Integration of Building Information Modelling and Life-Cycle Analysis in Early Structural Design; a Parametric Study

Master Thesis

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June 9th, 2022
Eindhoven

Preface

Studying at Chalmers University of Technology in Sweden introduced me to the concept of life-cycle analysis and how it applies to the built environment. Together with studying Structural Engineering and Design at Eindhoven University of Technology, it formed the basis for this thesis. With the increasing importance of reducing the carbon footprint of almost every sector, this master thesis was an opportunity to investigate how this can be achieved in the field of structural engineering. I want to thank the professors of Chalmers for the knowledge on LCA and the professors at Eindhoven for the guidance during this master thesis.

Abstract

The importance of sustainability is increasing every year, with many sectors trying to improve their carbon footprint. The building sector plays a major role in the world's carbon emissions, responsible for up to 40% of the total CO_2 emissions, with the structure accountable for a quarter of those emissions. Improvements have been made over the last decades, mainly focussing on the operational energy carbon emissions, reducing the carbon emissions per square meter significantly. However, the building sector is growing rapidly and effectively, outweighing the improvements resulting in a larger carbon footprint each year. With the considerable improvements in operational emissions, the embodied carbon, carbon released by constructing the buildings, becomes increasingly relevant and has an larger share of the total carbon footprint. Therefore, reducing the embodied carbon of buildings becomes more and more important.

Life-cycle analysis, or LCA, has been the standard methodology for assessing the environmental impact of services, products and processes. Therefore, this methodology can be applied to almost any scope and also the building sector. LCA could play a role in the design process of a building and its structure. However, currently, it is mainly used at a later design stage or after completion. The majority of the embodied carbon results from the structure of the building as a result of its material use. This leaves the potential to use LCA to reduce carbon structural design decisions, especially in the early design stages where the major global design choices are made. These design choices often cannot be changed in later designs without requiring large amounts of time and effort, increasing the importance of early sustainable design decisions.

Building Information Modelling, or BIM, is becoming the digital standard for almost all processes related to the building sector, such as design, construction, operation and maintenance. A design made within a BIM environment contains information about all elements used within the building. This same information can be used for performing an LCA. This leads to the basis of this thesis, developing a method in which LCA and BIM are integrated to show the environmental impact of the building design.

The early design stages give the largest potential for sustainable adjustments. This stage is often called the concept stage, in which multiple design variations are explored. These designs are not detailed and not near complete, but they set the basis for the rest of the design. Therefore, the goal is to explore different design concepts and compare them on their environmental impacts, in this case their embodied carbon. To do this, a parametric design tool will be developed. The parametric design allows for designing using a set of parameters which can be adjusted to create the desired design. This design method allows for a quick and straightforward generation of design concepts that can be explored on their embodied carbon. Grasshopper, a Rhino3D tool, will be used to develop this parametric design. The plug-in Karamba3D is used to perform structural analysis and assign cross-sections to the structural elements optimised for their minimum cross-sectional area. The tool is fully automated and

generates structural designs based on the design parameters set by the user and the boundary conditions.

The Structural Carbon Tool is used to perform an LCA, a Microsoft Excel-based tool calculating and visualising the embodied carbon. The parametric design tool allows for a live connection to Excel files, such as the Structural Carbon Tool, which will export the structural material data for the embodied carbon calculation. The Structural Carbon Tool is adjusted to read and filter the imported data automatically. The tool will match the material and volumes of the structural elements with environmental data gathered from Environmental Product Declarations, or EPDs. The result is an overview of embodied carbon caused by elements in the structure.

To investigate the potential of the developed methodology, a case study and a few parameter studies are performed. The case study aims to show the potential of using the integrated method as a design tool. Eighteen different structural designs, based on three different building shapes, are analysed to see their environmental impacts. The Structural Carbon Tool instantly visualises the results with which the engineers can make their conclusions and sustainable adjustments—showing that a higher building and the use of a shear wall are unfavourable compared to lower buildings and bracing systems. The parameter studies resulted in the first indications of the influences of a single parameter on the total embodied carbon. Indicating that the higher the building, the more embodied carbon. An increasing floor span has little influence on the total embodied carbon due to a decrease in the number of structural elements. An increase in reinforcement ratio reduces the embodied due to more slender beams and is also beneficial for non-structural embodied carbon due to the decrease in building height.

All in all, the developed method shows the potential of integrating LCA and BIM to make sustainable design decisions early on. The automated process allows quick design generation with almost instant embodied carbon results and design comparisons. The methodology also allows for research on specific design parameters that could set the basis for sustainable structural design guidelines if researched more extensively. A more developed and integrated method would further increase the potential and ease of use.

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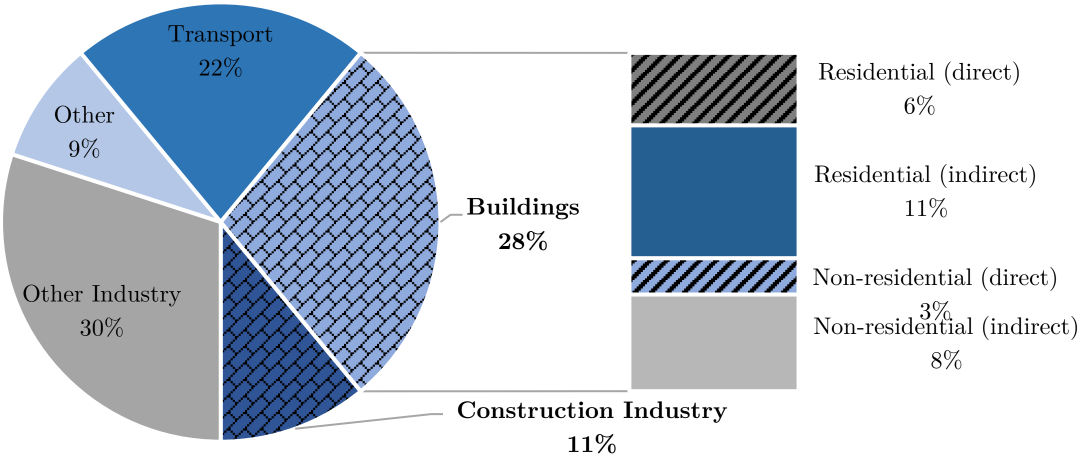
1 Introduction

1.1 Research Context

The building sector is one of the most significant contributors to global warming, with a large impact on the depletion of natural resources and the emission of greenhouse gasses. According to the 2017 UN Global Status Report (Abergel et al., 2017), the Building sector is responsible for approximately 39% of the global CO2 emissions (Figure 1.1). Most of these emissions come from energy use related to the use of the building, or operational energy, such as heating, cooling, and electricity. However, 11% is directly related to the construction industry. Since most of the CO2 emissions are related to building operations, this has been the main focus of sustainable improvements over the last decades, with a decrease of 1,5% per m^2 annually (Abergel et al., 2017). This means that the construction industry's impact increases relatively to the operational emissions every year, making it more relevant to reduce its impact.

Figure 1.1 Share of Global Energy-Related CO2 Emissions (Abergel et al., 2017)



All this becomes more relevant as the building sector is expected to grow rapidly over the following decades. With a majority of buildings expected to be built in the next two decades, mostly in countries with little to no building codes for sustainability. This significant increase in the number of buildings also leads to the important fact that the reduction in emissions currently achieved is outweighed by a large amount of extra gross floor area being built (Abergel et al., 2017). Thus, even though the sector becomes more sustainable, it will only increase in GHG emissions over the following years.

Therefore, the building sector will also need to focus on improving the sustainability of the physical building itself and its construction. Life Cycle Assessment (LCA) has been a tool to determine the environmental impact of all life stages for many products for decades. However, the application of LCA is limited in many sectors, and this also applies to the building sector. With this tool, the environmental impact of a building can be determined and analysed such that improvements can be made in areas that have large reduction potentials. Within the building sector, there is a significant potential to use this tool in combination with Building

Information Modelling (BIM), where the digital design could be instantly used to calculate its environmental impacts. However, currently there are a limited number of integrated tools. These tools often have limited ability or are still in development often due to a lack of commitment and costs of developing a tool of high accuracy, quality, and ease of use. Ultimately for an engineer, it would be ideal to be able to quickly know the impact of the design on multiple different impact categories. However, this would require extensive knowledge of LCA, which engineers do not have and are often not interested in learning. Therefore, in the building sector, especially the construction sector, the main category used is Global Warming Potential with its unit $kgCO_2m^2eq$, often referred to as Embodied Carbon (EC). This is the most relevant and well-known category, thus essential for ease of use and broad acceptance. Although this also means other relevant categories are currently left out, something that should undoubtedly be improved upon for future, more automated methods.

LCA has been used in the building industry more extensively in the past decade, but not to its full potential. The use of LCA has usually been after completing the design to generate a report and a sustainability score, often required for a green label. However, this means that LCA has not been used to design at all, and no improvements can be made anymore. In other words, LCA is often reactive and not proactive. This is a massive potential for LCA, and therefore it should be applied in earlier design stages to help make sustainable decisions and adjustments. The design of a building is a continuous process where most global decisions are made in the early stages. These decisions often determine a lot for the final design, so it is important to try and integrate LCA in the early stages, where changes can still be made without too many issues. Next to that research (Gholam, 2020) has shown that these global decisions have a much more significant impact on the reduction of EC than local element optimisation.

1.2 Problem Statement

To combat the increasing impact of the building sector on the environment more effort is required to make efficient and sustainable design choices. Where operational energy is reduced each year, there is still a lot of potential in embodied energy. LCA and BIM are both very efficient and valuable tools that have significant potential when used together, especially when used to design. Therefore, integrating these tools and use within the design process should be implemented and improved.

1.3 Research Goal

This research aims to explore and analyse the potential of using LCA in an early design stage using parametric design tools. To help the engineers or designers to make sustainable design decisions in the early stages of building design. By exploring the use of parametric design software for easily adjustable design choices, creating a BIM model with this software, and linking this model to LCA data, the goal is to show that integrating these software can be beneficial for reducing the embodied carbon of the building structure.

The research will focus on the structural design of the building as this is the majority of the embodied carbon, and its global design is often determined early in the design process. Elements that are not part of the main structure but do account for embodied carbon, such as floor finishing and windows, are also relevant and should be considered if an LCA study is done later in the design process. However, these elements are often not entirely dependent on early design decisions and are not feasible within the project scope.

1.4 Research Question

The beforementioned goal leads to a research question which is stated as follows:

> *'How can Life Cycle Analysis, Building Information Modelling and Parametric Design be integrated to assist designers in reducing embodied carbon emissions in the early design stages?'*

1.4.1 Sub-questions

The research question will be answered using the following sub-questions:

- How can parametric design generate quick and structural valid early designs?
- Which life cycle stages are relevant for embodied carbon in early design?
- How can the embodied carbon and its feedback be visualised?
- What assumptions and simplifications have to be made?
- Can an integrated method be used to generate guidelines?

1.5 Research Structure

The research will consist of five main stages, as shown in Figure 1.2.

1.5.1 Stages

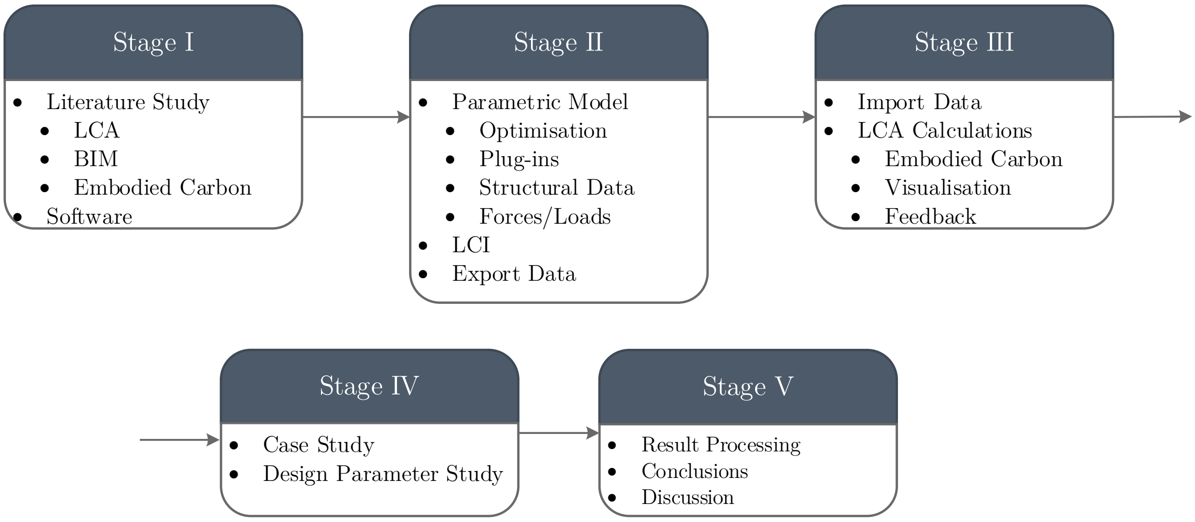


Figure 1.2 Stage Overview

1.5.1.1 Stage I

The first stage will focus on researching and defining the most important aspects of LCA, BIM, and the possible integration methods. This will mainly be achieved by doing a literature study on these topics individually and combined. It will be essential to understand their potential and limitations, as this will help define the project's scope and what will be achievable. This stage should explore the scope of the LCA study, the use of embodied carbon, LCA data, and which parametric software to use.

1.5.1.2 Stage II

The second stage will mainly consist of building the parametric model. This stage will be the most extensive and will require some continuous research on topics that arise during the modelling. The software which will be used, as defined in Stage I, will need to be able to model and generate a structure feasible and realistic structure based on user inputs. Therefore, research will be done into plug-ins and manual methods for the optimisation of elements such that it will create consistency in the design process. Next to that, the loads and forces that apply to the structure must be researched and defined. Finally, the software should deliver a bill of quantities or Life Cycle Inventory (LCI) of the generated structure. This can be exported to another software for the LCA analysis and requires some data structuring.

1.5.1.3 Stage III

In the third stage, the LCA calculation will be done. There are multiple options, and Stage I should be the most feasible option. The LCI will have to be imported from the BIM software and matched with its correct category and environmental data to do an LCA calculation on the embodied carbon for each defined life cycle stage. This also results in a total embodied carbon score that can be normalised compared to other design options. This will all result in a proof of concept where the designer will get the embodied carbon results of its design and can easily make adjustments and compare his designs. Next to that, it will also allow investigation of the impact of specific design decisions and the final embodied carbon of the design.

