool have a high transparency and the data/results can be verified.
Overall impression	Low	Low-Mid

B

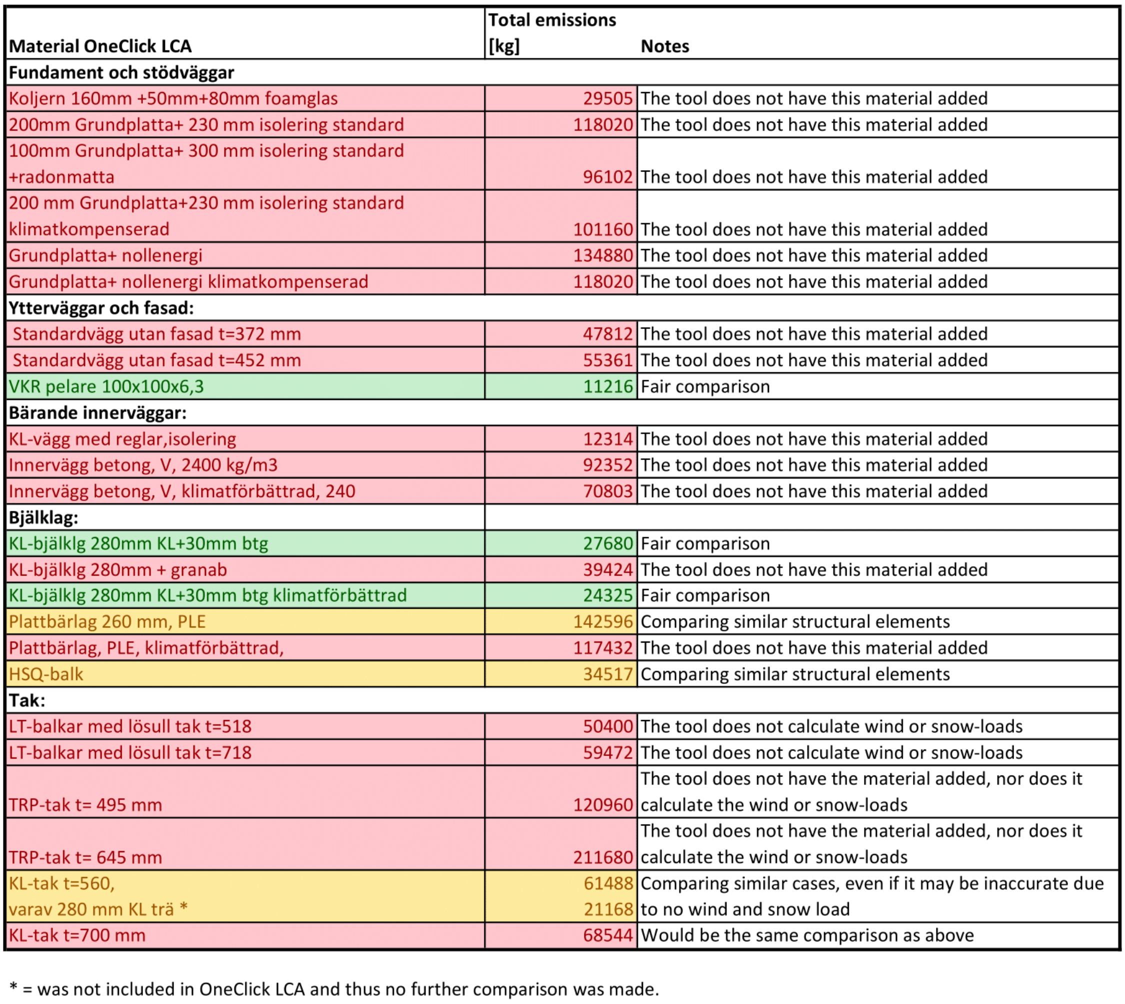
Case Study Results

In this appendix the materials used in the reference building and the results from the case study are presented.

B.1 Material List

The material list is presented in this section together with the total embodied carbon for each element.

In the list of materials each material has been identified and labelled with red, yellow, or green colour. The red colour indicates that a comparison is not possible, the yellow colour indicated that a comparison is possible with similar elements and green indicates that the element exists in the tool and a direct comparison is possible.



Material OneClick LCA	Total emissions [kg]	Notes
Fundament och stödväggar		
Koljern 160mm +50mm+80mm foamglas	29505	The tool does not have this material added
200mm Grundplatta+ 230 mm isolering standard	118020	The tool does not have this material added
100mm Grundplatta+ 300 mm isolering standard +radonmatta	96102	The tool does not have this material added
200 mm Grundplatta+230 mm isolering standard klimatkompenserad	101160	The tool does not have this material added
Grundplatta+ nollenergi	134880	The tool does not have this material added
Grundplatta+ nollenergi klimatkompenserad	118020	The tool does not have this material added
Ytterväggar och fasad:		
Standardvägg utan fasad t=372 mm	47812	The tool does not have this material added
Standardvägg utan fasad t=452 mm	55361	The tool does not have this material added
VKR pelare 100x100x6,3	11216	Fair comparison
Bärande innerväggar:		
KL-vägg med reglar,isolering	12314	The tool does not have this material added
Innervägg betong, V, 2400 kg/m3	92352	The tool does not have this material added
Innervägg betong, V, klimatförbättrad, 240	70803	The tool does not have this material added
Bjälklag:		
KL-bjälklg 280mm KL+30mm btg	27680	Fair comparison
KL-bjälklg 280mm + granab	39424	The tool does not have this material added
KL-bjälklg 280mm KL+30mm btg klimatförbättrad	24325	Fair comparison
Plattbärlag 260 mm, PLE	142596	Comparing similar structural elements
Plattbärlag, PLE, klimatförbättrad,	117432	The tool does not have this material added
HSQ-balk	34517	Comparing similar structural elements
Tak:		
LT-balkar med lösull tak t=518	50400	The tool does not calculate wind or snow-loads
LT-balkar med lösull tak t=718	59472	The tool does not calculate wind or snow-loads
TRP-tak t= 495 mm	120960	The tool does not have the material added, nor does it calculate the wind or snow-loads
TRP-tak t= 645 mm	211680	The tool does not have the material added, nor does it calculate the wind or snow-loads
KL-tak t=560,	61488	Comparing similar cases, even if it may be inaccurate due
varav 280 mm KL trä *	21168	to no wind and snow load
KL-tak t=700 mm	68544	Would be the same comparison as above

* = was not included in OneClick LCA and thus no further comparison was made.

B.2 Design Alternatives for the Reference Building and Comparison

The case study included seven design alternatives of a reference building which were compared against a similar structural system produced by the parametric tool which was developed in this thesis.

Some material with a total emission of 1 tonne CO_2 ($\sim$ 0.3% of total embodied carbon) or less has been omitted from the list to make it more compact. This includes planed timber and sawn timber from the roofs (0.4 *tonne* CO_2 and 1.0 *tonne* CO_2 respectively), and planed timber and plastic film for the standard wall (0.7 *tonne* CO_2 and 0.9 *tonne* CO_2 respectively).

The same colour coding has been used as the previous section.

To be able to make a fair comparison between the design alternatives and the tool, it needs to be able to select the element by itself based on span lengths or applied load. For example, a CLT wall is similar to a CLT slab however since the tool cannot pick the dimensions for the CLT wall it is deemed that a fair comparison is not possible.

Detailed list of materials in reference building

Alternative 1		
Choosen alternative		
Material	Volume [m^3] / Mass [kg]	Embodied carbon [t CO2]
Foundation - 115t (50%)		
Concrete 30/37	843x0,2 m3	61
Steel rebar	25290 kg	23
XPS, extruded polystyrene	6238 kg	31
-		
Slab 28t (12%)		
CLT floor slab	843x0,28 m3	18
Floor screed	843x0,03 m3	10
Beams 15t (6%)		
HEA200 (101,5m)	4297,3 kg	15
Roof		
-	0	0
-		
-		
-		
Standard wall without facade 48t (21%)		
Rock wool insulation	252,02 m3	16,6
Fibre cement board	5 m3	25
Gypsum plasterboard	839x0,023 m3	4,7
Columns 11t (5%)		
VKR100x100x6,3	3298,75 kg	11
Internal walls 12t (4%)		
CLT-wall	769x0,1 m3	5,8
Gypsum plasterboard	769x0,026 m3	4,9
Rock wool insulation	32 m3	1,6
Total embodied carbon:		227,6
Structural system embodied carbon:		**59,8**

Summary of the structural system in the reference building:

Choosen alternative		
Structural element	Material	Embodied carbon [t CO2]
Slab	CLT + screed	28
Beam	HEA (100m)	15
	-	
Load bearing wall	CLT-wall	5,8
Column	VKR	11
Structural system embodied carbon:		**59,8**

Summary of a comparable system generated by the parametric tool:

Structural element	Material	Embodied carbon [t CO2]
Slab	CLT-slabs: 848 m^2 L8D 300mm + 30 mm floor screed	29,5
Beam*	Glulam beams (5.15m): 32 x GL30c 215x630 32 x GL30c 165x630	3
Column	VKR columns (3m): 72 x 100x100x6,3	13,3
Structural system embodied carbon:		**45,8**

Difference in embodied carbon between the two options:

Structural system embodied carbon difference:	**-23%**
Comment:	As the HEA beams were only used for a small portion of the building the choice was made to pick glulam beams and match the CLT wall.

*=when given the oportunity, HEA260 beams were chosen, which is the smallest cross section available for 5.2m long beams according to Tibnor

Detailed list of materials in reference building

Alternative 2 **Concrete alternative**		
Material	Volume [m^3] / Mass [kg]	Embodied carbon [t CO2]
Foundation - 115t (23%)		
Concrete30/37	843x0,2 m3	61
Steel rebar	25290 kg	23
XPS, extruded polystyrene	6238 kg	31
-		
Slab 145t (29%)		
Lattice girder precast slab In situ concrete	843x0,26 m3	145
-		
Beams 34t (7%)		
HSQ 240-490-20-20 (101,5m)	10100 kg	34
Roof 51t (10%)		
Bitumen waterproofing	1008x0,0039 m3	4,9
membrane		
Glulam 400mm cc600	60,48 m3	4,6
Rock wool insulation	363,88 m3	34
Gypsum plasterboard	1008x0,023 m3	5,7
Standard wall without facade 48t (10%)		
Rock wool insulation	252,02 m3	16,6
Fibre cement board	5 m3	25
Gypsum plasterboard	839x0,023 m3	4,7
Columns 11t (2%)		
VKR100x100x6,3	3298,75 kg	11
Internal walls 89t (18%)		
Prefabricated concrete wall	769,6x0,2 m3	89
-		
-		
Total embodied carbon:		489,5
Structural system embodied carbon:		**283,6**

Summary of the structural system in the reference building:

Concrete alternative		
Structural element	Material	Embodied carbon [t CO2]
Slab	Concrete	145
Beam	HSQ (100m)	34
	Glulam	4,6
Load bearing wall	Prefabricated concrete wall	89
Column	VKR	11
Structural system embodied carbon:		**283,6**

Summary of a comparable system generated by the parametric tool:

Structural element	Material	Embodied carbon [t CO2]
Slab	Hollow core slabs: 848 m^2 HD120/20 + 30 mm floor screed	43,3
Beam	HEB beams (5.15m): 32 x HEB240 32 x HEB260	98,4
Column	VKR columns (3m): 72 x 100x100x6,3	13,3
Structural system embodied carbon:		**155**

Difference in embodied carbon between the two options:

Structural system embodied carbon difference:	**-45%**
Comment:	
Comment:	The prefabricated concrete wall have a large GWP and is a comparable match with HEB beams. However the concrete walls provide less flexibility than steel beams.

Detailed list of materials in reference building

Alternative 3 **Timber alternative - low U-value**		
Material	Volume [m^3] / Mass [kg]	Embodied carbon [t CO2]
Foundation - 134t (47%)		
Concrete30/37	843x0,2 m3	61
Steel rebar	25290 kg	23
XPS, extruded polystyrene	10116 kg	50
-		
Slab 28t (10%)		
CLT floor slab	843x0,28 m3	18
Floor screed	843x0,03 m3	10
Beams		
-	0	0
Roof 59t (21%)		
Bitumen waterproofing	1008x0,0039 m3	4,9
membrane		
Glulam 600mm cc600	45,36 m3	3,4
Rock wool insulation	576,3 m3	44
Gypsum plasterboard	1008x0,023 m3	5,7
Standardwall without facade 54t (19%)		
Rock wool insulation	306,56 m3	22,8
Fibre cement board	5 m3	25
Gypsum plasterboard	839x0,023 m3	4,7
Columns		
-	0	0
Internal walls 12t (4%)		
CLT-wall	769x0,1 m3	5,8
Gypsum plasterboard	769*0,026 m3	4,9
Rock wool insulation	32 m3	1,6
Total embodied carbon:		284,8
Structural system embodied carbon:		**37,2**

Summary of the structural system in the reference building:

Timber alternative - low U-value		
Structural element	Material	Embodied carbon [t CO2]
Slab	CLT + screed	28
Beam	-	
	Glulam	3,4
Load bearing wall	CLT-wall	5,8
Column	-	
Structural system embodied carbon:		**37,2**

Summary of a comparable system generated by the parametric tool:

Structural element	Material	Embodied carbon [t CO2]
Slab	CLT-slabs: 848 m^2 L8D 300mm + 30 mm floor screed	29,5
Beam	Glulam beams (5.15m): 32 x GL30c 215x630 32 x GL30c 165x630	3
Column	Glulam columns (3m): 4 x 90x135 GL 30h 22 x 90x270 GL 30c 32 x 115x270 GL 30c 14 x 140x315 GL 30c	0,5
Structural system embodied carbon:		**33**

Difference in embodied carbon between the two options:

Structural system embodied carbon difference:	**-11%**
Comment:	The glulam columns have a fraction of the volume that CLT walls have, which explains the difference between them. Other than that, it is a fairy good match between the systems.

Detailed list of materials in reference building

Alternative 4 Timber alternative - normal U-value		
Material	Volume [m^3] / Mass [kg]	Embodied carbon [t CO2]
Foundation - 115t (45%)		
Concrete30/37	843x0,2 m3	61
Steel rebar	25290 kg	23
XPS, extruded polystyrene	6238,2 kg	31
-		
Slab 28t (11%)		
CLT floor slab	843x0,28 m3	18
Floor screed	843x0,03 m3	10
Beams		
-	0	0
Roof 51t (20%)		
Bitumen waterproofing	1008x0,0039 m3	4,9
membrane		
Glulam 400mm cc600	60,48 m3	4,6
Rock wool insulation	363,88 m3	34
Gypsum plasterboard	1008x0,023 m3	5,7
Standard wall without facade 48t (19%)		
Rock wool insulation	252,02 m3	16,6
Fibre cement board	5 m3	25
Gypsum plasterboard	839x0,023 m3	4,7
Columns		
-	0	0
Internal walls 12t (5%)		
CLT-wall	769x0,1 m3	5,8
Gypsum plasterboard	769*0,026 m3	4,9
Rock wool insulation	32 m3	1,6
Total embodied carbon:		250,8
Structural system embodied carbon:		**38,4**

Summary of the structural system in the reference building:

Timber alternative - normal U-value		
Structural element	Material	Embodied carbon [t CO2]
Slab	CLT + screed	28
Beam	-	
	Glulam	4,6
Load bearing wall	CLT-wall	5,8
Column	-	
Structural system embodied carbon:		**38,4**

Summary of a comparable system generated by the parametric tool:

Structural element	Material	Embodied carbon [t CO2]
Slab	CLT-slabs: 848 m^2 L8D 300mm + 30 mm floor screed	29,5
Beam	Glulam beams (5.15m): 32 x GL30c 215x630 32 x GL30c 165x630	3
Column	Glulam columns (3m): 4 x 90x135 GL 30h 22 x 90x270 GL 30c 32 x 115x270 GL 30c 14 x 140x315 GL 30c	0,5
Structural system embodied carbon:		**33**

Difference in embodied carbon between the two options:

Structural system embodied carbon difference:	**-14%**
Comment:	The glulam columns have a fraction of the volume that CLT walls have, which explains the difference between them. Other than that, it is a fairy good match between the systems.

Detailed list of materials in reference building

Alternative 5 **Concrete alternative with load bearing steel**		
Material	Volume [m^3] / Mass [kg]	Embodied carbon [t CO2]
Foundation - 115t (27%)		
Concrete30/37	843x0,2 m3	61
Steel rebar	25290 kg	23
XPS, extruded polystyrene	6238,2 kg	31
-		
Slab 145t (34%)		
Lattice girder precast slab In situ concrete	843x0,26 m3	145
-		
Beams 68t (16%)		
HSQ 240-490-20-20 (202m)	20200 kg	68
Roof		
-	0	0
-		
-		
-		
Standard wall without facade 48t (11%)		
Rock wool insulation	252,02 m3	16,6
Fibre cement board	5 m3	25
Gypsum plasterboard	839x0,023 m3	4,7
Columns 47t (11%)		
VKR100x100x6,3	13912 kg	47
Internal walls		
-	0	0
-		
-		
Total embodied carbon:		421,3
Structural system embodied carbon:		**260**

Summary of the structural system in the reference building:

Concrete alternative with load bearing steel		
Structural element	Material	Embodied carbon [t CO2]
Slab	Concrete	145
Beam	HSQ (200m)	68
	-	
Load bearing wall	-	
Column	VKR	47
Structural system embodied carbon:		**260**

Summary of a comparable system generated by the parametric tool:

Structural element	Material	Embodied carbon [t CO2]
Slab	Hollow core slabs: 848 m^2 HD120/20 + 30 mm floor screed	43,3
Beam	HEB beams (5.15m): 32 x HEB240 32 x HEB260	98,4
Column	VKR columns (3m): 72 x 100x100x6,3	13,3
Structural system embodied carbon:		**155**

Difference in embodied carbon between the two options:

Structural system embodied carbon difference:	**-40%**
Comment:	There have most likely been a misscalculation for the columns used in the reference building, however the HEB beams provide a good comparison, especially considering the difference in length, 202m for the reference building and 330m for the building generated by the parametric tool.