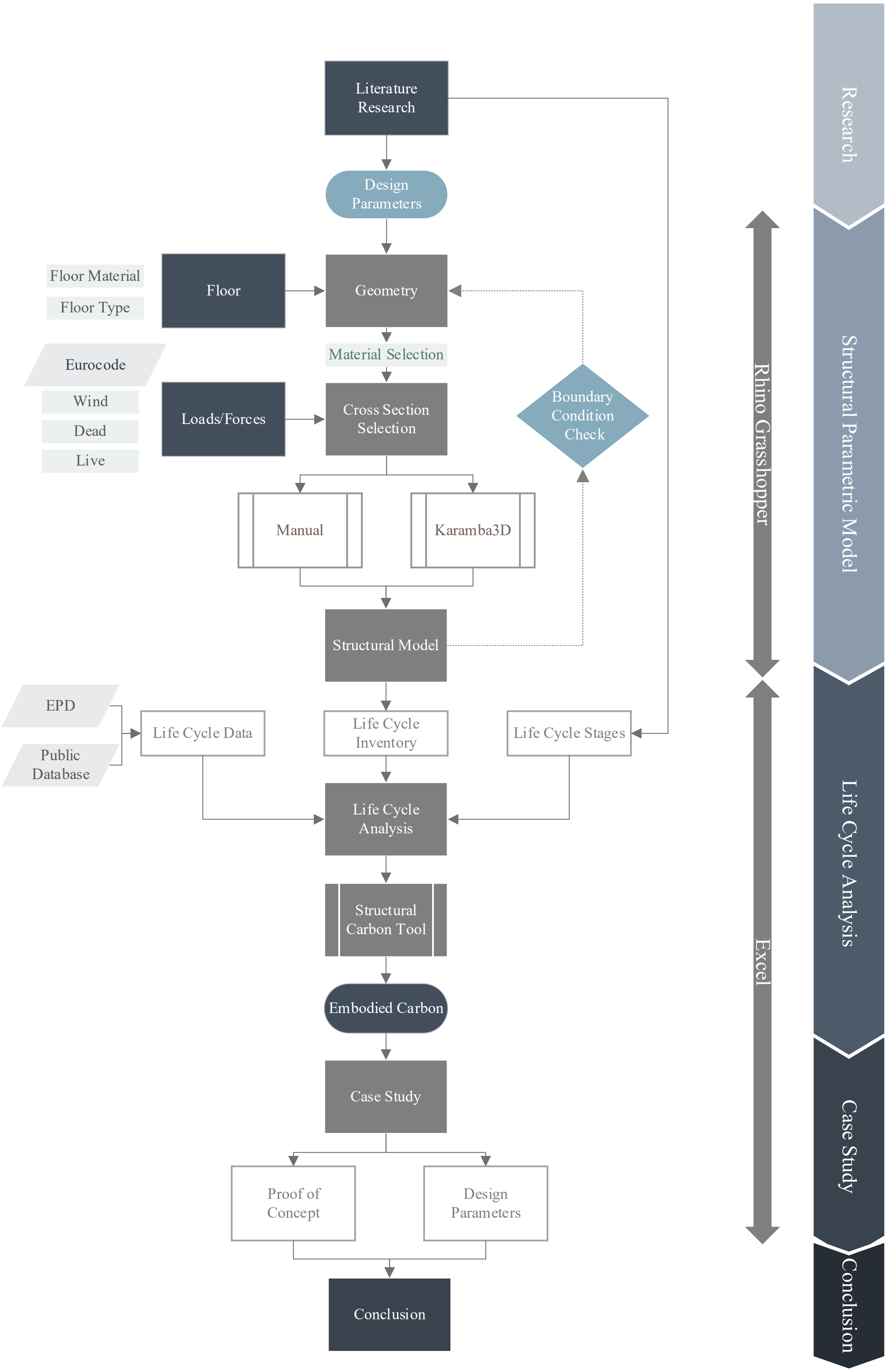
1.5.1.4 Stage IV

This stage will be a case study to show the proof of concept and the potential of this research. The case study will help show what impact decisions have and how results can assist the designer in making changes in the design to improve the total embodied carbon. Next, a study will be done on specific design parameters to see their impact if their design values are adjusted. This will result in an overview of favourable and unfavourable design decisions regarding total embodied carbon. All this will require some good data structuring for the final analysis.

1.5.1.5 Stage V

The proof of concept, case study, and parameter study will be analysed in the fifth and final stages. The proof of concept will mainly consist of practical results where both the case and parameter studies will need an analytical and statistical study. This will result in an overview of the potential of applying LCA with BIM in an early design stage, showing the model's practicality and the conclusions from the processed results of both the case and parameters study. Finally, this stage will report all the final data and finish the thesis.

1.6 Process Overview



2 Literature Research

2.1 Embodied Carbon

With the increased demand for sustainability within the built environment, more focus will have to be put on buildings' embodied greenhouse gas (GHG) emissions (Victoria & Perera, 2018). The term embodied refers to the construction, production, use, and end of life of the building and its materials. The impact category of Global Warming Potential (GWP) is often used to describe greenhouse gas emissions. However, multiple greenhouse gasses influence the GWP therefore, the most common GHG carbon dioxide (CO_2) is used to describe this category. The other gasses like methane are substituted for their equivalent impact in CO_2. Together this results in embodied carbon being the definition used for describing the embodied GHG emission of a building, with its unit being $kgCO_2eq$, eq for equivalent CO_2 values of other GHG.

Reports (World Green Building Council, 2019) show that embodied carbon will account for about 50% of the building's total greenhouse gas emissions by 2050. This is mainly attributed to the improvements made within the operational emissions, such as heating and electricity. These improvements lead to a relative increase in the embodied carbon, but also the improvements are accompanied by an increased material use (Röck et al., 2018). Influencing the embodied carbon directly with building material and indirectly by increasing loads.

2.1.1 Life Cycle Analysis

LCA has been accepted as the standard for assessing the environmental impact of buildings (Röck et al., 2018). The LCA consists of 4 different life cycle stages, as shown in Figure 2.1.

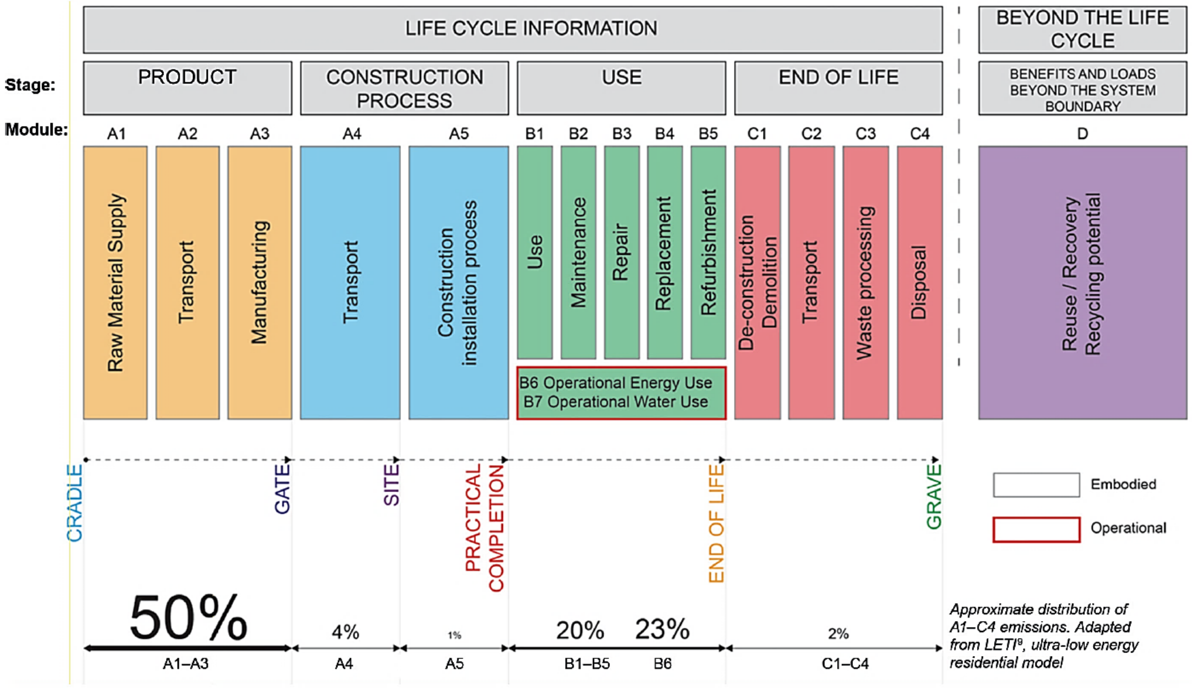


Figure 2.1 Life Cycle Stages (Gibbons & Orr, 2020)

First is the Product stage (A1-A3), which mainly considers the impact of the extraction of resources to the manufactured product. If recycled products are used, this stage will have a lower impact. This stage is also often referred to as Cradle to Gate. Secondly, the Construction stage (A4-A5) accounts for the impact of transport and construction of the building, including the impact of machines and material waste. The third stage is the Use stage (B1-B7) which consists primarily of impacts relating to maintenance and, very importantly, operational energy. As mentioned, the operational impact is not part of EC, which means that A6 and A7 will not be considered. The last stage is the End-of-Life stage (C1-C4) which accounts for the impacts of the destruction and disposal of the building—also referred to as the Cradle to Grave approach. Lastly, there is the D stage, where the potential positive effects of recycling and reusing can be shown (Gibbons & Orr, 2020). This is very dependent on the design of the building.

Figure 2.1 also shows that the Product stage can be up to half of the embodied carbon of a building's life cycle. This stage is directly related to the material choice, volume, and manufacturing, and it further shows the relevance of making educated sustainable design decisions. The most important stages for structural design are A1 to A5, with the Product stage accounting for most of the embodied carbon (Helal et al., 2020). The end-of-life stage is also considered for calculating embodied carbon for buildings. Stage D is up to the designer to consider depending on the recyclability of the structure (Gibbons & Orr, 2020).

2.1.2 Standardisation

Environmental Product Declarations (EPD) are standardised documents (ISO, 2006) that encompass the life cycle of a product and quantify its performance (Zeng et al., 2020). An EPD is the final report of an LCA analysis showing an overview of what was included in the LCA and standardised results of the impact categories of a product. The main goal of the EPD is to have a standardised system in which products can be compared based on their environmental impacts (Häkkinen et al., 2015). This system benefits EC calculations as GWP is always included in an EPD. However, the life cycle stages considered are not always Cradle to Grave since many manufacturers only consider the Product stage or Cradle to Gate. This is the most relevant stage since they only produce a product and then sell it; thus, the later life cycle stages are in the hands of another party. This means that even though many more EPD are produced, they do not always contain the desired information.

An important note for calculating embodied carbon is the variability in life cycle data per manufacturer and country (Victoria & Perera, 2018). Also, data availability can be a challenge since not every country demands this data to be provided or public (Zeng et al., 2020). The scope of the data is also very relevant for the final results as manufacturing is significantly different throughout the world (Häkkinen et al., 2015), meaning that North-Western European data is significantly different from Asian data. Not only does manufacturing play a role, but also the availability of resources influences the data a lot. Therefore, embodied carbon results from one country are relatively regional and do not apply to the whole world, increasing the call for more standardisation. EPDs can be found across multiple platforms, such as The International EPD® System(EPD International AB, 2022), which aims to make the data accessible.

With the increased awareness of the building sector's environmental impact, the interest in green labels or certificates on the finalised buildings has increased significantly. Many countries have developed their assessment methods and rating systems over the past decades (Häkkinen et al., 2015). However, other countries have adopted these methods, especially the systems BREEAM (Dutch Green Building Council, 2009) and LEED (U.S. Green Building Council, 1998) are widely used to rate a building's sustainability.

2.2 BIM and LCA

The use of BIM has been vastly increasing within the last years, therefore, giving an excellent opportunity for LCA to move towards this system (Röck et al., 2018). A large increase in research performed on topics such as LCA and embodied carbon shows that awareness of their importance is growing. They also contribute to the importance of improving and standardising the methods to perform LCA studies. Even though both BIM and LCA are increasingly used and developed, the integration of these methods has been minimal. This is primarily because BIM does not provide the details and data LCA studies require (Roberts et al., 2020).

Another challenge within the integration of BIM and LCA is the often-required knowledge to perform an LCA. A tool to improve the understanding of LCA results is using different visualisation tools. Too much information, especially quantitative data, will overwhelm and hinder a designer from processing the results (Roberts et al., 2020). Visualised results can help designers understand and make more intuitive design choices, especially when comparing design variations (Röck et al., 2018).

2.2.1 Early Design Applications

LCA use within the early design stages is often limited due to uncertainties within the design and lack of detailed information (Röck et al., 2018). Resulting in the use of LCA often after finishing design such that all information is available, meaning it is reactive LCA instead of proactive (Roberts et al., 2020). LCA is most efficient in the LOD 100 stage and not at LOD 300, which is currently done. However, multiple issues arise at this stage. Firstly, is the almost complete lack of integration between BIM and LCA at this stage. Next is the limited possibility of extracting relevant data for LCA (Rezaei et al., 2019). However, the LCA data is often also not adjusted for the simplicity of the LOD 100 stage. Therefore, LCA data needs to be adjusted for early BIM model stages to compare results (Roberts et al., 2020).

2.3 Existing Tools

Increasing awareness of LCA use has led to the development of multiple LCA tools. Some of which aim to reach many users by providing straightforward use of the software. One-Click LCA is one of the most advanced yet simple to use tools that can be used within the built environment. At the start of this project, One Click LCA aims to integrate their tool more efficiently into different BIM software. Another LCA tool, which aims more at structural engineers, is the Structural Carbon Tool developed by Elliot Wood and the Institute for Structural Engineers. This Excel-based tool will generate visualised embodied carbon results using user-defined material specifications and volumes. These tools partly have the same goal as this thesis and can therefore be used as inspiration for the to be developed methodology.

3 Parametric model

A parametric model will be used for the generation of different designs. With the use of design parameters, multiple design variations can be generated quickly and used for further analysis and comparisons. This parametric model will be built using Grasshopper (Rutten, 2014), a visual scripting tool used within the Rhinoceros7 (McNeel & Associates, 2020) design software. This model will aim to create a tool in which design parameters as input will generate a structural model that can be exported to be used in an LCA study. Using Grasshopper will also allow visual design feedback within the Rhino software, which can validate design choices and create design variants with immediate visual feedback.

3.1 Plug-ins

The parametric model will also need the help of multiple plug-ins that can be used within Grasshopper. These plug-ins are made by third party entities and can be used for free or with a license if required. The most essential plug-in for this model will be Karamba3D (Clemens Preisinger & Bollinger und Grohmann ZT GmbH, 2021), which is a parametric structural engineering tool used to calculate and generate structural models from user design input. This tool will be used to optimise and validate the structural elements. Another important tool is the plug-in TT Toolbox (CORE studio, 2017) which provides a component for exporting data from Grasshopper to Microsoft Excel (Microsoft, 2022), in which part of the LCA will be done. Lastly, the component Metahopper (Andheum, 2019) is used for its components that help to improve the workflow and usability of the parametric model. Table 3.1 shows the plug-ins and their use within the model. Their use will be explained in more detail throughout this chapter.

Table 3.1 Plug-in Functionality

Plug-in	**Functionality**
Karamba3D	▪ Structural Analysis o Loads o Cross-section Selection o Connections o Supports o Deformations ▪ Structural model o Element Inventory
TT Toolbox	▪ Excel Settings ▪ Data export to Excel
Metahopper	▪ Streamlining simulation process ▪ Clean visual script

3.2 Input Parameters

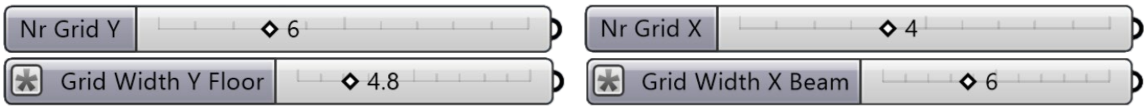
Multiple input parameters will have to be defined for the structural model's design. The parameters are geometry-related or material-related, as those two together will make up most of the design choices. These input parameters should be the structural model design's start and end in the finalised model. When the designer sets these parameters, the model should give live visual feedback of adjustments done on these parameters and generate a structural model for the design. There will be seven design parameters in total which will be elaborated below. Together these parameters will allow the designer to analyse the impact of changing the design whilst also making it possible to investigate the individual impact of these parameters.

3.2.1 Geometric

The first few parameters will determine the geometry of the structure. These parameters can be used to make visual design variations.