Detailed list of materials in reference building

Alternative 6 **Concrete alternative - climate improved**		
Material	Volume [m^3] / Mass [kg]	Embodied carbon [t CO2]
Foundation - 100t (23%)		
Concrete 30/37 Climate improved	843x0,2 m3	46
Steel rebar	25290 kg	23
XPS, extruded polystyrene	6238 kg	31
-		
Slab 114t (27%)		
Lattice girder precast slab Concrete, climate improved	843x0,26 m3	114
-		
Beams 34t (7%)		
HSQ 240-490-20-20 (101,5m)	10100 kg	34
Roof 51t (12%)		
Bitumen waterproofing membrane	1008x0,0039 m3	4,9
Glulam 400mm cc600	60,48 m3	4,6
Rock wool insulation	363,88 m3	34
Gypsum plasterboard	1008x0,023 m3	5,7
Standard wall without facade 48t (11%)		
Rock wool insulation	252,02 m3	16,6
Fibre cement board	5 m3	25
Gypsum plasterboard	839x0,023 m3	4,7
Columns 11t (3%)		
VKR100x100x6,3	3298,75 kg	11
Internal walls 71t (16%)		
Prefabricated concrete wall	769,6x0,2 m3	71
-		
-		
Total embodied carbon:		425,5
Structural system embodied carbon:		**234,6**

Summary of the structural system in the reference building:

Concrete alternative - climate improved		
Structural element	Material	Embodied carbon [t CO2]
Slab	Concrete	114
Beam	HSQ (100m)	34
	Glulam	4,6
Load bearing wall	Prefabricated concrete wall	71
Column	VKR	11
Structural system embodied carbon:		**234,6**

Summary of a comparable system generated by the parametric tool:

Structural element	Material	Embodied carbon [t CO2]
Slab	Hollow core slabs: 848 m^2 HD120/20 + 30 mm floor screed	43,3
Beam	HEB beams (5.15m): 32 x HEB240 32 x HEB260	98,4
Column	VKR columns (3m): 72 x 100x100x6,3	13,3
Structural system embodied carbon:		**155**

Difference in embodied carbon between the two options:

Structural system embodied carbon difference:	**-34%**
Comment:	
Comment:	The prefabricated concrete wall have a large GWP and is a comparable match with HEB beams. However the concrete walls provide less flexibility than steel beams.

Detailed list of materials in reference building

Alternative 7		
Timber alternative - normal U-value (100mm concrete foundation)		
Material	Volume [m^3] / Mass [kg]	Embodied carbon [t CO2]
Foundation - 96t (39%)		
Concrete30/37	843x0,1 m3	30
Steel rebar	25290 kg	23
XPS, extruded polystyrene	8092,8 kg	40
Radon and moisture membrane	843x0,0012 m3	2,5
Slab 28t (12%)		
CLT floor slab	843x0,28 m3	18
Floor screed	843x0,03 m3	10
Beams		
-	0	0
Roof 59t (24%)		
Bitumen waterproofing membrane	1008x0,0039 m3	4,9
Glulam 600mm cc600	45,36 m3	3,4
Rock wool insulation	576,3 m3	44
Gypsum plasterboard	1008x0,023 m3	5,7
Standard wall without facade 48t (20%)		
Rock wool insulation	252,02 m3	16,6
Fibre cement board	5 m3	25
Gypsum plasterboard	839x0,023 m3	4,7
Columns		
-	0	0
Internal walls 12t (5%)		
CLT-wall	769x0,1 m3	5,8
Gypsum plasterboard	769*0,026 m3	4,9
Rock wool insulation	32 m3	1,6
Total embodied carbon:		240,1
Structural system embodied carbon:		**37,2**

Summary of the structural system in the reference building:

Timber alternative - normal U-value (100mm concrete foundation)		
Structural element	Material	Embodied carbon [t CO2]
Slab	CLT + screed	28
Beam		
	Glulam	3,4
Load bearing wall	CLT-wall	5,8
Column		
Structural system embodied carbon:		**37,2**

Summary of a comparable system generated by the parametric tool:

Structural element	Material	Embodied carbon [t CO2]
Slab	CLT-slabs: 848 m^2 L8D 300mm + 30 mm floor screed	29,5
Beam	Glulam beams (5.15m): 32 x GL30c 215x630 32 x GL30c 165x630	3
Column	Glulam columns (3m): 4 x 90x135 GL 30h 22 x 90x270 GL 30c 32 x 115x270 GL 30c 14 x 140x315 GL 30c	0,5
Structural system embodied carbon:		**33**

Difference in embodied carbon between the two options:

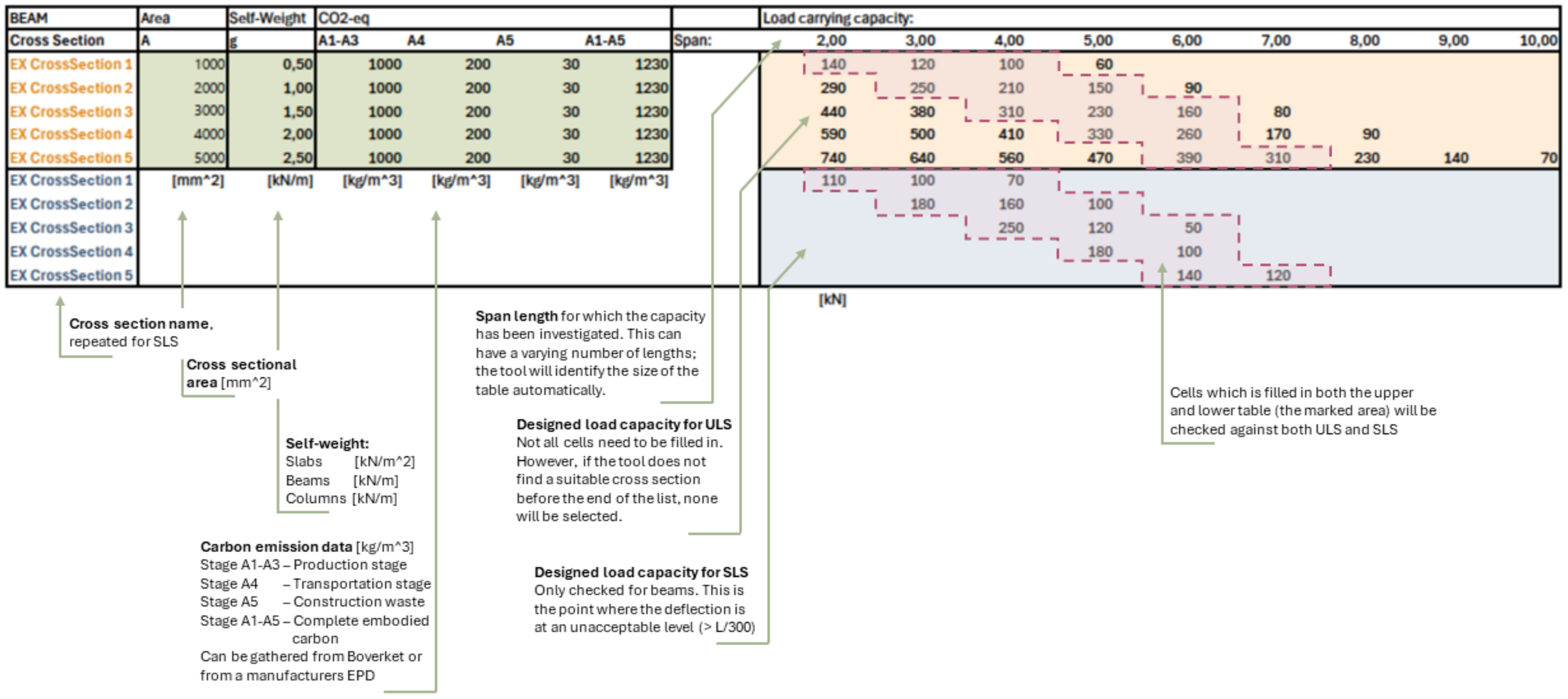
Structural system embodied carbon difference:		**-11%**
Comment:	The glulam columns have a fraction of the volume that CLT walls have, which explains the difference between them. Other than that, it is a fairy good match between the systems.	

C

Datasets for Structural Elements

In this appendix examples of the dataset used for the tool is presented. For an example of the dataset structure, see Figure C.1 The capacity depends on the cross-section and the span length. In the dataset, the capacity has been taken from preliminary design tables found at manufacturers and trade associations. However, for a few glulam beams and all concrete columns the capacity was calculated with in-house tools from VBK. The emissions in LCA stage A1-A5 has been taken from Boverket's database (Boverket, 2024a).

The elements included in this appendix are hollow core slabs, CLT slabs, HEB steel beam, glulam beam and concrete columns.



BEAM	Area	Self-Weight	CO2-eq					Load carrying capacity:								
Cross Section	A	g	A1-A3	A4	A5	A1-A5	Span:	2,00	3,00	4,00	5,00	6,00	7,00	8,00	9,00	10,00
EX CrossSection 1	1000	0,50	1000	200	30	1230		140	120	100	60					
EX CrossSection 2	2000	1,00	1000	200	30	1230		290	250	210	150	90				
EX CrossSection 3	3000	1,50	1000	200	30	1230		440	380	310	230	160	80			
EX CrossSection 4	4000	2,00	1000	200	30	1230		590	500	410	330	260	170	90		
EX CrossSection 5	5000	2,50	1000	200	30	1230		740	640	560	470	390	310	230	140	70
EX CrossSection 1	[mm^2]	[kN/m]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]		110	100	70						
EX CrossSection 2									180	160	100					
EX CrossSection 3										250	120	50				
EX CrossSection 4											180	100				
EX CrossSection 5												140	120			
								[kN]								

Cross section name, repeated for SLS

Cross sectional area [mm^2]

Self-weight:
Slabs [kN/m^2]
Beams [kN/m]
Columns [kN/m]

Carbon emission data [kg/m^3]
Stage A1-A3 – Production stage
Stage A4 – Transportation stage
Stage A5 – Construction waste
Stage A1-A5 – Complete embodied carbon
Can be gathered from Boverket or from a manufacturers EPD

Span length for which the capacity has been investigated. This can have a varying number of lengths; the tool will identify the size of the table automatically.

Designed load capacity for ULS
Not all cells need to be filled in. However, if the tool does not find a suitable cross section before the end of the list, none will be selected.