3.2.1.1 Grid dimensions

The grid dimension plays a prominent role in the size of the building and directly determines the lengths of the floor and beam elements. The grid can be adjusted with steps of 1,2 meters in the beam direction, and this increment is chosen as many floor systems have a width multiple of this size. The direction of the floor span is free to be chosen with 0,1 increments, and this means that the grid also determines the floor span and, thus indirectly, the floor dimension. As the design process is still in an early phase, these step sizes will allow for variation and optimisation whilst not demanding immense computing power and detailing.



Nr Grid Y ◇ 6

Nr Grid X ◇ 4

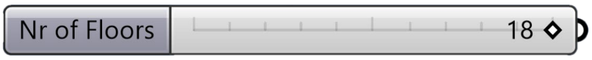
Grid Width Y Floor ◇ 4.8

Grid Width X Beam ◇ 6

Figure 3.1 Parametric Grid Dimension, Sliders

3.2.1.2 Nr. of Floors

The second geometric parameter is the number of floors. This parameter will determine the building height and the total floor area of the building. In combination with the grid dimension, multiple building shapes can be generated with similar floor areas, allowing for variating designs with the same floor space. This parameter will also directly influence the wind load acting on the building and the total load on the columns. This parameter can be increased from 1 floor to 18 floors.



Nr of Floors 18 ◇

Figure 3.2 Parametric Number of Floors Selection, Slider

3.2.1.3 Free height

The free height per floor will be set to the Bouwbesluit (Rijksoverheid, 2012) guideline minimum of 2,6 meters. Since it is in the early design stage, the complete floor and ceiling systems are still unknown. Thus, a decision is made to define the free height as the distance between the top of the structural floor and the bottom of the beams. This parameter will start at 2.7 meters and can be increased by 0,05 meters each step for design variations. Together with the number of floors it will determine the total building height. A small loop will have to be created to set the floor-to-floor height, which is used for the design geometry, based on the height of the chosen beam elements and the free height conditions.

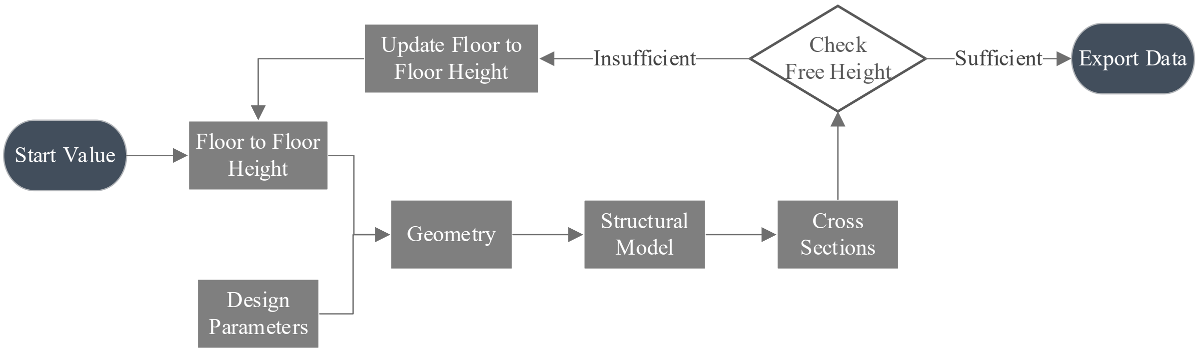


Figure 3.3 Flow chart Free Height check

3.2.2 Stability

Literature studies have also concluded that the structural system plays a significant role (Moussavi Nadoushani & Akbarnezhad, 2015); therefore, this will also be a design parameter. Three options will be available to be chosen, shear walls, bracing, and moment fixed connections. The shear wall will be made of reinforced concrete, and the bracing will be either steel or timber.

Bracing

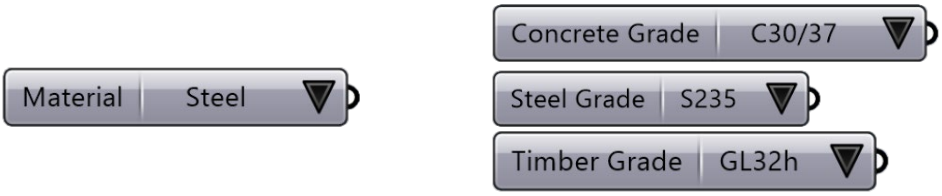
Figure 3.4 Parametric Stability Selection, List

3.2.3 Material

Next to geometric parameters, there are also a few parameters related to material choice. These parameters do not influence the shape of the building but will have a considerable influence on the dimensions of elements and the amount of material used.

3.2.3.1 Beams and Columns

The beams and columns each have three different material options: Concrete, Steel, and Timber. This means there are nine possible material combinations to choose from. After this, the user can choose the material grade, allowing for more variation in design and more freedom. The material choice and its grade will significantly impact the dimensions of these elements and the data related to the LCA. The optimisation process for the cross-sections will be different for concrete elements due to the limited reinforcement capabilities of the Karamba3D. The material properties used are provided by the Karamba3D tool itself.



Material Steel

Concrete Grade C30/37

Steel Grade S235

Timber Grade GL32h

Figure 3.5 Parametric Material Property Selection for Beams and Columns, Lists

3.2.3.2 Reinforcement ratio

The limited implantation of reinforcement leads to some manual workarounds to compensate for this limitation, which will be further explained in the optimisation chapter. However, the reinforcement ratio can still be used parametrically to see its influence on the design and environmental impact. The reinforcement ratio will allow for a more slender element design, thus decreasing the concrete volume whilst increasing the reinforcement volume. This decrease will influence the floor-to-floor height, and even total building height as slender beams will lead to meeting free height requirements quicker.

Reinforcement % 3

Figure 3.6 Parametric Reinforcement Ratio, Slider

3.2.3.3 Floor-type

The floor can be chosen from a list of pre-defined floor types. These floor types can be divided into three material categories, concrete, timber, and composite. The thickness of the floor will be based on the floor span and the data provided by the manufacturers. As mentioned, the width of the floor will be a factor of 1,2 meters for ease of use.

Material Hollow Core Slab

Figure 3.7 Parametric Floor Selection, List

Table 3.2 Input Parameters

Input Parameter	Type	Step size	Nr. of Options
Grid Dimension X [m]	Slider	1.2	-
Grid Extension X	Slider	1	-
Grid Dimension Y [m]	Slider	0.2	-
Grid Extension Y	Slider	1	-
Number of Floors	Slider	1	18
Free Height [m]	Slider	0.05	-
Stability	List	-	3
Material	List	-	3
Material Grade	List	-	3 to 15
Reinforcement Ratio [%]	Slider	0.5	8
Floor Type	List	-	3

3.3 Geometric model

The first input parameters will determine the geometry of the model. This geometry will firstly be built up with lines. These lines will represent all the elements that are used within the model and can be given their specific structural properties based on the input parameters. The model will consist of multiple elements: Beams, Columns, Floors, Walls, and Bracing. The lines are given artificial volumes for visual purposes to help the engineer design the structure, as seen in Figure 3.8.

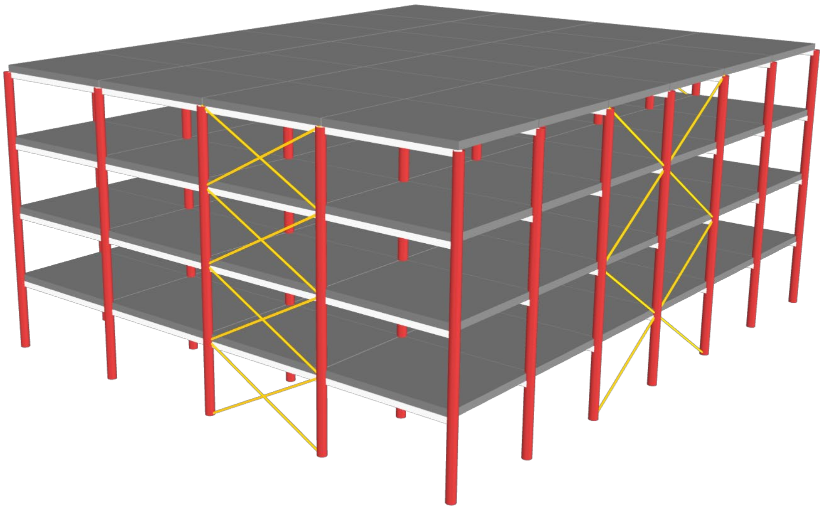


Figure 3.8 Geometric model in Viewport, Example

3.3.1 Columns

The columns of the geometric model will be defined by two input parameters: Grid dimensions and Free height. The grid dimensions will define the location of the columns, while the free height will determine the length of the columns. The input parameters that define the structural properties of the columns are the material and the joints based upon the stability. The support connections are also relevant for the columns and are assumed to be fixed at all columns located on the bottom floor.

3.3.2 Beams

The same input parameters define the beams as the columns and span in the largest grid direction such that the floors will have a shorter span. The beams are located on every floor and span between two columns. The roof beams will span between the top of the top columns and can be defined independently of the other beams. The material will define the structural properties again, and the stability system determines the joints.

For all line elements to be used in the structural analysis and optimisation, they need to be converted to a Beam. This conversion will be done with the component LineToBeam in which the lines can be entered and given relevant properties. This process must be done for each group of elements, such as columns, beams, and roof beams. The geometry of the lines will go into the Line input. With the Id input, these lines can be given an Identifier which can later be used to perform actions on elements with a specific Identifier. The elements can also be given a cross-section; however, this is only needed if Karamba3D itself will not optimise the elements. This component turns the lines into elements with structural properties that can later be used for structural analysis. The options for this component will be left to the default settings.

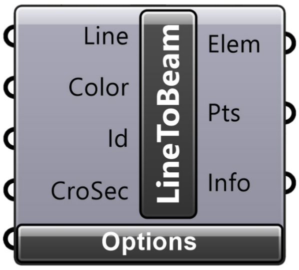


Figure 3.9 Karamba3D Line To Beam Component

3.3.3 Floors

Lines within the geometric line model will represent the floor. Therefore, it is important to note that the floors are connected to the beams every 1,2 meters as this is the defining factor of the floor width. The joint of the floor will be modelled as a hinged floor, thus free to rotate along the Y-axis but fixed along the X and Z-axis. This way, the floors will have diaphragm actions and create stability for the structure. The other structural properties will follow from the cross-section and the material of the chosen floor. The cross-section itself will be based on the data provided by the manufacturer and floor span.

3.3.4 Stability

The stability of a structure is essential, and the way it is achieved influences the element dimensions significantly. Research (Moussavi Nadoushani & Akbarnezhad, 2015) has shown that the structural system also significantly impacts the embodied carbon results. Therefore, for this model, it is chosen to use three different methods of structural stability; shear walls, bracing, and fixed connections.

3.3.4.1 Walls

Shear walls are very common and can be applied in many different ways. For this project, the shear walls will be located on the outside of the structure on all four sides. The design of shear walls is very complicated and thus has been simplified for this research. Dimensions of the wall will be the same as the grid dimension of the respective side and across the entire height. The thickness is based on the typical value of 200 mm as used in research (Bozdogan, 2013)(Sharma et al., 2018). The thickness can be decreased over the height of the building, but this has been excluded as the number of floors will be limited in this research. However, this must be noted in the final results.

3.3.4.2 Bracing

Steel elements will be used in a cross pattern on each building floor for the bracing. Many of the same conditions for shear walls will also apply to allow for fair comparisons. Thus the location of the braces will be the same as the shear walls. The elements will only be able to resist normal forces as their purpose will be to create stability using tension. The cross-sections will be chosen by Karamba3D and will be uniform, along with the height of the building for each side.

3.3.4.3 Fixed Connections

The last option is the use of fixed connections. This option will set all connections between elements to moment fixed, and the building will be entirely made of a frame structure. The main issue that will arise for this type of stability is the relatively large deformation across the building height and will require stronger and stiffer components to stay within limits.

3.4 Loads

The loads applied on the elements follow the guidance set in EN 1990 and EN 1991 (European Committee for Standardization, 2019). The load combinations used in this model all follow the Ultimate Limit State (ULS) design, and the function of the building will be an office.

3.4.1 Permanent load

The permanent loads acting on the structure will consist of the load caused by the self-weight of the structural elements (G_{kw}), the loads caused by the finishing and permanent services (G_{ks}), and the load of the façade (G_{kf}). The self-weight will be based on the volume of the element and its unit weight. The finishing and permanent services are assumed to cause a load of $\underline{3\ kN/m^2}$ (Curbach & Just, 2011), and the load of the façade is assumed to be $\underline{8\ kN/m}$ and is applied to the exterior beam elements. The total permanent load, Eq. 3.1, acting on the structural elements differs per location within the structure; there, the load is determined for each element individually, taking into account only the necessary loads for that element.

$$G_k = G_{kw} + G_{ks} + G_{kf} \qquad 3.1$$

3.4.2 Variable load

The variable loads consist of imposed loads due to the use of the building and the environmental loads such as the wind. The imposed load applied is $\underline{2{,}5\ kN/m^2}$ follow from EN 1991-1-1 Table NB.1 – 6.2, which can be seen in Appendix A, Table A.5. The wind load will be elaborated further below.

3.4.2.1 Wind Load

To analyse the influence of material and geometric parameters, it is also necessary to consider wind loading. The wind significantly influences the stability and, thus, necessary structure stiffness. The wind is also variable over the height of the building, and thus the geometry will also influence the wind load applied, as is described in NEN 1991-1-4 (NEN, 2011b). Table NB-1 of the NEN 1991-1-4 will be used for the extreme wind loads required for Eq. 3.2. It is assumed that the building is located in a built-up area within zone II. The value of q_p follows from reference height z_e and Appendix A, Table A.3. The pressure coefficient c_{pe} follows from Table NB.6 – 7.1 of NEN 1991-1-4 zone D, shown in Appendix A, Table A.4.

$$w_e = q_p(z_e)c_{pe} \tag{3.2}$$

with:

- w_e is the external wind pressure
- $q_p(z_e)$ is the extreme pressure at z_e
- z_e is the height of the building
- c_{pe} is the pressure coefficient

The wind load will be applied in four directions: x, -x, y, and -y. This will cover most of the important wind directions and is sufficient for the early design stage. The building is variable in size in both horizontal axis; therefore, the wind load will be calculated for both the x and y-axis individually, and the load will be applied to the façade of the building in the appropriate positive or negative direction.