Designed load capacity for SLS
Only checked for beams. This is the point where the deflection is at an unacceptable level (> L/300)

Cells which is filled in both the upper and lower table (the marked area) will be checked against both ULS and SLS

Figure C.1: *Explanation of the dataset structure.*

C.1 Slabs

Hollow core slabs uses data from an archived webpage of the trade association Svensk Betong (Svensk Betong, 2017). This has been cross verified with tables from Bygga med prefab, a handbook for prefabricated concrete elements (Betongelementföreningen, 2013). Slabs for both office- and residential buildings are included in the tool. However, the dataset is only shown for the office variant in this appendix.

The CLT slabs uses data from the manufacturer Setra (Setra, 2021). Where cross sections are selected based on span length and applied loads. The assumed loads are 1.5 kN/m^2 self-weight and 2.5 kN/m^2 imposed load for the office building, and 2.0 kN/m^2 self-weight and 2.0 kN/m^2 imposed load for the residential building. Again, only the dataset for the office building is shown in this appendix.

Hollow core slab, office building

Profile	Area	Self-weight	A1-A3	A4	A5	A1-A5		Span length
HD120/20	124000	2,7	253,8	60,8	0,0	314,6		8
HD120/27	165000	3,5	253,8	60,8	0,0	314,6		13
HD120/32	178000	3,9	253,8	60,8	0,0	314,6		15
HD120/40	234000	5,1	253,8	60,8	0,0	314,6		18
	mm^2	kN/m^2	kg/m^3	kg/m^3	kg/m^3	kg/m^3		m

CLT slab, office building

Profile	Area	Self-weight	A1-A3	A4	A5	A1-A5		Span length
130 L5S	130000	0,56	55,8	16,0	3,6	75,4		3
150 L5S	150000	0,64	55,8	16,0	3,6	75,4		4
180 L5S	180000	0,77	55,8	16,0	3,6	75,4		5
200 L7D	200000	0,85	55,8	16,0	3,6	75,4		5,5
230 L7D	230000	0,98	55,8	16,0	3,6	75,4		6
260 L7D	260000	1,11	55,8	16,0	3,6	75,4		6,5
300 L8D	300000	1,28	55,8	16,0	3,6	75,4		7
	mm^2	kN/m^2	kg/m^3	kg/m^3	kg/m^3	kg/m^3		m

C.2 Beams

The steel beams used in this tool uses data from Tibnor, a manufacturer of steel elements. The tables from Tibnor contains ULS capacity and the corresponding deflection (Tibnor, 2023). To get the load capacity for a given deflection, e.g. the L/300 limit, the deflection can be assumed to have a linear relationship with the load. The load capacity was recalculated to get a maximum deflection of L/300 in SLS.

The glulam beams used in this tool uses data from the trade association Svenskt Trä (Svenskt Trä, n.d.-b). The load capacity for the elements included in the table is relatively low, this because the table is supposed to be used to design timber joists, not beams. To include elements with a higher capacity, an in-house tool from VBK was used. The capacity for GL30c 90x630, 165x630, 215x630, 115x765 and 215x765 was calculated and the elements were added to the dataset.

Steel beams, HEB

Profile	Area	Self-weight	A1-A3	A4	A5	A1-A5	Span length [m]	1,20	1,50	1,80	2,10	2,40	2,70	3,00	3,30	3,60	4,80
HEB100	2604	0,20	24728	624,1	1264	26615	**ULS Capacity:**	196	131	91,1	66,8	51,1					
HEB120	3401	0,26	24728	624,1	1264	26615	**[kN/m]**	261	208	144	106	81,1	64				
HEB140	4296	0,33	24728	624,1	1264	26615		332	266	215	158	121	95,2	77	63,5		
HEB160	5425	0,42	24728	624,1	1264	26615		439	351	292	227	174	137	111	91,7	77	
HEB180	6525	0,50	24728	624,1	1264	26615		529	423	352	302	237	187	151	125	105	
HEB200	7808	0,60	24728	624,1	1264	26615		626	501	417	358	313	249	202	167	140	78,4
HEB220	9104	0,70	24728	624,1	1264	26615		731	585	487	417	365	321	260	215	180	101
HEB240	10600	0,82	24728	624,1	1264	26615		820	655	546	468	409	364	322	266	223	125
HEB260	11840	0,91	24728	624,1	1264	26615		895	716	596	511	447	397	357	324	272	152
HEB280	13140	1,01	24728	624,1	1264	26615		1020	815	679	582	509	452	407	370	325	182
HEB300	14910	1,15	24728	624,1	1264	26615		1150	917	764	654	572	509	458	416	381	222
HEB320	16130	1,25	24728	624,1	1264	26615		1280	1020	850	729	637	566	510	463	424	256
HEB340	17090	1,32	24728	624,1	1264	26615		1420	1130	945	810	708	629	566	514	471	287
HEB360	18060	1,39	24728	624,1	1264	26615		1570	1250	1040	894	782	695	626	568	521	319
HEB400	19780	1,52	24728	624,1	1264	26615		1890	1510	1260	1080	944	839	755	686	629	385
HEB450	21800	1,68	24728	624,1	1264	26615		2220	1770	1480	1270	1110	984	886	805	738	475
HEB500	23860	1,84	24728	624,1	1264	26615		2560	2050	1710	1460	1280	1140	1020	930	852	574
HEB550	25410	1,95	24728	624,1	1264	26615		2940	2350	1960	1680	1470	1300	1170	1070	977	667
HEB600	27000	2,08	24728	624,1	1264	26615		3330	2660	2220	1900	1660	1480	1330	1210	1110	767
HEB650	28630	2,21	24728	624,1	1264	26615		3740	3000	2500	2140	1870	1660	1500	1360	1250	874
HEB700	30640	2,37	24728	624,1	1264	26615		4300	3440	2870	2460	2150	1910	1720	1560	1430	994
HEB800	33420	2,57	24728	624,1	1264	26615		5110	4090	3410	2920	2560	2270	2040	1860	1700	1220
HEB900	37130	2,86	24728	624,1	1264	26615		6110	4890	4070	3490	3050	2710	2440	2220	2040	1500
HEB1000	40000	3,08	24728	624,1	1264	26615		7010	5610	4670	4000	3500	3110	2800	2550	2330	1750
HEB100	mm^2	kN/m	kg/m^3	kg/m^3	kg/m^3	kg/m^3	**SLS Capacity:**	140,0	71,2	42,0	26,0	17,8					
HEB120							**[kN/m]**		136,8	78,5	49,5	34,1	24,0				
HEB140									241,8	138,7	85,1	60,5	40,8	29,6	22,5		
HEB160										230,5	144,5	99,4	68,5	50,5	37,4	28,9	
HEB180											222,5	145,8	105,2	75,5	57,3	45,0	
HEB200											329,7	227,6	160,1	112,2	83,5	64,6	27,9
HEB220												314,0	222,2	162,5	118,3	93,9	39,4
HEB240													297,8	230,0	172,1	127,4	54,1
HEB260														297,5	222,8	171,8	71,5
HEB280														370,0	290,7	216,7	93,9
HEB300															381,3	285,8	122,5
HEB320																363,4	151,7
HEB340																434,8	176,6
HEB360																480,9	212,7
HEB400																	280,0
HEB450																	380,0
HEB500																	510,2
HEB550																	
HEB600																	
HEB650																	
HEB700																	
HEB800																	
HEB900																	
HEB1000																	

6,00	7,20	8,40	9,60	10,80	12,00	13,20	14,40	15,60	16,80
79,6									
97,1									
116	80,3								
142	97,9								
163	113	82,4							
183	126	92,4							
204	141	103							
246	170	124	94,7						
303	210	153	117	91,9					
367	254	186	142	111	89,8	73,7			
426	295	216	165	130	104	85,9	71,1		
490	339	248	190	149	120	98,9	82,7	70	
558	387	282	216	170	137	113	94,4	80	68,5
635	440	322	246	194	156	129	108	91,2	78,2
781	541	397	303	238	193	158	133	112	96,5
961	666	488	373	294	237	195	164	139	119
1130	787	577	441	347	280	231	193	164	141
27,9									
37,3									
48,3	27,9								
63,1	36,1								
75,8	44,5	28,1							
91,5	53,1	33,2							
107,4	62,7	39,0							
144,7	83,3	51,8	35,2						
202,0	114,5	72,6	48,6	34,1					
271,9	156,3	96,4	64,9	45,4	32,7	24,9			
340,8	196,7	123,4	83,8	58,5	42,4	31,5	24,4		
426,1	246,5	154,3	104,8	72,5	53,3	39,6	30,5	24,3	
531,4	299,6	188,0	128,0	90,0	65,2	49,7	37,8	29,7	24,0
	364,1	231,2	157,4	109,1	80,0	60,4	47,1	36,5	29,2
	519,4	326,9	220,4	153,0	111,9	83,8	65,1	48,5	41,6
		440,8	298,4	211,7	152,9	115,9	89,5	72,3	55,5
			392,0	277,6	200,0	151,7	115,8	90,7	71,8