3.4.3 Load Combinations

To apply the loads, they will be combined using the ULS load combination as stated in NEN-EN 1990_2002 (NEN, 2011a). Table NB.4 of the Eurocode provides the values for the partial factors of γ_g and γ_q, 1,35 and 1.5 respectively, seen in Appendix A Table A.1. The combination factor ψ for variable loads is 0,5 and will be applied to the wind load and follows from Table NB.4 shown in Appendix A Table A.2. Combining all the factors results in the load combination Eq. 3.4, which will calculate the loads applied to each element.

$$\gamma_g G_k + \gamma_q Q_{k,1} + \psi\gamma_q Q_{k,w} \tag{3.3}$$

$$1.35G_k + 1.5Q_{k,1} + 0.75Q_{k,w} \tag{3.4}$$

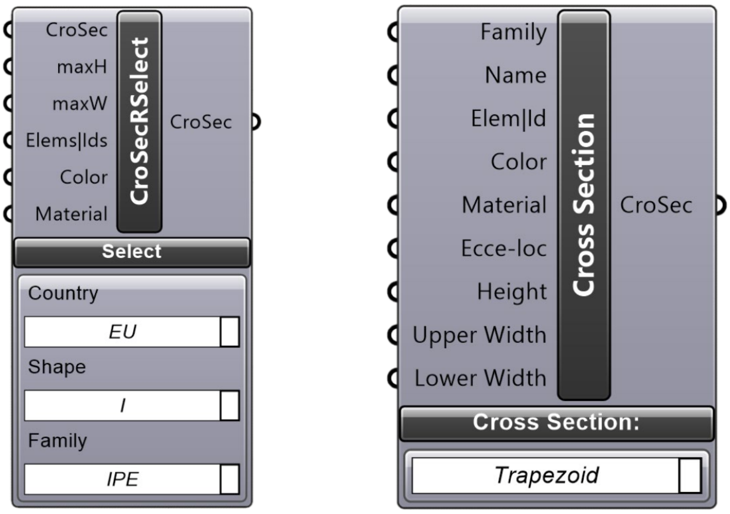
with:

- γ_g is the partial safety factor for permanent loads
- G_k is the permanent load
- γ_q is the partial safety factor for variable loads
- $Q_{k,1}$ is the imposed variable load
- ψ is the combination factor
- $Q_{k,w}$ is the imposed wind load

3.5 Cross-sections

There are two ways to define the cross-sections available to the tool. First of all, Karamba3D provides an extensive list of cross-sections with all their relevant properties. These cross-sections can be filtered using the Cross-Section Range Selector (CroSecRSelect), which can filter the cross-sections based on geometrical properties and material. It is also possible to set the range manually by choosing a value from the drop-down menu at the bottom of the component, as shown in Figure 3.10(a), where IPE cross-sections have been used as an example.

However, the list provided by Karamba3D is mainly focused on standard steel element cross-sections; therefore, another component will be used to generate a list of rectangular cross-sections which can be used for concrete and timber elements. The trapezoid shape option, Figure 3.9(b), will be used as there is no direct rectangular option. By keeping the Upper and Lower Width the same, it will be a rectangular cross-section. The height of the cross-section will always be equal to or larger than the width as this is more suitable for the moment resistance. The name of each cross-section will be its dimensions in millimetres. These two lists of cross-sections together will give a large database to choose from and includes all relevant cross-sections.



Country: EU

Shape: I

Family: IPE

Cross Section: Trapezoid

Figure 3.10 Karamba3D Cross-Section Range Selector (a) and Cross-section Component (b)

The Cross-Section Range Selector will be used for the list of steel sections, whereas the Cross-Section component will create the list for concrete and timber elements. These lists will all be combined such that they can later be filtered based on the Material input parameter set by the user. This filter allows the user to set the Material and its Material Grade to filter out the relevant cross-section and apply the correct material grade for the specified elements.

3.5.1 Karamba3D Optimisation

Since the entire model should be generated based on the input parameters, creating an automated cross-section selection process will be necessary. There are two main methods used to assign the cross-sections for the structural model. The first one is the plug-in Karamba3D which allows for cross-section optimisation. Even though optimising cross-sections is not the goal of this parametric model, it will create consistency in assigning these cross-sections, and most importantly, this optimisation is entirely automated.

3.5.1.1 Assemble

Before the cross-section selection can start, the geometric model must first be fully defined and given its structurally relevant properties. This is done using the Assemble competent, as shown in Figure 3.11. This component has nine inputs, of which six will directly be used for this tool. Firstly the elements(Elem) are the lines defined in the geometric model; the joints(Joint) and supports(Support) define the way these elements are connected and the foundation. All loads will go into the Load input, and each element will be given a cross-section(CroSec) to begin with. The Set input defines the name for a set of elements that will be considered a group from this point on. The inputs points(Pt), materials(Material), and duplication filter(LDist) are already defined earlier in the process when the elements and cross-sections themselves are defined.

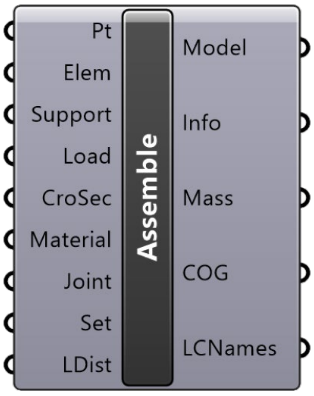


Figure 3.11 Karamba3D Assemble Component

3.5.1.2 Cross-section Optimisation

The only output of the Assemble component used within the tool is the model output which contains the assembly of all earlier inputs and turns it into a model that can be used for Karamba3D calculation components. This output will be used as input for the cross-section optimisation component OptiCroSec (Figure 3.12). The component has six inputs and a few more settings. As mentioned, the model input will be connected to the model output of the Assemble component. All elements that will have their cross-section assigned by this component will be selected based on their identifiers (ElemIds); these identities are given to the elements in the geometric modelling phase. GroupIds can be used to group elements such that their cross-section will be identical, with the largest necessary cross-section of these elements being applied to all.

The list of possible cross-sections will go into the CroSec input, where each cross-section list is also linked to a specific element or group such that only these cross-sections can be assigned to those elements. The optimiser will choose the first item that satisfies the structural requirements. Therefore, the list is, and must be, ordered based on their most favourable property, which in this case is the cross-sectional area, as this would lead to the least amount of material used within the structure. The utilisation can be set with the MaxUtil input, and the maximum displacement can be set with MaxDisp, where a single value will account for the entire structure. A list of displacement values has to be entered, matching each element to set a displacement limit for each element.

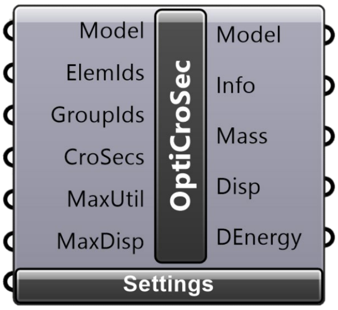


Figure 3.12 Karamba3D Cross-section Optimisation Component

There are a few settings that are important for this component. The first setting is the ULS Iterations which defines the number of optimisation iterations done for the ULS loading. A too-small number might lead to incorrect selection, while a large number will increase the computation time; therefore, the base value of 5 is used. Varying this value did not result in any significant different cross-sections to be selected. The following setting is the Displacement Iterations, which determines the cross-section based on displacement criteria. Like the ULS Iterations, the base value of 5 will be used after no clear deviations arose from varying this value. Another important setting is the number of samples taken along each element for which it will be checked on its cross-section resistance. The elements will be checked based on three samples. Furthermore, the elements will be based on elastic design and as a non-sway system.

3.5.1.3 Eurocode 3

To optimise the steel cross-sections, the Karamba3D component applies procedures from Eurocode 3, EN 1993-1-1 (NEN, 2021). This method calculates the cross-sectional forces according to EN 1993-1-1 Appendix B. The cross-section will be checked for normal force, biaxial bending, torsion, and shear force to determine the required cross-section (C. Preisinger, 2013). A similar method will be used to determine cross-sections of other materials. Cross-sections of Class 4 will also be checked on local buckling, which will apply to the steel cross-sections. The optimal cross-section is chosen based on the first option on the list that satisfies all requirements. This allows the user to order the cross-section in the favourable order, either based on the minimal cross-sectional area, minimal height, or another property if desired. However, this order of data must be set by the user itself and used as the cross-section input for the optimiser component. In this study, the principle of minimum weight is used; therefore, the smaller cross-sectional area will be the order of the cross-sections. This entire procedure will be applied to every element set to be optimised with the component input. The structural model is also visible in the viewport, as seen in Figure 3.13.

The output gives a lot of information; however, the only output needed is the model output. This model output will now contain the complete structure of the parametric design and all its information. This model can later be used to extract relevant information regarding the elements and the material used which will be needed for the LCA.

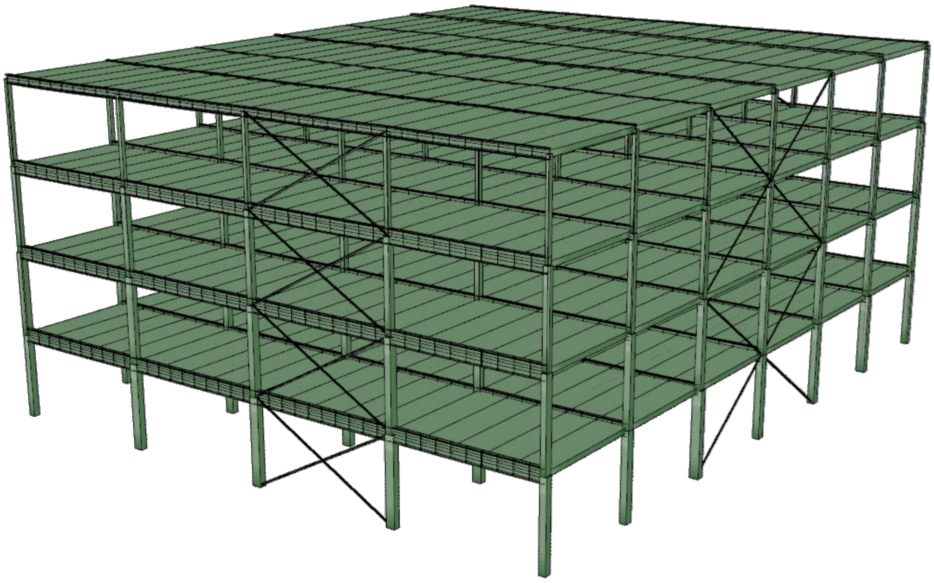


Figure 3.13 Structural Model in Viewport, Example

3.5.2 Manual Optimisation

A limitation of the Karamba3D cross-section optimiser is the lack of reinforced cross-sections. This limitation will need a workaround for many concrete cross-sections, especially those loaded in bending. Therefore both the reinforced concrete beams and the floors will be manually optimised. This optimisation will be less extensive than the Karamba3D optimiser and mainly focuses on bending and shear forces. Timber beams will also be optimised manually because deflection, or SLS, will most likely be the determining factor in the cross-section design. Therefore a separate optimisation for the SLS conditions will be made. The only rectangular cross-section will be considered, with the height always larger than the width defined in 3.5 Cross-sections.

3.5.2.1 Fictive E-modulus

Since the cross-section for the before mentioned elements will be optimised according to manually set conditions, these elements will already have a cross-section when entered into the Assembly model and, therefore, also in the model used by the cross-section optimiser. This means that the structural properties must be accurate so that the optimiser will use these properties when optimising the other elements. This is mainly important for the stiffness and thus deformation of the elements and structure. For these reinforced elements, the primary material, usually concrete, will be used for the material properties; however certain attributes need to be compensated for the reinforcement. Again, these adjustments focus on the stiffness, in other words, the product of the modulus of elasticity E and the second moment of inertia I.

The NEN-EN-1-1 2005 (NEN, 2020) provides an alternative method for determining the EI of reinforced elements. Table NB-1 (Appendix A, Table A.6) of the NEN-EN-1-1 2005 provides the calculation for a fictive modulus of elasticity E_f of all concrete classes with reinforcement. Each concrete class has its own equations for both the elements loaded in bending only and those loaded in bending in combination with a normal force. To illustrate the method of determining E_f, the equations for a commonly used concrete class C30/37 will be elaborated in the equations 3.6, 3.7, and 3.8 below. For elements loaded in both bending and normal force, the normal force ratio α_n will have to be determined first Eq. 3.5. This load combination can be the case for the columns when wind loading is applied.

$$\alpha_n = \frac{N_{Ed}}{f_{cd}A_c + A_s f_y} \tag{3.5}$$

Bending and normal force:

$\alpha_n \leq 0{,}45$

$$E_f = (1{,}96 + 432\rho + (20{,}0\text{-}196\rho)\alpha_n)\cdot 10^3 \geq 4450 \tag{3.6}$$

$0{,}45 \leq \alpha_n \leq 0{,}9$

$$E_f = (14{,}0 + 501\rho)(1\text{-}0{,}5\alpha_n)\cdot 10^3 \tag{3.7}$$

Bending only:

$$E_f = (2{,}85 + 620\rho)\cdot 10^3 \geq 4450 \tag{3.8}$$

$$\rho = \frac{A_s}{A_C} \tag{3.9}$$

with:

- E_f is the fictive modulus of elasticity [MPa]
- ρ is the reinforcement ratio [-]
- A_s is the steel reinforcement area [mm^2]
- A_c is the concrete area [mm^2]
- α_n is the normal force ratio [-]
- N_{ed} is the normal force [kN]
- f_{cd} is the design compressive strength of concrete [MPa]
- f_y is the design yield stress of steel [MPa]

The beam elements will often exceed the deflection limits set for serviceability when using E_f as the modulus of elasticity. A small test has been performed using the serviceability (SLS) conditions set in Eurocode 2 with E_{cd}, Eq. 3.10, as the modulus of elasticity for the cross-section is assumed that the section is not cracked. This test has shown that even with ULS loads applied, the beams will suffice the deflection limits of SLS if non-cracked cross sections are assumed.

$$E_{cd} = {}^{E_{cm}}/_{\gamma_{cE}} \tag{3.10}$$

with:

- E_{cd} is the design modulus of elasticity for concrete
- E_{cm} is the elasticity modulus of the concrete class
- γ_{cE} is the partial factor of 1.2

3.5.2.2 Forces

The forces acting on the elements need to be determined individually for each element. Multiple forces act upon each element, but they will be checked on two forces that greatly influence the cross-section selection. These two forces are the bending moment and shear force. The bending moment is determined for a linear distributed load with hinged connections Eq. 3.11 and a linear distributed load with fixed connections Eq. 3.12. The shear force is determined using Eq. 3.13 and is equal for both types of connections.

$$\mathrm{M_{ed}} = {}^{1}/_{8}\,\mathrm{q_d L^2} \tag{3.11}$$

$$\mathrm{M_{ed}} = {}^{1}/_{12}\,\mathrm{q_d L^2} \tag{3.12}$$

$$\mathrm{V_{ed}} = {}^{1}/_{2}\,\mathrm{q_d L \cdot 10^3} \tag{3.13}$$

with:

- M_{ed} is the design moment force [kN/m]
- V_{ed} is the design shear force [kN]
- L is the beam length [m]
- q_d is the design load [kN/m]

3.5.2.3 Load

The uniform distributed load q_d is derived from the load combinations explained in 3.4.3 Load Combinations. The load caused by the weight of the floor is determined from its cross-sectional area, unit weight and the land of the floor span. Because the floors are 1,2 meters wide, the weight will be divided by this width such that the unit of q_d will be kN/m, as shown in Eq. 3.16. All other loads are derived from Eurocode 1 and follow the same procedure. For the elements located on the outside of the building, an additional façade load, G_{fa}, will be applied, as defined in 3.4.1 Permanent load; for all other elements, G_{fa} will be ignored. The partial safety factors γ_G and γ_q follow from 3.4.3 Load Combinations. The wind will be applied to the entire structure and is therefore not used in the manual optimisation of these elements.

$$q_d = G_k\gamma_G + Q_k\gamma_q \tag{3.14}$$

$$G_k = (G_{fl} + G_P)L_f + G_{fa} \tag{3.15}$$

$$G_f = \frac{(A_f/10^4)\gamma}{b_f} \tag{3.16}$$

$$Q_k = q_k L_f \tag{3.17}$$

with:

- G_k is the total permanent load [kN/m]
- Q_k is the variable load [kN/m]
- γ_G is the permanent safety factor [-] 1,35
- γ_q is the variable safety factor
- L_f is the floor-length [m]
- G_{fl} is the dead load of floor ULS [kN/m^2]
- G_{fa} is the façade load [kN/m^2]
- A_f is the cross-sectional area floor [cm^2]
- γ is the unit weight [kN/m^3]
- b_f is the width of floor element [m]
- G_P is the permanent load on the floor [kN/m^2]
- q_k is the variable load [kN/m^2]

3.5.2.4 Timber

Timber elements must satisfy two conditions: a sufficient bending moment capacity and stay within maximum deflection limits. Due to the stiffness of timber being significantly lower than reinforced concrete, the deflection limit will be governing in most situations. A distinction is made between the deflection based on the connection with the columns. When hinged connections are used, Eq. 3.18 w_h defines the deflection, whereas Eq. 3.18 w_f is used in the case of fixed connections. The deflection limit is defined as w_{max} Eq. 3.20 and is derived from NEN-EN 1995-1-1 (NEN, 2014).

$$w_h = \frac{5q_d(L \cdot 10^3)^4}{384EI} \text{ or } w_f = \frac{q_d(L \cdot 10^3)^4}{348EI} \tag{3.18}$$

$$I = {}^1\!/_{12}\, bh^3 \tag{3.19}$$

$$w_{max} = \frac{L \cdot 10^3}{333} \tag{3.20}$$

with:

- w is the maximum displacement [mm]
- q_d is the design load [kN/m]
- L is the beam length [m]
- E is the modulus of elasticity [MPa]
- I is the second moment of area [mm^4]
- b is the cross-section width [mm]
- h is the cross-section height [mm]
- w_{max} is the maximum allowable deflection [mm]

Next to the deflection limit, the timber elements must also have sufficient bending resistance. This is unlikely to be governing but will be checked nonetheless. The moment resistance, Eq. 3.21, is determined using the design strength f_{md} of the timber class, Eq. 3.22, and the section modulus W, Eq. 3.23. The design strength is a factor of the characteristic strength f_m and modification factor k_{mod} divided by the material safety factor γ_m. k_{mod} is determined using Table NB.1 of Eurocode 5 (NEN, 2011a), which results in a value of 0.8.

$$M_{rd} = f_{md}W \tag{3.21}$$

$$f_{md} = \frac{f_m k_{mod}}{\gamma_m} \tag{3.22}$$

$$W = {}^1\!/_6\, bh^2 \tag{3.23}$$

with:

- M_{rd} is the design moment resistance [kNm]
- f_{md} is the design material strength [MPa]
- f_m is the material strength [MPa]
- k_{mod} is the time-dependent adjustment
- γ_m is the material partial factor [-] 1,2
- W is the moment of area [mm^3]
- b is the cross-section width [mm]
- h is the cross-section height [mm]

3.5.2.5 Concrete

Concrete elements will be checked on their moment resistance M_{rd} and shear strength V_{rd}. Both Eq. 3.24 for the moment resistance and Eq. 3.26 for the shear strength are taken from the NEN-EN 1992-1-1 (NEN, 2020). These equations are applicable for reinforced concrete elements that require no additional shear reinforcement.

$$M_{rd} = \frac{zA_sf_y}{10^6} \tag{3.24}$$

$$A_s = \rho A_c \tag{3.25}$$

$$V_{rd}=0{,}12\left(1+\sqrt{200/_{d}}\right)(100\rho f_{ck})^{\frac{1}{3}}bd \tag{3.26}$$

with:

- M_{rd} is the design moment resistance [kN]
- Z is the moment lever arm [mm]
- A_s is the steel reinforcement area [mm^2]
- f_y is the yield strength steel [MPa]
- A_c is the concrete area [mm^2]
- V_{rd} is the design shear resistance [kN]
- d is the effective depth [mm]
- ρ is the reinforcement ratio [-]
- f_{ck} is the characteristic concrete strength [MPa]
- b is the cross-section width [mm]

3.5.2.6 Optimisation

To assign cross-sections with this manually defined optimisation process, the cross-section must satisfy both conditions set for the concrete or timber elements. Each element will be checked individually, and the first cross-section that will satisfy the conditions will be applied to this element. The cross-sections are sorted based on their minimal cross-sectional area to encourage minimal weight design. If all cross-sections are determined and applied, the elements will go into the aforementioned Assemble component and will be excluded for optimisation by the OptiCroSec component. This allows the OptiCroSec component to take the structural properties of these elements into account when optimising all other components.

3.5.3 Standardised Floor Elements

The floors used within this model are standardised elements with a simple optimisation based on the span of the floor. Therefore data from different manufacturers will be sued to define these standardised elements. Three types of floors will be used as mentioned before: concrete, timber, and composite floor. The concrete floor is a hollow core slab, and the structural data (VBI, 2021) that will be used is from the Dutch manufacturer VBI. The timber floors are from Lignatur, and there will be three options (Lignatur AG, 2014) possible based on the acoustic levels required to achieve. The third option is the composite floor; for this floor, the ComFlor (Dutch Engineering, 2022) will be used, a floor made of steel sheeting and concrete. In combination with the varying floor height, there will be a total of 33 standardised elements which can be used for the structural model; the distribution can be seen in Table 3.3. The timber floors have much smaller height increments resulting in more options and thus possibly a more efficient cross-section.

Table 3.3 Standardised Floor Elements

Material	Type	Variations	Options
Concrete	Hollow Core	1	5
Timber	Lignatur	3	21
Composite	ComFlor	4	7

3.6 Life-Cycle Inventory

The last step of the parametric model is to create an inventory of all elements and materials used within the structural model. This inventory will be used as the so-called Life Cycle Inventory (LCI), containing the product information needed to conduct a life cycle analysis. This data will be extracted from the structural model using Karamba3D Disassemble components.

3.6.1 Data Structure

The model contains a lot of data, and only the relevant data will have to be extracted. The relevant data depends on the analysis done with this data. For the purpose of this research, two types of data sets will be used where most data will overlap. Firstly the data needs to be extracted such that the LCA tool will receive all the required information. Table 3.4 shows which data will be extracted for the LCA tool. Secondly, more data can be extracted to do a more specified and detailed analysis of the design choices. This, however, will differ for each analysis due to the difference in scope.

Table 3.4 Data Structure Life Cycle Inventory Export, Example

Element Type	Cross-section Class	Material	Volume [m^3]	Cross-section Name
Column	CHS	Steel	0.015	CHS 139.7x12.5

Data structuring will have to be done manually using data branches. These branches will each represent one of the data categories that will be used for the LCA. The order of these branches will be based on the structure used within the LCA tool. However, it is possible to add more branches if needed for additional separate analyses. The order of the data within these branches should be the same for each branch such that all data in each row will match. This is essential for the LCA, where each row of data will represent a single structural model element.

3.6.2 Data Exporting

In order to export the data to the LCA tool, the plug-in TT Toolbox will be used. This plug-in will allow for exporting the data branches to a Microsoft Excel file which is used for the LCA tool used within this research. The plug-in will also allow for more data structuring settings when exporting to Excel. This gives the option to automate the LCA as it will be possible to write data to different sheets within the LCA tool and make for quick and easy comparisons. Each branch will represent a column within Excel and thus must have a matching order of data. This data exported to excel will still be raw data for every single element used within the structural model. Therefore, they will need more processing after it has been exported before the tool can do the analysis.

4 Life Cycle Assessment

To analyse the environmental impact of products, a life cycle assessment (LCA) is performed. For the purpose of this project, the LCA will focus on the embodied carbon emissions in the relevant life cycle stages of a structure.

4.1 Embodied Carbon

Embodied carbon is used to define the structure's environmental impact, and as the name suggests, it will include carbon emissions released in the structure's lifetime, Figure 4.1. The unit of embodied carbon is $kgCO_2eq$ which accounts for all GHG emissions by taking equivalent CO_2 emissions of GHG such as Methane (CH_4) and Nitrous Oxide (N_2O). For comparison, the unit will be normalised by m^2 of gross floor area, allowing different building designs to be compared even when different in size. Embodied carbon is also often referred to as Global Warming Potential (GWP).

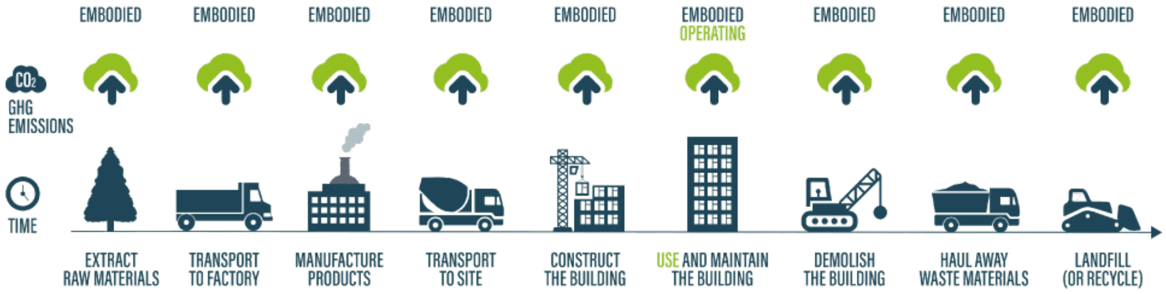


Figure 4.1 Embodied Carbon Life Cycle (Buildpass, 2020)

4.2 LCA Data

To perform a Life Cycle Analysis, environmental data is needed for every product used within the project. Since embodied carbon is the only impact category used within this and many other studies, the data is often limited to GWP. This data can be found within national and international databases or Environmental Product Declarations (EPD).

4.2.1 Life Cycle Stages

Within the LCA, the environmental impact is divided over the product's main life cycle stages to categorise each phase of its life. As mentioned in 2.1.1 Life Cycle Analysis, the stages are grouped into four main stages, A-D. However, not every stage is as relevant as the other, which is different for every product. For the structure of a building, the most important stages are A1-A3 (Product) and C2-C4 (End Of Life), which can be seen in Figure 2.1. The USE stage B is also relevant for carbon emissions of buildings; however, this is mainly related to operational emissions and not construction. The Product stage A1-A3 generates the biggest impact (Gibbons & Orr, 2020), resulting in some product manufacturers in the construction sector only doing LCA on this stage. However, the other stages can still play a significant role within the embodied carbon structures and will therefore be considered. Stage A4 is the transportation stage and the most variable stage of the LCA. This stage must be calculated fully and accurately for detailed LCA with the distances between the supplier and the building site. However, as this research focuses on the global process in the early design stage, the manufacturers' values are taken as a reference. Stage D is the reuse/recycle stage and can be used the reduce the embodied carbon. However, it is unknown or difficult to define how much can be recycled or reused for most structures. Therefore, this stage will be taken into account separately, as certain design parameters do have a significant impact on the structure's reusability, which will be important to note and consider in the results.

4.2.1.1 Embodied Carbon Calculation

The embodied carbon is calculated by multiplying the quantity of the material, either in kg or m^3, with the carbon factor of the material, resulting in the $kgCO_2eq$. To compare different LCA, the embodied carbon is normalised using the GIA such that the unit is $kgCO_2eq/m^2$. This calculation is done for each of the relevant life cycle stages, and the summation of these calculations is the total EC, Eq. 4.1. Some carbon factors require some additional calculations and are shown below.

$$\mathrm{EC} = \sum_{i=1}^{n} (\mathrm{Q_i} \cdot \mathrm{CF_i}) \qquad 4.1$$

- EC is the embodied carbon [$kgCO_2eq/m^2$]
- Q is the material quantity [kg]
- CF is the material carbon factor [$kgCO_2eq/kg$]
- GIA is the gross internal floor area [m^2]
- $_i$ is the material

The transportation stage A4 calculates the EC resulting from the products' transportation. This stage is very project-specific and therefore difficult to compare. The impact often accounts for a modest part of the total EC, and the distances are based on the average transport distance supplied by the manufacturer.

$$\mathrm{CF_{A4}} = \sum_{tm} (\mathrm{D_{tm}} \cdot \mathrm{EF_{tm}}) \qquad 4.2$$

- CF_{A4} is the transportation carbon factor [$kgCO_2eq/kg$]
- D_{tm} is the transport distance of each transport mode [tkm]
- EF_{tm} is the emission factor for each transport mode per tonne.km [$CO_2eq/kg/tkm$]

There will be material wasted within the construction process, which is accounted for in stage A5w. Where the carbon factor of each material is multiplied by the waste factor, resulting in a carbon factor for the wasted material.

$$\mathrm{CF_{A5w}} = \mathrm{WF_i} \cdot \mathrm{CF_i} \qquad 4.3$$

$$WF_i = \frac{1}{1 - WR_i} - 1 \qquad 4.4$$

- CF_{A5w} is the material waste carbon factor [kgCO$_2$eq/kg]
- WF_i is the waste factor of the material [-]
- CF_i is the carbon factor of the other stages [kgCO$_2$eq/kg]
- WR_i is the waste rate of the material [-]

4.2.1.2 Sequestration

For timber elements, there is an additional environmental aspect called sequestration. Sequestration is the storage of carbon, which is an inherent property of wood. Therefore the initial stages of timber products are more favourable as structural timber production is lower in embodied carbon. However, the stored carbon will be released at the end of life stage over its entire life cycle due to decomposition or burning of the waste. Therefore it must be considered an emission at the final stage of its life. Expanding the timber life span allows using the sequestration to its advantage reduction in carbon emissions is extended significantly.

4.2.2 Database

The environmental data resulting from product-specific LCA is often aggregated in a database for ease of use. Some of these databases are Ecoinvent, Ökobaudat, ICE V3 and Nationale Milieudatabase. However, these databases have different data from different countries, and almost all of them require the purchase of licenses. For this study, only public data is used from product-specific EPD due to limited access to databases and to create a manual consistency in the geographical scope.

4.2.3 Geographical Scope

One of the most important aspects of LCA data is the geographical scope. This scope defines which area of the world the data, and eventually, the result applies. There can be significant discrepancies in data from different parts of the world, all due to logistics and manufacturing methods. This is and will always be something to consider with LCA. It has the consequence that the LCA results from one country will be significantly different when performed in a country on another continent. This is especially true when the economic differences between the countries are large. Often databases offer multiple options for the scope of an LCA, such as European average, World Average or a specific country. Nevertheless, this data can and will differ significantly for every product. Therefore for this study, the scope is North-Western Europe, as seen in Figure 4.2.

Figure 4.2 North-Western Europe Map (MapChart, 2022)

4.2.4 Environmental Product Declarations

Almost all of the environmental data will be extracted from Environmental Product Declarations. These declarations contain the embodied carbon of the products for the relevant life cycle stages. The International EPD System provides a database of publicly available EPDs. The database is based in Sweden and therefore contains many Swedish manufacturers that publish their EPD, wherein in many other countries, the EPDs are not publicly available. Since the scope of the data is North-Western Europe, this is set as a filter for the database. Some of the data is not from North-Western manufacturers; however, these manufacturers are the leading suppliers for North-Western countries. All these EPDs are generated in accordance with ISO 14025 (ISO, 2006) and EN 15804:2012+A2:2019 (European Committee for Standardization, 2019). The EPDs used in this research are listed in Table 4.1 below, including the manufacturer and the manufacturing location. Here it can be seen that multiple suppliers are based in the Baltic countries, but they do supply many of the North-Western countries with their products.

Table 4.1 Environmental Product Declarations

Material	Type	Location	Manufacturer
Concrete	Precast Beam	Lithuania	(INHUS, 2021)
	Precast Column		
	Precast Wall		
	Precast Slab		
	Hollow Core Slab	Netherlands	(VBI, 2021)
	Concrete In Situ	United Kingdom	(ASBP, 2019)[1]
Steel	Hollow Sections	Sweden	(Tibnor AB, 2020)
	Open Sections		(BE GROUP AB, 2021)
	Reinforcement Bars		
		Norway	(CELSA Nordic, 2021)
	ComFlor Sheeting	United Kingdom	(TATA Steel Europe, 2021)
Timber	Beams/Columns	Latvia	(ZAZA Group, 2021)
	Floor		

[1] Data from ICE V3 Database

4.2.5 Stage D Recycling

The reuse or recycling of a material or element is covered in stage D of the LCA. Often the value given for the recycling stage is negative as recycling or reusing reduces the impact of the element. However, the extent to which the element is reused or recycled is full of uncertainties and challenging to predict. A structure's life span is often decades, making it hard to predict what will be done with the structure at the end of its life. Therefore an assumption has to be made about how much of the element will be reused or recycled, and this value is not directly taken into account for the final embodied carbon.