Glulam beams								Load carrying capacity [kN]													
Profile	**Area**	**Self weight**	**A1-A3**	**A4**	**A5**	**A1-A5**	**Span length [m]**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
GL30c 56x360	20160	0,09	57,7	15,0	3,6	76,3		4	2												
GL30c 56x405	22680	0,10	57,7	15,0	3,6	76,3		6	4	2											
GL30c 56x450	25200	0,11	57,7	15,0	3,6	76,3		7	5	3											
GL30c 66x405	26730	0,11	57,7	15,0	3,6	76,3		8													
GL30c 66x450	29700	0,13	57,7	15,0	3,6	76,3		10	6	4	2										
GL30c 66x495	32670	0,14	57,7	15,0	3,6	76,3		12	8	5	3	2									
GL30c 78x495	38610	0,16	57,7	15,0	3,6	76,3			10	6	4	3	2								
GL30c 78x540	42120	0,18	57,7	15,0	3,6	76,3			12	7	5										
GL30c 78x585	45630	0,19	57,7	15,0	3,6	76,3				10	7	4	3								
GL30c 90x540	48600	0,21	57,7	15,0	3,6	76,3				8											
GL30c 90x585	52650	0,22	57,7	15,0	3,6	76,3				12	8	5	4								
GL30c 90x630	56700	0,24	57,7	15,0	3,6	76,3		21	17	12	10	7	5								
GL30c 165x630	103950	0,44	57,7	15,0	3,6	76,3		39	33	25	16										
GL30c 215x630	135450	0,58	57,7	15,0	3,6	76,3		49	42	33	21	14									
GL30c 90x675	60750	0,26	57,7	15,0	3,6	76,3					12	9	6								
GL30c 90x720	64800	0,28	57,7	15,0	3,6	76,3						10	8	6							
GL30c 90x765	68850	0,29	57,7	15,0	3,6	76,3							9								
GL30c 115x720	82800	0,35	57,7	15,0	3,6	76,3						12	10	7							
GL30c 115x765	87975	0,37	57,7	15,0	3,6	76,3		33	27	23	19		12	9	7						
GL30c 215x765	164475	0,70	57,7	15,0	3,6	76,3		59	50	43	36	28	19								
GL30c 115x810	93150	0,40	57,7	15,0	3,6	76,3								10	8	6					
GL30c 115x855	98325	0,42	57,7	15,0	3,6	76,3								12	10	7	6				
GL30c 115x900	103500	0,44	57,7	15,0	3,6	76,3								15		9	7				
GL30c 115x945	108675	0,46	57,7	15,0	3,6	76,3									12	10	8				
GL30c 115x990	113850	0,49	57,7	15,0	3,6	76,3										12					
GL30c 140x855	119700	0,51	57,7	15,0	3,6	76,3												6			
GL30c 140x900	126000	0,54	57,7	15,0	3,6	76,3								18				7	6		
GL30c 140x945	132300	0,56	57,7	15,0	3,6	76,3								20	15		10	8			
GL30c 140x990	138600	0,59	57,7	15,0	3,6	76,3									18			9	8	6	
GL30c 140x1035	144900	0,62	57,7	15,0	3,6	76,3								25	20	15	12	10	9	7	6
GL30c 140x1080	151200	0,64	57,7	15,0	3,6	76,3								30		18	15	12	10	8	7
GL30c 140x1125	157500	0,67	57,7	15,0	3,6	76,3									25	20				9	8
GL30c 140x1170	163800	0,70	57,7	15,0	3,6	76,3														10	9
GL30c 165x1080	178200	0,76	57,7	15,0	3,6	76,3											18		12		
GL30c 165x1125	185625	0,79	57,7	15,0	3,6	76,3									30	25	20	15			
GL30c 165x1170	193050	0,82	57,7	15,0	3,6	76,3												18	15	12	10
GL30c 165x1215	200475	0,85	57,7	15,0	3,6	76,3										30	25	20			12
GL30c 165x1260	207900	0,89	57,7	15,0	3,6	76,3													18	15	
GL30c 165x1305	215325	0,92	57,7	15,0	3,6	76,3													20		15
GL30c 190x1260	239400	1,02	57,7	15,0	3,6	76,3											30	25		18	
GL30c 190x1305	247950	1,06	57,7	15,0	3,6	76,3												30		20	
GL30c 190x1350	256500	1,09	57,7	15,0	3,6	76,3													25		18
GL30c 190x1395	265050	1,13	57,7	15,0	3,6	76,3													30	25	20
GL30c 190x1485	282150	1,20	57,7	15,0	3,6	76,3															25
GL30c 215x1530	328950	1,40	57,7	15,0	3,6	76,3															30
	mm^2	kN/m^2	kg/m^3	kg/m^3	kg/m^3	kg/m^3															

The yellow cells have been added to the original table

C.3 Columns

In the following section the capacity for concrete columns is presented according to an in-house tool from VBK with respect to buckling. The columns are assumed to have either 4x12 mm reinforcement or 4x16 mm reinforcement. The emission has been approximated, as the tool cannot compute the emission from a composite material. See Appendix D for how the approximation was calculated.

Concrete column, 4x12mm reinforcement **Buckling length [m]**

Profile	Area	Self weight	A1-A3	A4	A5	A1-A5		2	2,25	2,5	2,75	3	3,25	3,5	3,75	4	4,25	4,5	4,75	5
30x30 4x12Ø	90000	2,2	513,0	9,8	15,7	538,4		2850	2775	2650	2500	2325	2100	1850	1600	1375	1200	1025	900	775
30x40 4x12Ø	120000	2,9	513,0	9,8	15,7	538,4		3600	3450	3300	3100	2850	2600	2300	1975	1650	1400	1200	1025	875
30x50 4x12Ø	150000	3,7	513,0	9,8	15,7	538,4		4075	3875	3650	3400	3125	2800	2425	2050	1725	1450	1225	1025	900
40x40 4x12Ø	160000	3,9	513,0	9,8	15,7	538,4		5175	5075	4975	4850	4700	4525	4300	4025	3675	3350	2975	2625	2300
40x50 4x12Ø	200000	4,9	513,0	9,8	15,7	538,4		6275	6175	6025	5850	5675	5450	5175	4850	4450	4075	3625	3175	2725
40x60 4x12Ø	240000	5,9	513,0	9,8	15,7	538,4		7150	6950	6750	6500	6225	5950	5625	5225	4800	4325	3825	3275	2800
50x50 4x12Ø	250000	6,1	513,0	9,8	15,7	538,4		8125	8025	7925	7825	7675	7525	7325	7100	6825	6550	6200	5800	5325
50x60 4x12Ø	300000	7,4	513,0	9,8	15,7	538,4		9625	9500	9350	9225	9050	8850	8625	8350	8025	7725	7350	6925	6400
	mm2	kN/m	kg CO2/m^3					Load carrying capacity [kN]												

Concrete column, 4x16mm reinforcement **Buckling length [m]**

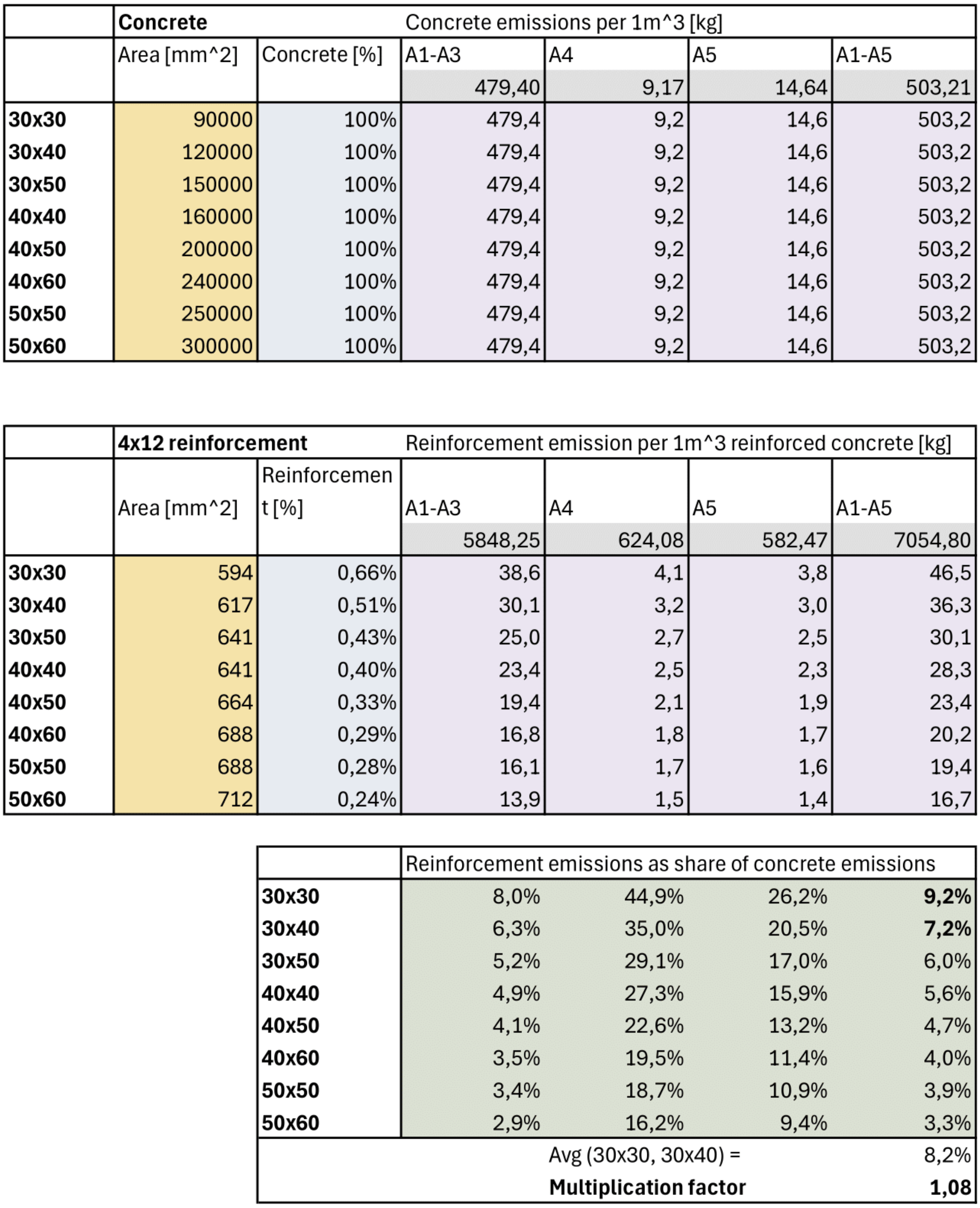
Profile	Area	Self weight	A1-A3	A4	A5	A1-A5		2	2,25	2,5	2,75	3	3,25	3,5	3,75	4	4,25	4,5	4,75	5
30x30 4x16Ø	90000	2,2	539,3	10,3	16,5	566,1		3050	2975	2875	2775	2650	2475	2325	2100	1900	1725	1525	1375	1225
30x40 4x16Ø	120000	2,9	539,3	10,3	16,5	566,1		3800	3700	3575	3400	3225	3050	2825	2575	2325	2075	1825	1600	1425
30x50 4x16Ø	150000	3,7	539,3	10,3	16,5	566,1		4375	4175	3975	3775	3550	3325	3025	2725	2425	2150	1875	1650	1450
40x40 4x16Ø	160000	3,9	539,3	10,3	16,5	566,1		5350	5275	5200	5100	4975	4825	4700	4475	4250	4025	3775	3500	3200
40x50 4x16Ø	200000	4,9	539,3	10,3	16,5	566,1		6500	6400	6275	6125	5975	5800	5600	5375	5100	4825	4525	4175	3825
40x60 4x16Ø	240000	5,9	539,3	10,3	16,5	566,1		7425	7250	7050	6850	6625	6400	6125	5825	5500	5175	4825	4425	4000
50x50 4x16Ø	250000	6,1	539,3	10,3	16,5	566,1		8325	8225	8150	8050	7925	7800	7650	7475	7275	7075	6850	6600	6300
50x60 4x16Ø	300000	7,4	539,3	10,3	16,5	566,1		9825	9725	9600	9475	9325	9150	8975	8775	8500	8300	8025	7725	7400
	mm2	kN/m	kg CO2/m^3					Load carrying capacity [kN]												

D

Emission Calculations for Concrete Columns

This appendix outlines the emissions calculations for concrete columns, considering two sets of columns with either 4x12mm or 4x16mm reinforcement bars. The calculations determine the reinforcement area as a percentage of the total cross-sectional area, see blue columns in Figure D.1 and D.2. Emissions, represented in purple cells, are calculated by multiplying the said percentage with the emissions per cubic meter material, $kgCO_2/m^3$. This assumes that the cross-section consists of 100% concrete, the emissions from the reinforcement is added on top of that.

The final part compares the extra CO_2 emissions from reinforcement with those of concrete alone, establishing a default multiplication factor. The assumption is that the two smallest cross sections will be sufficient for most cases and therefore an average between them will be used. The multiplication factors were set to 1.08 for 4x12 and 1.125 for 4x16.

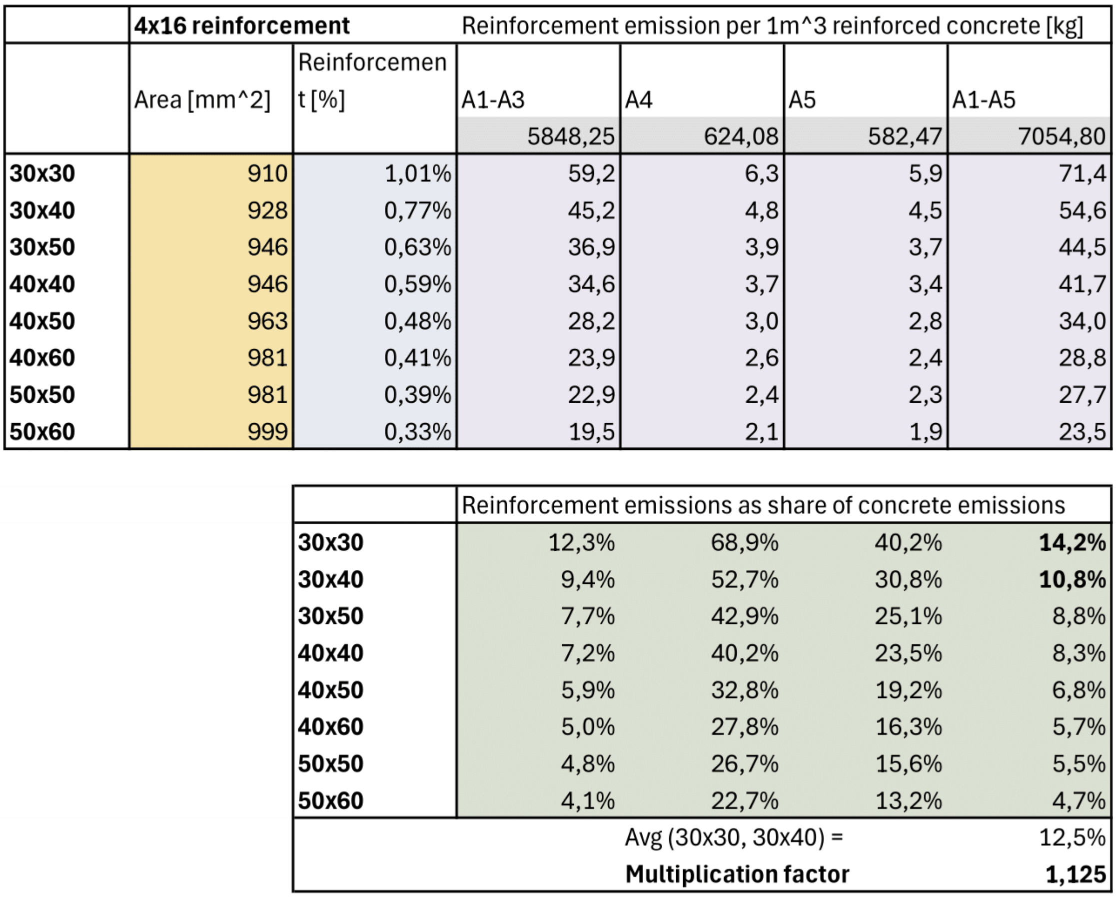


	Concrete		Concrete emissions per 1m^3 [kg]			
	Area [mm^2]	Concrete [%]	A1-A3	A4	A5	A1-A5
			479,40	9,17	14,64	503,21
30x30	90000	100%	479,4	9,2	14,6	503,2
30x40	120000	100%	479,4	9,2	14,6	503,2
30x50	150000	100%	479,4	9,2	14,6	503,2
40x40	160000	100%	479,4	9,2	14,6	503,2
40x50	200000	100%	479,4	9,2	14,6	503,2
40x60	240000	100%	479,4	9,2	14,6	503,2
50x50	250000	100%	479,4	9,2	14,6	503,2
50x60	300000	100%	479,4	9,2	14,6	503,2

	4x12 reinforcement		Reinforcement emission per 1m^3 reinforced concrete [kg]			
	Area [mm^2]	Reinforcement [%]	A1-A3	A4	A5	A1-A5
			5848,25	624,08	582,47	7054,80
30x30	594	0,66%	38,6	4,1	3,8	46,5
30x40	617	0,51%	30,1	3,2	3,0	36,3
30x50	641	0,43%	25,0	2,7	2,5	30,1
40x40	641	0,40%	23,4	2,5	2,3	28,3
40x50	664	0,33%	19,4	2,1	1,9	23,4
40x60	688	0,29%	16,8	1,8	1,7	20,2
50x50	688	0,28%	16,1	1,7	1,6	19,4
50x60	712	0,24%	13,9	1,5	1,4	16,7

	Reinforcement emissions as share of concrete emissions			
30x30	8,0%	44,9%	26,2%	**9,2%**
30x40	6,3%	35,0%	20,5%	**7,2%**
30x50	5,2%	29,1%	17,0%	6,0%
40x40	4,9%	27,3%	15,9%	5,6%
40x50	4,1%	22,6%	13,2%	4,7%
40x60	3,5%	19,5%	11,4%	4,0%
50x50	3,4%	18,7%	10,9%	3,9%
50x60	2,9%	16,2%	9,4%	3,3%
		Avg (30x30, 30x40) =		8,2%
		Multiplication factor		**1,08**

Figure D.1: *Table which present the calculations used to extract the multiplication factor for columns with 4x12mm reinforcement.*



	4x16 reinforcement		Reinforcement emission per 1m^3 reinforced concrete [kg]			
	Area [mm^2]	Reinforcement [%]	A1-A3	A4	A5	A1-A5
			5848,25	624,08	582,47	7054,80
30x30	910	1,01%	59,2	6,3	5,9	71,4
30x40	928	0,77%	45,2	4,8	4,5	54,6
30x50	946	0,63%	36,9	3,9	3,7	44,5
40x40	946	0,59%	34,6	3,7	3,4	41,7
40x50	963	0,48%	28,2	3,0	2,8	34,0
40x60	981	0,41%	23,9	2,6	2,4	28,8
50x50	981	0,39%	22,9	2,4	2,3	27,7
50x60	999	0,33%	19,5	2,1	1,9	23,5

	Reinforcement emissions as share of concrete emissions			
30x30	12,3%	68,9%	40,2%	**14,2%**
30x40	9,4%	52,7%	30,8%	**10,8%**
30x50	7,7%	42,9%	25,1%	8,8%
40x40	7,2%	40,2%	23,5%	8,3%
40x50	5,9%	32,8%	19,2%	6,8%
40x60	5,0%	27,8%	16,3%	5,7%
50x50	4,8%	26,7%	15,6%	5,5%
50x60	4,1%	22,7%	13,2%	4,7%
		Avg (30x30, 30x40) =		12,5%
		Multiplication factor		**1,125**