Certain materials or elements have a very high potential for recycling, such as steel elements. Recyclability must therefore be considered when making conclusions based on the embodied carbon results, as steel structures will have high initial emissions but give much greater opportunity for reuse. This is different for all materials and depends on the types of connections made within the structure.

4.3 Structural Carbon Tool

Many tools exist for performing an LCA; however, most are behind a paywall and can do far more detailed analyses than necessary for this study. Therefore, it has been chosen to use the Structural Carbon Tool (SCT) developed by Elliot Wood and The Institution of Structural Engineers. This tool was developed for its ease of use such that engineers could easily do their own carbon calculations quickly, and therefore this tool is also free to use. As this study is focused on exploring the potential of combining parametric BIM with LCA, this tool is a good first option.

The tool fully focuses on calculating embodied carbon of structures and is based upon the guide “How to Calculate Embodied Carbon” (Gibbons & Orr, 2020). Most life cycle data is from the ICE V3 database and multiple EPDs. However, as mentioned, most of the data will be manually selected from different EPDs, with North-Western as the scope for this study. The tool is entirely based in Microsoft Excel and, therefore, easy to use and modify for the purposes of this research. Also, the option for custom environmental data is provided, which will be used for the EPDs of Table 4.1.

4.3.1 Importing Data

To perform the analysis, it will be necessary to import the data of the parametric model from the Grasshopper software. TT Toolbox will be used for this purpose as the tool allows for exporting to Excel, where the Structural Carbon Tool is based. TT Toolbox will write the data of the structure in a single column per data branch. Thus the order of this data must match to ensure each row in the SCT has matching data. All of this should be set correctly within the Parametric model.

4.3.2 Filtering Data

The imported data is still raw data for every single element used within the structure, and therefore the data must be filtered before the SCT can use it. All this filtering will be done within separate Excel sheets of the SCT. The function UNIQUE(), Eq. 4.5, within Microsoft Excel allows for a dynamic array filtering out all unique rows of the imported data. This function is only used on textual data such that a summary of all unique elements is created. Essentially all elements that fall within the same category will now be grouped.

=UNIQUE (array, [by_col], [exactly_once]) 4.5

with:

- array is the range of data
- by_col is set to FALSE to use rows
- exactly_once is set to FALSE for all unique combinations

The data exported from Grasshopper contains names and categories which differ from the SCT. Therefore it is needed to replace the names and categories with their matching equivalent of the SCT tool such that the tool can understand the data. This second important step is done using two functions together: INDEX() and MATCH(). The INDEX() function, Eq. 4.6, returns the data from a specified cell. The MATCH() function, Eq. 4.7, returns the names of the cells that match the criteria set within this function. By combining the two functions, Eq. 4.8, it is possible to pick(INDEX) the equivalent name or category based on the imported data(MATCH). Since the UNIQUE() function is a dynamic function, the arrays must also be selected dynamically by referencing the first cell of the array followed by the hash symbol (#).

=INDEX (array, row_num, [col_num], [area_num]) 4.6

with:

- array is the range of data
- row_num is the row position in the array
- col_num is optional and not used
- area_num is optional and not used

=MATCH (lookup_value, lookup_array, [match_type]) 4.7

with:

- lookup_value is the matching data
- lookup_array is the range of data to be matched
- match_type is set to 0 for an exact match

=INDEX (array, MATCH (lookup_value, lookup_array, [match_type])) 4.8

The volumes of the elements will be added together based on their unique grouping to create a total overview. Some categories also do not exist yet in the tool and are therefore added manually. This can be done for as many categories as wanted for this research. Many of the visualisation and calculations are based on data ranges set by the developers of this tool, and these data ranges must be adjusted accordingly to ensure that all data is included.

4.3.3 Tool

The Structural Carbon Tool has three main tasks: calculating the embodied carbon, visualising the results and comparing multiple design options. All three are very useful for this research and will be used to different degrees. The embodied carbon is the core of this research and is thus the most important feature of the SCT.

4.3.3.1 Process

The tool follows the same process for every design variation generated, shown in Figure 4.3. The tool starts by receiving data that is exported from Grasshopper. This data represents the Life Cycle Inventory (LCI) and includes all information needed to perform an LCA. This data will be filtered and adjusted for the purpose of this research. Once the data is ready, it is sent to the Excel sheet corresponding to the design concept. A total of six different concepts can be analysed simultaneously within the tool. The LCA can be done in combination with the life cycle data from the tool and manually picked EPDs.

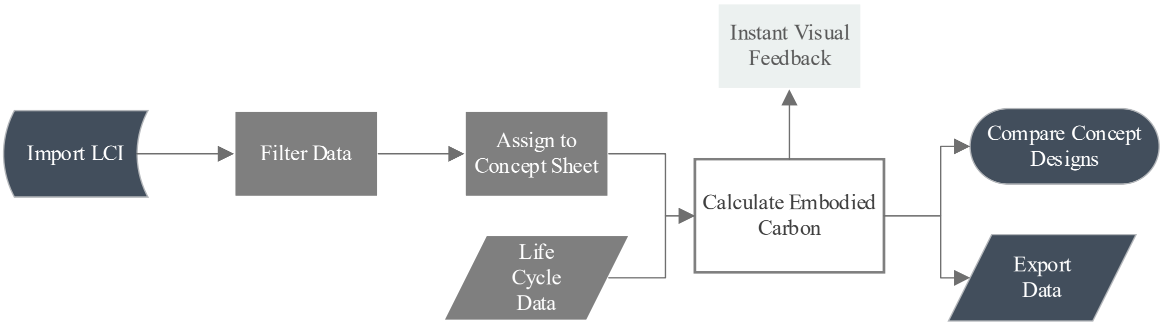
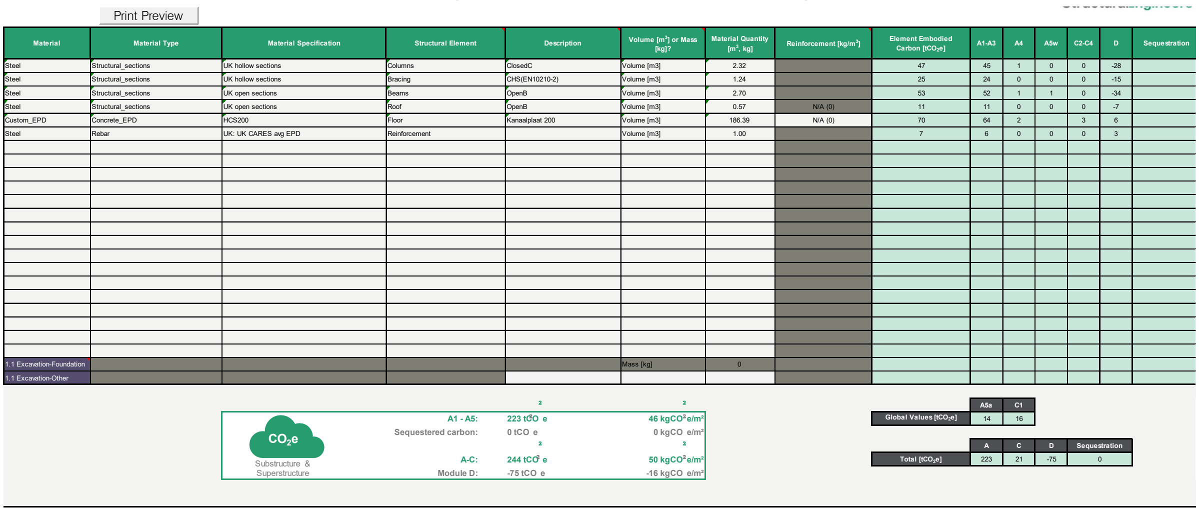


Figure 4.3 Flowchart Structural Carbon Tool

The tool will calculate the embodied carbon of the relevant life cycle stages and will display them accordingly, as seen in Figure 4.4. The total embodied carbon will be shown below the results, and the total will also be normalised by dividing it by the total gross floor area. This is done for the purpose of comparing the different concept designs.



Material	Material Type	Material Specification	Structural Element	Description	Volume [m^3] or Mass [kg]?	Material Quantity [m^3, kg]	Reinforcement [kg/m^3]	Element Embodied Carbon [tCO$_2$e]	A1-A3	A4	A5w	C2-C4	D	Sequestration
Steel	Structural_sections	UK hollow sections	Columns	ClosedC	Volume [m3]	2.32		47	45	1	0	0	-28	
Steel	Structural_sections	UK hollow sections	Bracing	CHS(EN10210-2)	Volume [m3]	1.24		25	24	0	0	0	-15	
Steel	Structural_sections	UK open sections	Beams	OpenB	Volume [m3]	2.70		53	52	1	1	0	-34	
Steel	Structural_sections	UK open sections	Roof	OpenB	Volume [m3]	0.57	N/A (0)	11	11	0	0	0	-7	
Custom_EPD	Concrete_EPD	HCS200	Floor	Kanaalplaat 200	Volume [m3]	186.39	N/A (0)	70	64	2		3	6	
Steel	Rebar	UK: UK CARES avg EPD	Reinforcement		Volume [m3]	1.00		7	6	0	0	0	3	
1.1 Excavation-Foundation					Mass [kg]	0								
1.1 Excavation-Other														

CO$_2$e
Substructure & Superstructure

A1 - A5:	223 tCO$_2$e	46 kgCO$_2$e/m^2
Sequestered carbon:	0 tCO$_2$e	0 kgCO$_2$e/m^2
A-C:	244 tCO$_2$e	50 kgCO$_2$e/m^2
Module D:	-75 tCO$_2$e	-16 kgCO$_2$e/m^2

	A5a	C1
Global Values [tCO$_2$e]	14	16

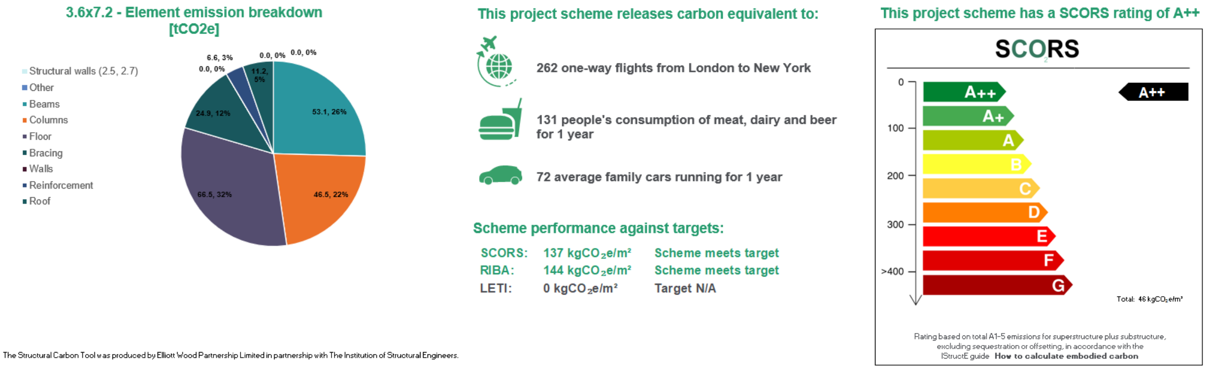
	A	C	D	Sequestration
Total [tCO$_2$e]	223	21	-75	0

Figure 4.4 Numeric Results

At the same time, the tool instantly visualises the results in a pie chart and a SCORS rating (Arnold et al., 2020), as seen in Figure 4.5. Finally, the tool will combine all data in the Comparisons sheet, which compares all concepts at once or individually.

4.3.3.2 Visualisation

The instant visualisation of the results can be used to gain quick insight into embodied carbon generated by the concept design. This feature is not essential for this research but can be an addition in proofing the potential of this method. The pie chart shows how much each category impacts the total embodied carbon, and this can be used to identify areas where big gains can be made quickly. The carbon equivalent section is not of relevance for this project. The SCORS rating shows a sustainable performance label in the style of most appliances.



The Structural Carbon Tool was produced by Elliott Wood Partnership Limited in partnership with The Institution of Structural Engineers.

This project scheme releases carbon equivalent to:

262 one-way flights from London to New York

131 people's consumption of meat, dairy and beer for 1 year

72 average family cars running for 1 year

Scheme performance against targets:

SCORS:	137 kgCO$_2$e/m²	Scheme meets target
RIBA:	144 kgCO$_2$e/m²	Scheme meets target
LETI:	0 kgCO$_2$e/m²	Target N/A

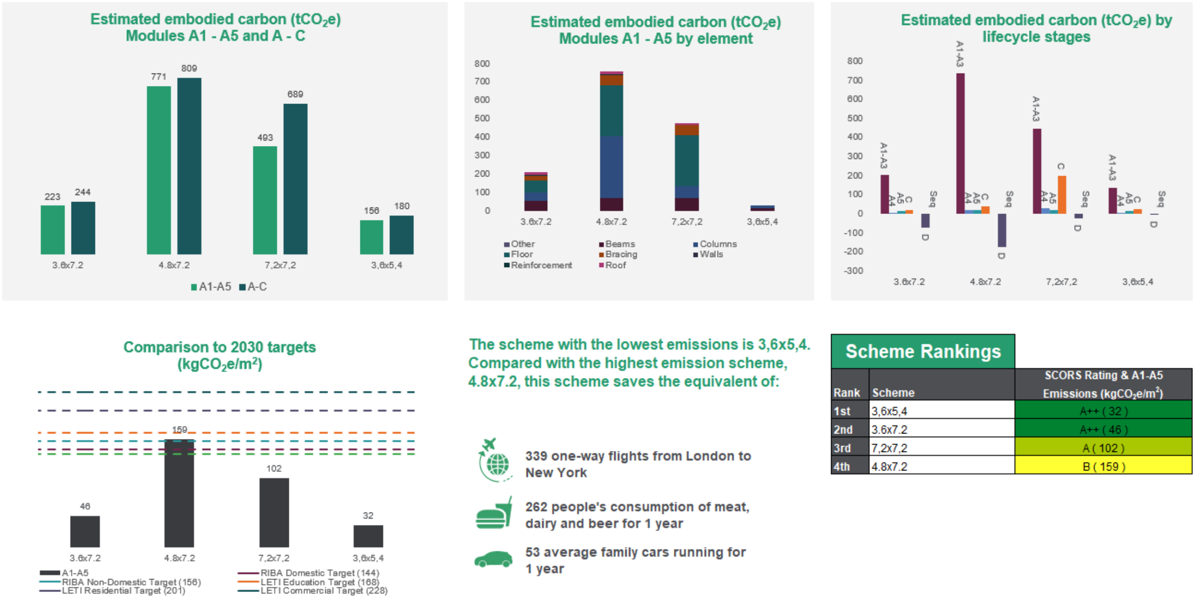
This project scheme has a SCORS rating of A++

Rating based on total A1-5 emissions for superstructure plus substructure, excluding sequestration or offsetting, in accordance with the IStructE guide **How to calculate embodied carbon**

Figure 4.5 Instant Result Visualisation of the Structural Carbon Tool (Elliott Wood, 2021)

4.3.3.3 Comparisons

The purpose of the SCT is to allow engineers to explore multiple design options and compare them based on their embodied carbon. As seen in Figure 4.6, the SCT has a sheet dedicated for comparing the different designs. This sheet will be used as an inspiration for the performed case studies.