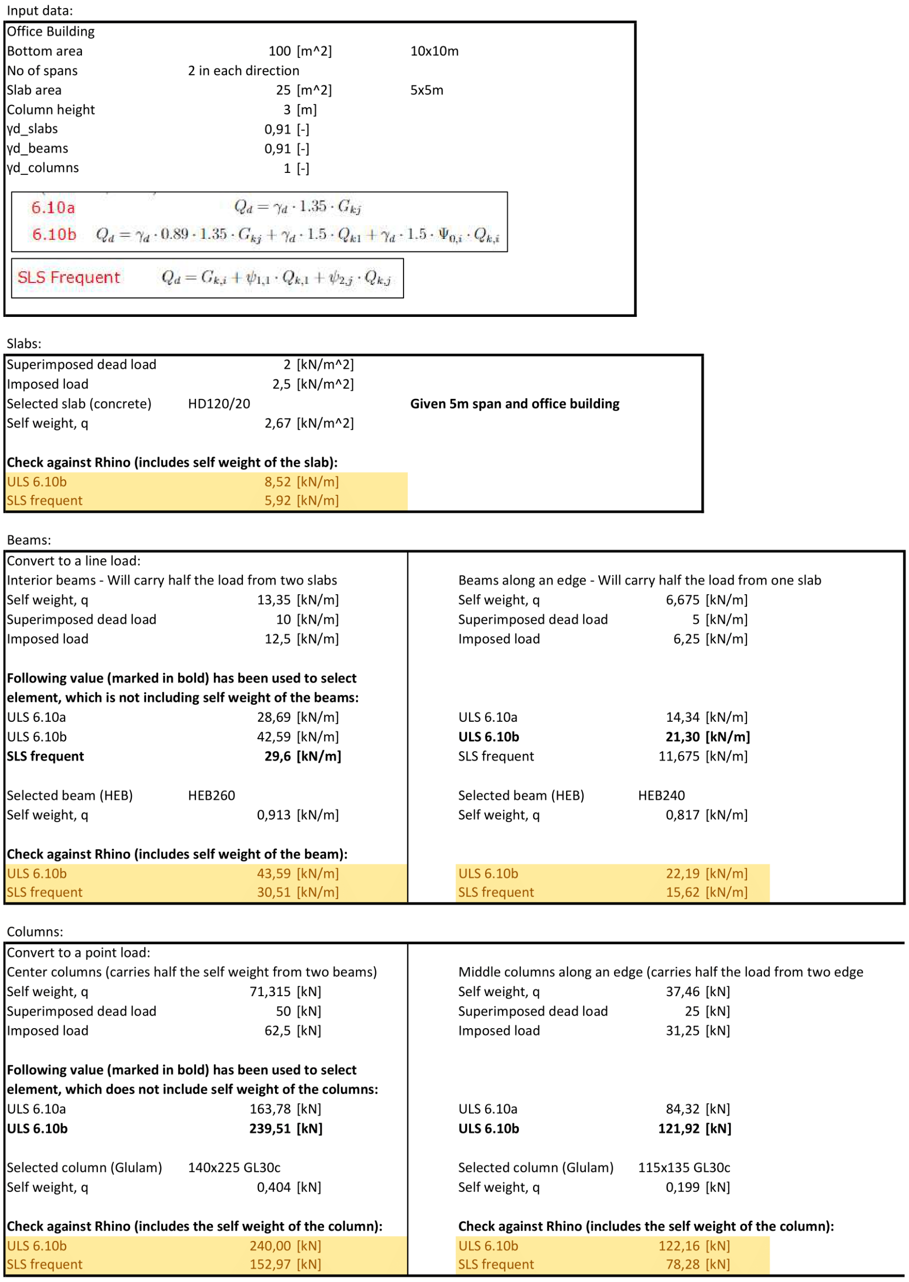
Figure D.2: *Table which present the calculations used to extract the multiplication factor for columns with 4x16mm reinforcement.*

E

Load Takedown Verification

In this appendix the hand calculations and the loads calculated by the tool are presented. ULS 6.10b and SLS frequent load combination has been calculated for slabs, beams, and columns, according to 2.2 and 2.4, as those were the governing load cases for this structure.

For slabs there is only one case as all areas are the same, for beams there is a central beam and an edge beam case, and for columns there is a central column, an edge column in the middle and a corner column. For the slabs the load is calculated as a distributed load, for the beams the load is calculated as a line load and for columns it is calculated as a point load.



Input data:

Office Building			
Bottom area	100	[m^2]	10x10m
No of spans	2 in each direction		
Slab area	25	[m^2]	5x5m
Column height	3	[m]	
γd_slabs	0,91	[-]	
γd_beams	0,91	[-]	
γd_columns	1	[-]	

6.10a $Q_d = \gamma_d \cdot 1.35 \cdot G_{kj}$

6.10b $Q_d = \gamma_d \cdot 0.89 \cdot 1.35 \cdot G_{kj} + \gamma_d \cdot 1.5 \cdot Q_{k1} + \gamma_d \cdot 1.5 \cdot \Psi_{0,i} \cdot Q_{k,i}$

SLS Frequent $Q_d = G_{k,i} + \psi_{1,1} \cdot Q_{k,1} + \psi_{2,j} \cdot Q_{k,j}$

Slabs:

Superimposed dead load	2	[kN/m^2]	
Imposed load	2,5	[kN/m^2]	
Selected slab (concrete)	HD120/20		**Given 5m span and office building**
Self weight, q	2,67	[kN/m^2]	

Check against Rhino (includes self weight of the slab):

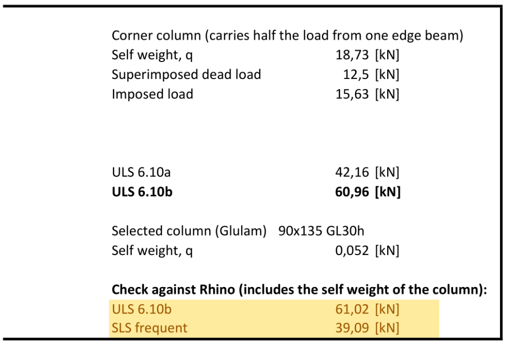
ULS 6.10b	8,52	[kN/m]
SLS frequent	5,92	[kN/m]

Beams:

Convert to a line load:					
Interior beams - Will carry half the load from two slabs			Beams along an edge - Will carry half the load from one slab		
Self weight, q	13,35	[kN/m]	Self weight, q	6,675	[kN/m]
Superimposed dead load	10	[kN/m]	Superimposed dead load	5	[kN/m]
Imposed load	12,5	[kN/m]	Imposed load	6,25	[kN/m]
Following value (marked in bold) has been used to select element, which is not including self weight of the beams:					
ULS 6.10a	28,69	[kN/m]	ULS 6.10a	14,34	[kN/m]
ULS 6.10b	42,59	[kN/m]	**ULS 6.10b**	**21,30**	**[kN/m]**
SLS frequent	**29,6**	**[kN/m]**	SLS frequent	11,675	[kN/m]
Selected beam (HEB)	HEB260		Selected beam (HEB)	HEB240	
Self weight, q	0,913	[kN/m]	Self weight, q	0,817	[kN/m]
Check against Rhino (includes self weight of the beam):					
ULS 6.10b	43,59	[kN/m]	ULS 6.10b	22,19	[kN/m]
SLS frequent	30,51	[kN/m]	SLS frequent	15,62	[kN/m]

Columns:

Convert to a point load:					
Center columns (carries half the self weight from two beams)			Middle columns along an edge (carries half the load from two edge		
Self weight, q	71,315	[kN]	Self weight, q	37,46	[kN]
Superimposed dead load	50	[kN]	Superimposed dead load	25	[kN]
Imposed load	62,5	[kN]	Imposed load	31,25	[kN]
Following value (marked in bold) has been used to select element, which does not include self weight of the columns:					
ULS 6.10a	163,78	[kN]	ULS 6.10a	84,32	[kN]
ULS 6.10b	**239,51**	**[kN]**	**ULS 6.10b**	**121,92**	**[kN]**
Selected column (Glulam)	140x225 GL30c		Selected column (Glulam)	115x135 GL30c	
Self weight, q	0,404	[kN]	Self weight, q	0,199	[kN]
Check against Rhino (includes the self weight of the column):			**Check against Rhino (includes the self weight of the column):**		
ULS 6.10b	240,00	[kN]	ULS 6.10b	122,16	[kN]
SLS frequent	152,97	[kN]	SLS frequent	78,28	[kN]

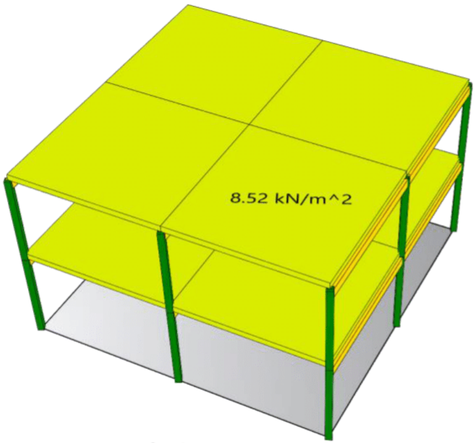


Corner column (carries half the load from one edge beam)

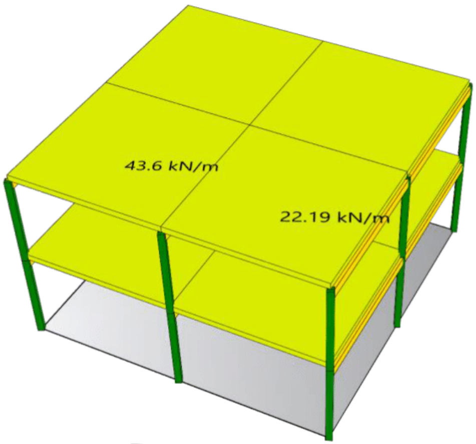
Self weight, q	18,73	[kN]
Superimposed dead load	12,5	[kN]
Imposed load	15,63	[kN]
ULS 6.10a	42,16	[kN]
ULS 6.10b	**60,96**	**[kN]**
Selected column (Glulam)	90x135 GL30h	
Self weight, q	0,052	[kN]

Check against Rhino (includes the self weight of the column):

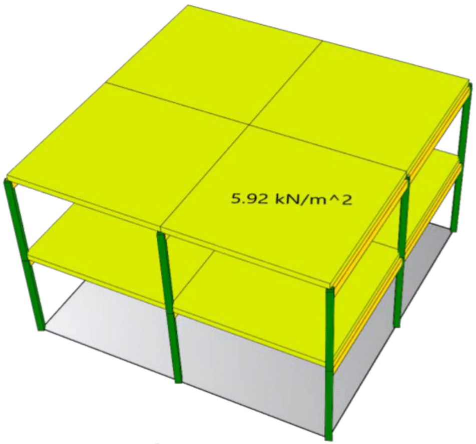
ULS 6.10b	61,02	[kN]
SLS frequent	39,09	[kN]



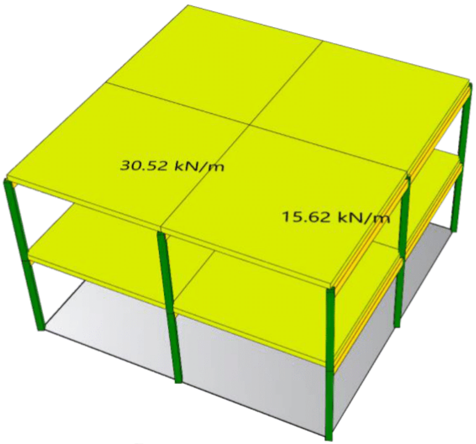
Slabs
ULS eq. 6.10b



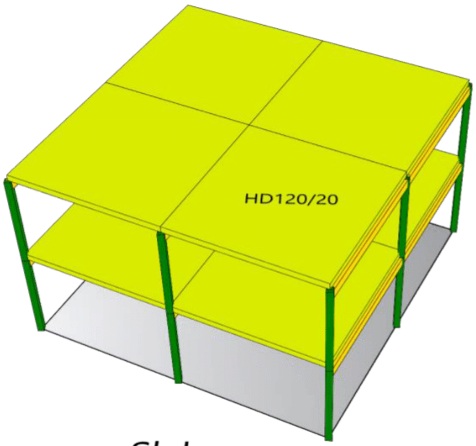
Beams
ULS eq. 6.10b



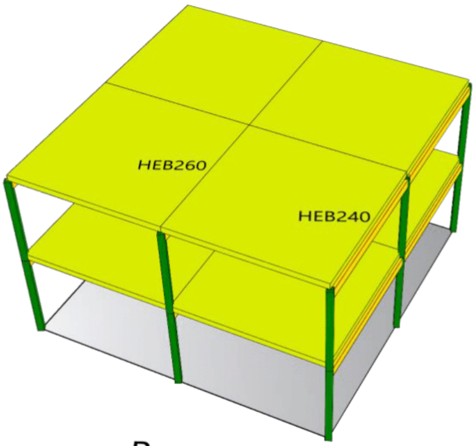
Slabs
SLS Frequent



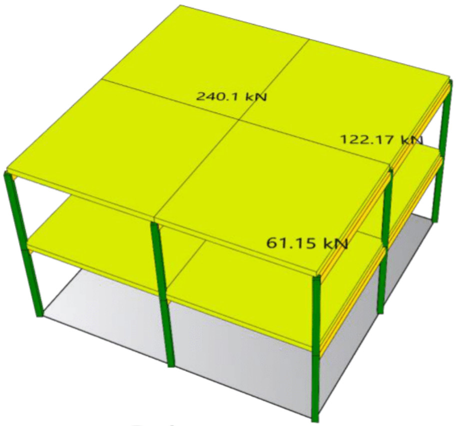
Beams
SLS Frequent



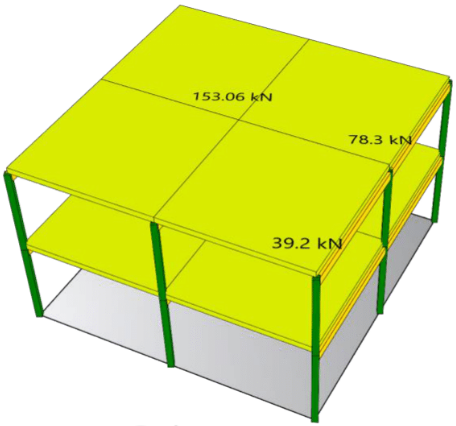
Slabs
Cross section



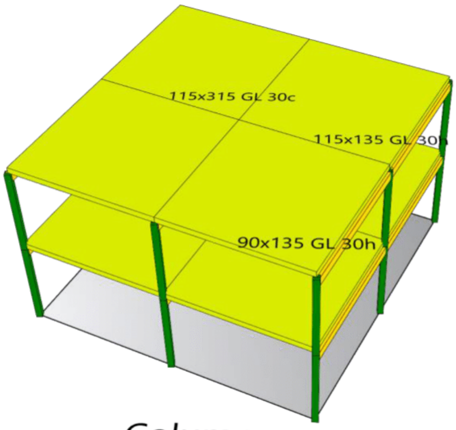
Beams
Cross section



Columns
ULS eq. 6.10b



Columns
SLS Frequent



Columns
Cross section

F

Interview

The results from the interview with Jonathan Söderqvist, VBK, are presented below. Question 1 through 5 are looking at the current work process and his experience. Question 6 and 7 are to find out more about the clients and question 8 to 12 aim to find out what he would want from this kind of tool being developed in this thesis.

1. **What are you looking at in an early LCA analysis?**

I am usually looking at what parts of the building that has the largest amount of emissions to target them. For example, the three elements with the highest environmental impact could account for up to 60% of the emissions, and they can sometimes be easy to reduce. Almost two thirds of the emissions can be cut from steel elements by switching to steel that is produced with a high share of recycled steel.

2. **How much time do you have allocated for early stage LCA in a project?**

That can differ very much, it mostly depends on the level of ambition of the project. Many companies do not charge specifically for the LCA analysis, it is just expected that it gets done. But as a guess, in the range of 8 to 20 hours depending on the detail level.

3. **How many design alternatives do you typically look at?**

Two or three alternatives usually, the time does not allow for more than that. But two or three are usually enough to give a clue where to look to make improvements.

4. **What kind of programs do you use when doing these kinds of assessments?**

I use either OneClick LCA or Excel. I have tried the Revit plugin that OneClick offers but it is not reliable. It can sometimes have a hard time reading all the elements properly, and sometimes the designer takes a shortcut when making the model, which makes it difficult to rely on the plugin.

5. **Have you used a similar tool? What is your opinion of that tool?**

I have used Carbon Designer 3D, but I was not very impressed. You set the building height, span lengths and the desired type of structural system. The outputs are quite messy and hard to grasp to be frank. They have a list of materials that are difficult to trace where it is used in the building.

6. **What types of buildings are VBK mostly working with?**

Before 2022 it was mostly office buildings and residential buildings, after 2022 it has been mostly industrial buildings. And for industrial buildings you are not required to hand in a climate declaration.

7. **What are the goal of the clients? To pass climate declaration? To gain certification points?**

It varies a lot, some clients just want to have the LCA done while other are looking at acquiring a certification. The clients that are interested in certifications are usually looking to pass Miljöbyggnad's targets, which are set to 30% reduction compared to the limits set in the climate declaration, I think.

8. **What functionality would you like to see in an early stage LCA tool?**

I would like to be able to get the early approximation and to be able to visualise it to the developer or decision maker. What part of the building that are responsible for what emissions for example. It would also be great to be able to compare alternatives, the best option would be to display them side by side, but at the very least you should be able to flip between them. What is good with option A, what is good with B?

I would also like to see that it is easy to use, as we currently are two, three people that do these kind of assessments. No one else has really wanted or dared to learn how to do them. My wish is that the entry barrier is low, which would let anyone participate and conduct these assessments, not just talking about the environmental impact. Because this is something that everyone should include in their work process for the early stages.

9. **What parameters do you expect have the largest impact on the embodied carbon?**

I think that span lengths and the height of the building have the largest impact. The load transfer between stories will have a significant impact on the amount of material that are needed in order to carry down the loads to the foundation. And also, material selection, of course.

10. **What outputs would you like to see in this kind of tool?**

I would like to see amount of emission and amount of material. And also, a cost estimate, as that could support your argument when it comes to arguing for a specific choice. I would also like to see the results per element type, columns, beams for example.

11. **What would you consider an acceptable margin of error for this kind of tool? When comparing to the final results.**

For a proper analysis I expect the difference to be quite low. But for an assessment with lower level of detail, maybe 10-15% error would be a good figure. Around 10% is in general considered to be a reasonable margin of error.

12. **Why would you like to use this kind of tool?**

I would like to use it to get a better understanding myself, but also to allow others at the company to get a better understanding. When we have a better understanding, we can sell it to the client and architects in a better way:
"This choice is going to have this effect on cost, flexibility, emissions, etc..."

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