The scheme with the lowest emissions is 3,6x5,4. Compared with the highest emission scheme, 4.8x7.2, this scheme saves the equivalent of:

339 one-way flights from London to New York

262 people's consumption of meat, dairy and beer for 1 year

53 average family cars running for 1 year

Scheme Rankings

Rank	Scheme	SCORS Rating & A1-A5 Emissions (kgCO$_2$e/m²)
1st	3,6x5,4	A++ (32)
2nd	3.6x7.2	A++ (46)
3rd	7,2x7,2	A (102)
4th	4.8x7.2	B (159)

Figure 4.6 Embodied Carbon Comparison of the Structural Carbon Tool (Elliott Wood, 2021)

4.3.4 Data Export

After the full LCA is performed, the data can be exported for further analysis of the results themselves. Microsoft Excel will be used to export data using the Append function. This function imports all data from the specified data sheets and arranges them based on their mutual categories. Some small data filtering will be done again such that the structure is more suitable for data analysis. All data will be in a single sheet allowing further analysis and comparisons of the LCA results of all design concepts.

5 Case Study

In order to discover the potential of the developed method, a case study will be performed. This case study will also help answer the research question and some sub-questions. The case study focuses on using this method within the design process, whereas the following parameter study will focus on the research potential.

5.1 Case

The case study will be defined within the limits of the method and this project. This case study will be done on the design of a simple office building, and therefore all specifications will be based on this function. This method aims to show the potential of using LCA within the early design. The case study will include three different building designs with the same gross internal floor area. The three designs will mainly differ in building shape while keeping other parameters similar for better and fair comparisons. The different design variants are shown in Figure 5.1 and are named A, B and C.

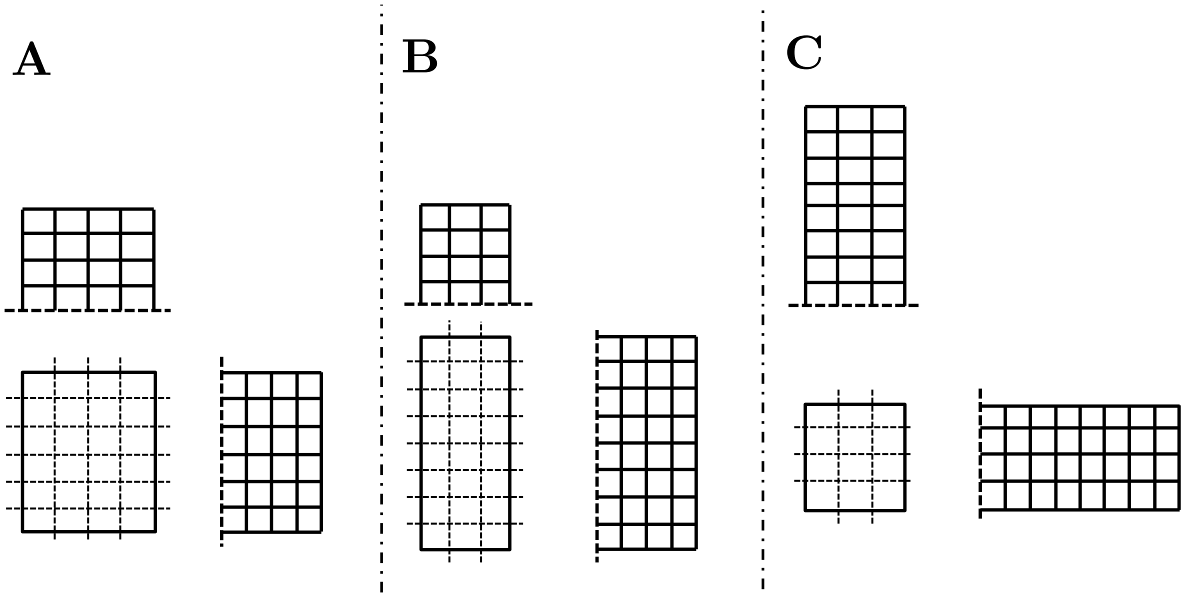


Figure 5.1 Case Study Variants

All designs will have the same grid dimension of 4,8m by 6,0m and are only varied in the distribution of this grid, with design A having 6x4, design B having 8x3 and design C having 4x3 times this fixed grid dimensions. Design A and B both have four floors, while design C has eight floors. Many of the parameters are fixed for the purpose of fair comparisons and limiting the number of variations possible. All the fixed parameters are listed in Table 5.1 below.

Table 5.1 Fixed Parameters Case Study

Parameter		**Value**
Grid [m]		4.8x6.0
Floor Type		Hollow Core Slab
Free Height [m]		2.6
Steel Grade		S235
Concrete Class		C30/37
Timber Grade		GL28h
Floor Area [m^2]		2675
Reinforcement Ratio [%]	Beams	1.5
	Columns	2.0

To create several variations within the design variations, some parameters are varied; these parameters are listed in Table 5.2. The structure's stability is chosen to vary between the use of a bracing system and a shear wall. The beams and columns will be made of the same material, which can be varied between concrete, steel and timber. The dimension and number of floors result from the building design variation. In total, these variations will give 18 different design options compared within this case study.

Table 5.2 Varying Parameters Case Study

Variant	**Stability**	**Frame (Beams + Columns)**			**Dimension [m]**	**Floors**
A	Bracing	Concrete (**1**)	Steel (**2**)	Timber (**3**)	24x28.8	4
	Shear Wall					
B	Bracing	Concrete (**1**)	Steel (**2**)	Timber (**3**)	16x38.4	4
	Shear Wall					
C	Bracing	Concrete (**1**)	Steel (**2**)	Timber (**3**)	18x19.2	8
	Shear Wall					

5.1.1 Study

The first part of the method will be performed within the parametric model. Since the goal of the parametric model is the quick and easy generation of different designs, only a few of the parameters will have to be changed. Each time a parameter is changed, the parametric model will assign the cross-sections based on the set optimisation, in this case minimal cross-sectional area. The varying design specifications will automatically be noted and are part of the final data set of the parametric model. After the model has done its structural analysis and assigned all cross-sections, a complete list of elements and their properties is generated and structured. By pressing a button, all this data will be written to the correct Microsoft Excel file of the SCT. The second part is done in the SCT, in which the LCA will be done. The tool will calculate the embodied carbon of different life cycle stages for the elements in the structure. This tool makes it possible to do the first part of this analysis and draw the first conclusions by comparing the different design variations in the Comparisons sheet, as seen in Figure 4.6.

All of the data structuring is already automated such that after writing the data from the parametric model to the SCT, it is possible to make the first comparisons instantly.

The final step is to export the data from the SCT to analyse the results further. This process is semi-automated and done within a new Microsoft Excel file. All the data of the different design variations is aggregated using queries and stored within a single file. This allows for detailed analysis of more specific elements and is the main part of the results.

5.2 Analysis

The data of all the design variations will be analysed to compare the variations, investigate the potential of this method, and answer some of the research questions. The design variations are numbered based on the material used for the beams and columns to avoid confusion over the variant and material names. These numbers only represent a parameter variation and not a specific material.

- **1** is a variation with a concrete frame
- **2** is a variation with a steel frame
- **3** is a variation with a timber frame

5.2.1 Results

The first results of the method can be seen in the comparison sheet of the SCT, as seen in Figure 5.2. This sheet will give direct insight into up to six design variations, in this case, design A with all six parameter variations. The left three results are with a bracing system and all three material options, while the right three results have s shear wall in combination with the different column and beam material. From these results, it can be quickly concluded that using concrete or steel for the beams or columns does not make a significant difference, and timber is always more sustainable. Also, it can be seen that the shear walls increase the total EC by about 10% compared to the bracing system, even 20% for a timber frame structure. Also, as could be expected, the right graph in Figure 5.2 shows that the floors are the majority of the EC due to the large size of these elements. The columns are also reduced in EC for the variants with a shear wall, but this can be explained by the fact that the shear walls replace eight columns per floor.

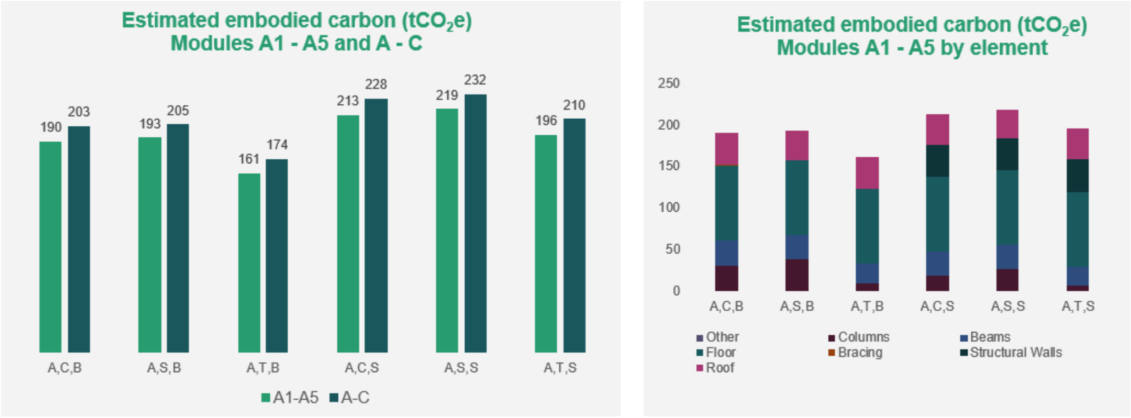


Figure 5.2 Comparison Sheet Structural Carbon Tool Variant A

However, it is necessary to analyse the data more to find relations and more detailed information. As the SCT limits the number of variations per file to six, the data will be aggregated into a new file, including all variations. This makes it possible to analyse all variations across a range of parameters.

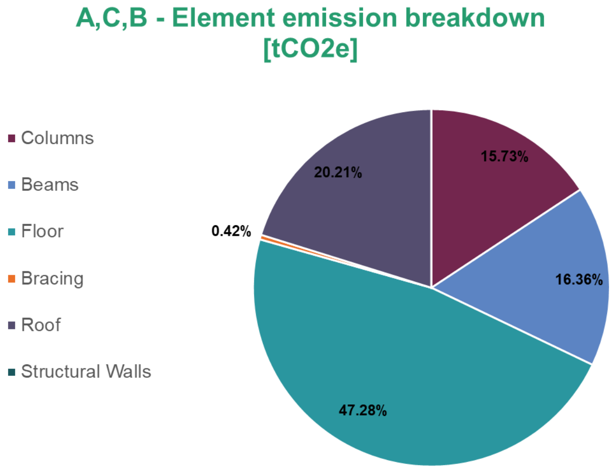


Figure 5.3 Pie Chart Embodied Carbon Visualisation SCT, Variant A, Concrete, Bracing

By comparing the total EC of each variation in a single chart, as seen in Figure 5.4, it is possible to identify the differences between the design variations. Figure 5.4 shows that using a shear wall results in more EC in all variations than when using a bracing system. Next to that, a timber frame always results in lower EC than concrete or timber frames. An interesting difference is found in Variant C, where the steel frame has a significantly higher EC, which will be investigated further. Variant C with shear walls also shows a higher EC than the other variants with shear walls; however, this can be explained by the fact that the building is twice as high, resulting in a shear wall twice as high. This indicates that more floors result in a higher EC. While the floor plan is significantly different, design variants A and B have very similar EC results for all of their six parameter variations, as shown in Figure D.1.

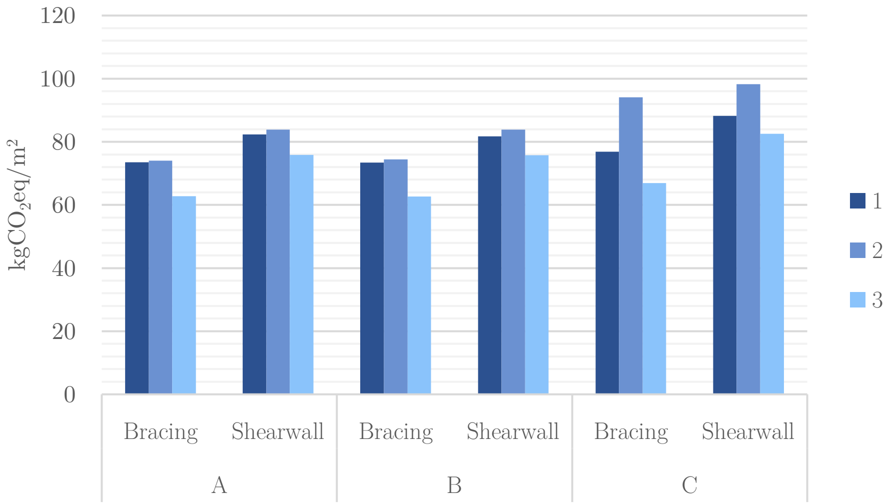


Figure 5.4 Total Embodied Carbon Case Study Variants

To investigate the differences more deeply, a bar chart is used to show the contribution of the different structural elements to the total EC, as seen in Figure 5.5. This figure shows a lot of information and gives much more insight. From this chart, it can be seen that all elements have a constant contribution to the total EC except for the columns, which have a wildly varying contribution. The columns account for the majority of the differences between the design variants. The columns are significantly less impactful for timber frames than the other two materials, explaining why the total EC is less for this variation. It is also clear that the significant increase in EC for the steel frame structures of variant C is also caused by the columns. Lastly, the increase of EC due to the shear walls in Variant C can also be seen, as was expected with an increase in building height.

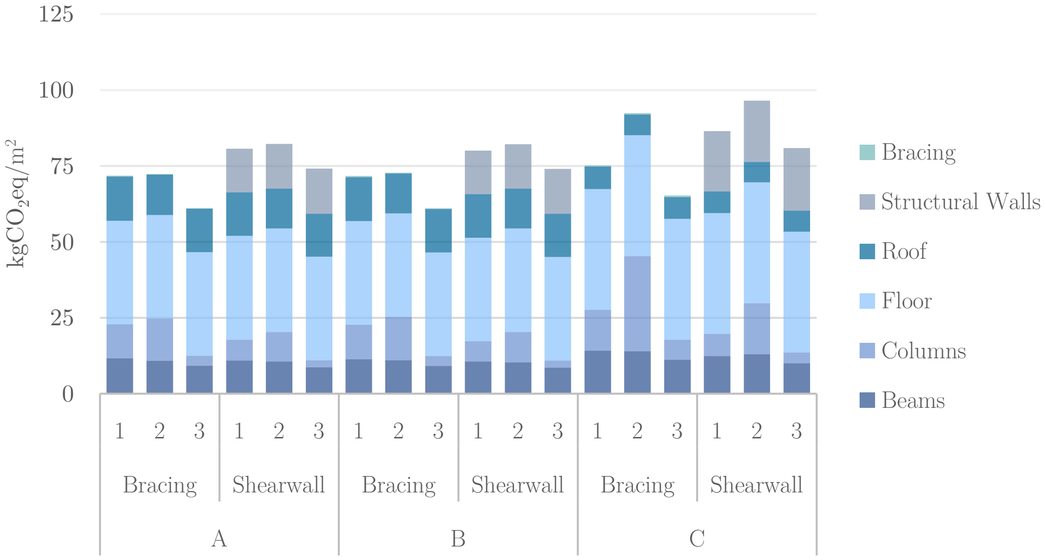


Figure 5.5 Embodied Carbon Distribution by Element Type

Next to the EC distribution, it is also helpful to look at the volume distribution of the elements, as seen in Figure 5.6. This figure shows some contrasting results to the EC distribution, especially the case for the steel columns. While the steel columns account for a good part of the total EC, they account only for a marginal amount of the total material volume.

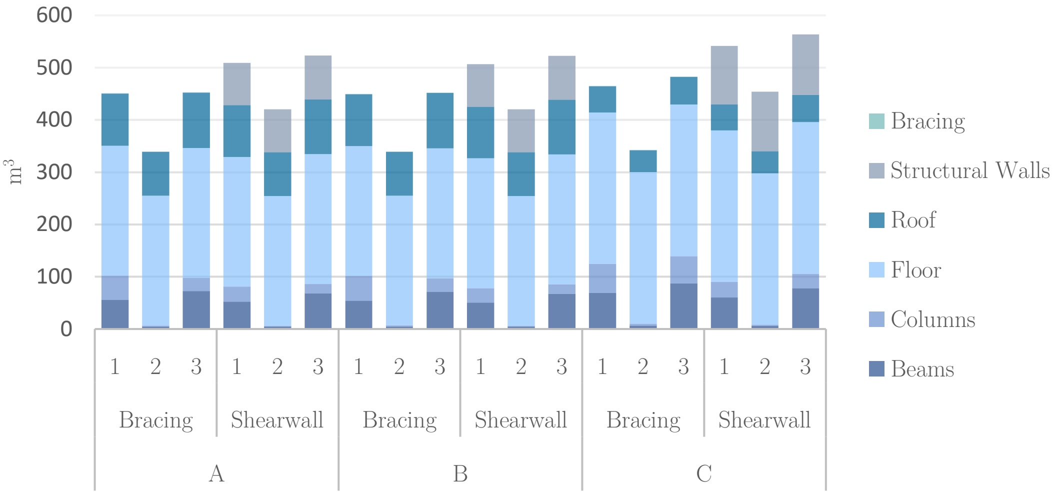


Figure 5.6 Volume Distribution by Element Type

While Figure 5.5 and Figure 5.6 give great insight into the distribution of EC and volume, it is also relevant to see their relation. This relation is shown in Figure 5.7 and shows a clear difference between the chosen design variants A and C; B is left out as the results were almost identical to A. It is chosen to use the bracing system for the data as it includes more columns that are sensitive to changes. The figure also clearly highlights the significant impact a small amount of steel has on the total EC. Since the floors are the largest elements, and they are hollow-core slabs, it is concrete that has the most volume. However, in variant C with a steel frame, the relatively small volume of steel already accounts for nearly the same amount of EC as the concrete. Indicating that steel has way higher carbon emissions than concrete, and even though the volume is small, it contributes largely to the carbon emissions. Meanwhile, timber frame structures show a relatively linear relation between volume and EC.

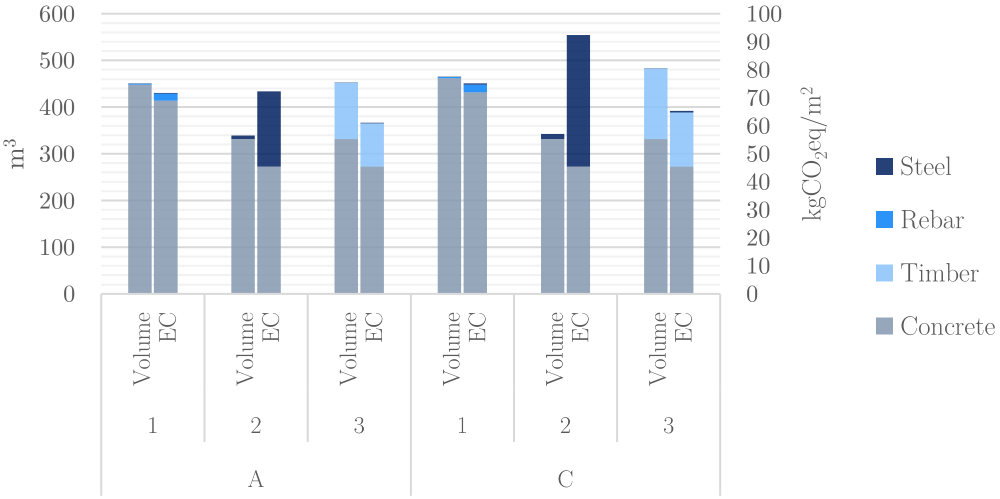


Figure 5.7 Material Volume vs Embodied Carbon of Variant A and C, Bracing

The previous results show that the columns are the structural element that is most sensitive to both the design variations and the parameter variations. Therefore, the columns are investigated to determine how much changes influence them. The data of Figure 5.7 is arranged in Table 5.3, together with the total volume and EC percentage. This table shows the big differences in volume between the different materials for the columns, wherein design variant A the volume of concrete columns is about 25 times as much as the steel column volume, while steel columns still account for more EC. With only 0,5% of the volume, the steel columns still account for almost 20% of the EC, explaining why the EC caused by the steel columns is so sensitive to changes.

When comparing variants A and C, it can be seen that the doubling in the number of floors influences the columns differently for each material. The most notable change, or lack of change, is noted for the concrete columns, which only increase by 20% in volume and EC. Concrete columns are thus relatively insensitive to the increase in building height. In contrast, steel and timber columns are more than double in volume and EC, which results in a much higher contribution to the total EC by both steel and timber, with steel columns already accounting for a 3rd of the total EC. The increase in timber EC is significant; however, the total EC is still much lower than that of the steel column structure.

Table 5.3 Column Volume and Embodied Carbon of Variant A and C, Bracing

Variant	Material	Volume [m³]	% of Total Volume	EC [kgCO₂eq/m²]	% of Total EC
A	Concrete	46.1	10.2%	11.2	15.6%
	Steel	1.8	0.5%	13.9	19.3%
	Timber	25.1	5.6%	3.2	5.3%
C	Concrete	55.5	12.0%	13.5	17.9%
	Steel	4.1	1.2%	31.4	34.0%
	Timber	51.8	10.7%	6.6	10.2%

Combining the sensitivity to the building height and the much higher emissions per m³ results in the large impact of the steel columns on the total EC of the structure. This can be seen clearly in Figure 5.8, where the column volume is plotted against the EC emissions. This figure confirms how a small amount of steel already results in more EC than a large amount of concrete. This figure also shows the low sensitivity for change of the concrete columns and the high sensitivity of timber columns when comparing A and C; however, timber columns still result in the lowest EC emissions of the three materials.

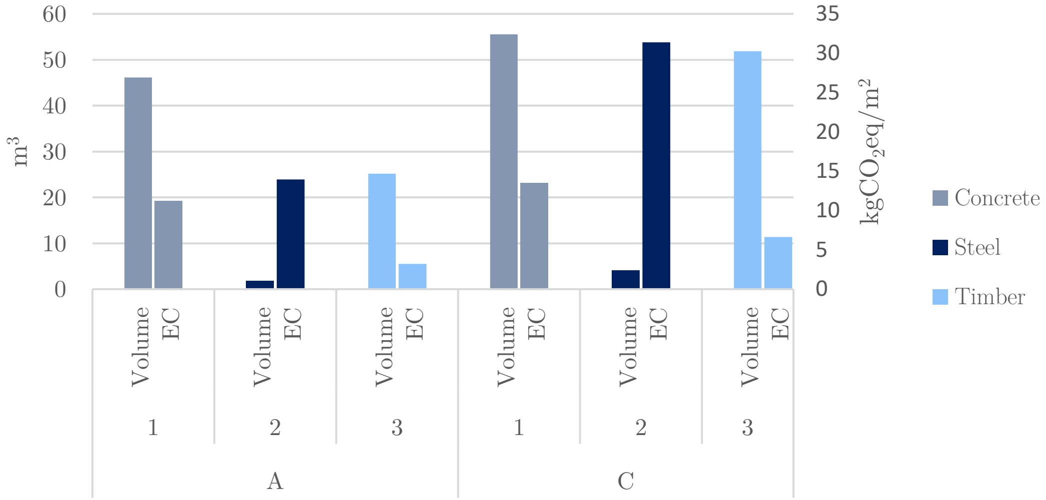


Figure 5.8 Volume vs Embodied Carbon of Column Elements

The literature study concluded that the production stage A1-A3 is responsible for the majority of the EC. In Figure 5.9, the life-cycle stages are plotted in a bar chart for design variant C. The figure shows that the production stage accounts for around 90% of the total EC for the structures, higher than the literature study suggested, but that is likely due to this case study only including the structural elements. Timber structures (3) show a large amount of EC for the end of life stage C2-C4, a result of the carbon sequestration properties of timber, which is deducted from the total EC but is released at the end of life stage. So effectively, the sequestration and end of life stages balance each other out.

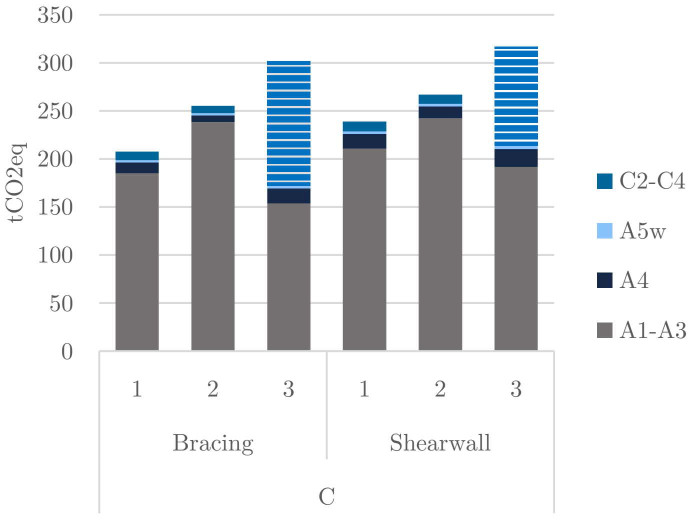


Figure 5.9 Embodied Carbon Distribution Life-Cycle Stages

5.2.2 Recyclability

The recyclability of the materials and elements is also essential to consider, as this could change the final results significantly. However, the difficulty is that recyclability is a very broad concept and can be done in multiple ways. Therefore, the data provided by the manufacturers can be very different from one to the other. Also, fully reusing elements would mean very high recyclability; this is not considered within the provided data. In Figure 5.10, the recyclability of the entire structure has been highlighted with the diagonal pattern. In theory, this diagonal part could be fully recycled at the end of the building's life. The figure shows that when using the full recycling potential in many cases, the steel structures end up with a lower total EC than the concrete structures due to the much higher recycling potential of steel over concrete. Even the steel frame structures of variant C end up with similar EC as the concrete frame structures. The timber structures become even more sustainable and have a higher recycling potential than the steel elements resulting in a much lower total EC.

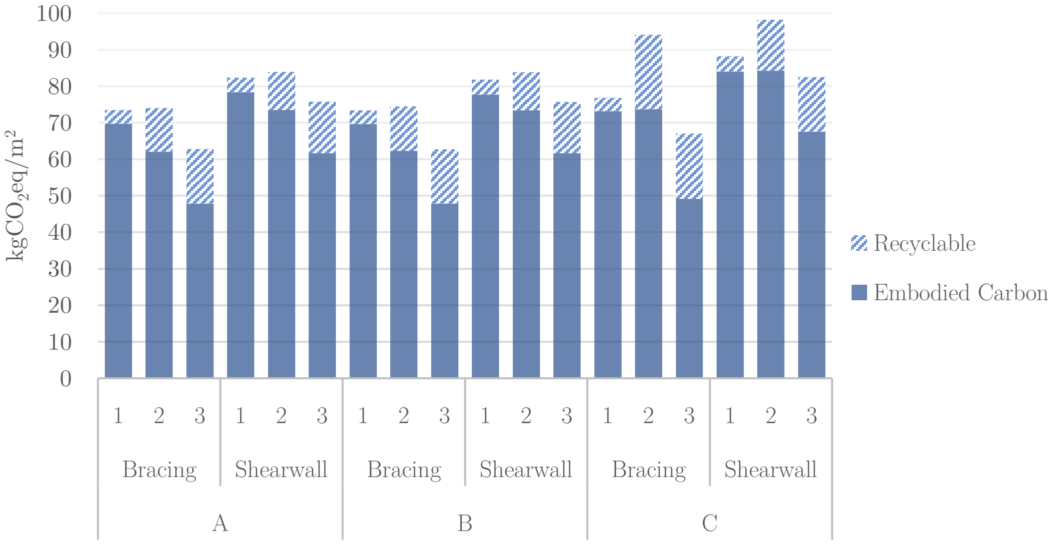


Figure 5.10 Recyclability of Design Variants

5.3 Evaluation

The case study has given multiple insights into the potential of using the method developed in this thesis. The method has shown that it can be used simultaneously as a design and research tool. The use of the SCT makes it possible to gain quick insights into the differences and the hotspots of different design variations. Aggregating the data of the 18 different design variations allowed for a more detailed analysis. The research done on the data showed multiple indications of the influence of the design parameters, the most important of which are listed and discussed below.

- The SCT gives the first indications of the influence of the design variation. From Figure 5.2, it can be seen that the use of shear walls is unfavourable for the total EC and that the timber frame is the most sustainable option. The tool makes it possible to make decisions based on the quick comparisons provided in the comparisons sheet.
- Design variant C results in the most EC, indicating that more floors result in more EC. Whereas variants A and B are almost identical, suggesting that the shape of the building is of little influence if the height stays identical.
- In all material variants, the columns are the most sensitive to changes in variant C. The increase in normal forces likely causes this because of the higher number of floors; however, this must be investigated further.
- The steel elements have a small volume but account for a significant part of the total EC, 0,5% of the total material volume already equals to 20% of the total EC. Therefore, the steel elements are most sensitive to changes as a small change has a significant impact. Timber elements are also sensitive to the increase in building height; however, the timber structure remains the most sustainable option. Where steel and timber more than double in EC between variants A and C, concrete has a low sensitivity to this change in design with an increase of only 20%.
- The hollow core floor slabs account for most of the material volume used within the structure. As the GIA stays constant, the volume of the floors will not change; therefore, the floors are not sensitive to any of the parameters changed in this study.
- The recyclability of the different design variations changes the final results significantly as the steel structures allow for much more recycling than concrete structures, resulting in similar total EC for these two frame materials. The timber structure becomes even more favourable because of its high recyclability. An important note is that recyclability is an end-of-life scenario and does not help the current directly improve the current climate situation. Next to that, there is some ambiguity around the recyclability of the materials used. The interpretation of recycling can be subjective and is provided by the manufacturers themselves. Next to that, fully reusing elements would completely change this data as well; therefore, the recyclability is more an approximation of the recycling potential and should be looked at critically.

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6 Parameter Study

The case study has shown that it is possible to compare multiple designs, analyse the results of the LCA study and make decisions based on the EC results. However, it also showed that some are sensitive to a change in specific design parameters. A parameter study will be done on a few parameters to investigate the relation and influence of these parameters on the total and element-specific EC results. The chosen parameters that will be investigated are based on the first results from the previous case study and findings throughout the parameter studies. The number of parameters is limited to stay within the scope and feasibility of the study.

6.1 Number of Floors

The case study performed in chapter 5 showed a significant difference between the design variants A and B with four floors and variant C with eight floors. Therefore, a parameter study is performed on the influence of the number of floors on the total EC.

6.1.1 Case

The total GIA will not be the same from the case study as the floor plan will remain identical, with an additional floor added in each step. Like the case study, the structure's frame will have three material variants: concrete, steel, and timber. All other parameters are fixed for this study to ensure that only the number of floors influences the data. It is chosen to use the bracing system for stability, and the maximum number of floors is 18, as this fits within the boundaries of this study. The shape of variant A, Figure 6.1, including all fixed parameters of the case study, Table 5.1, is chosen as the bases for the parameter study.

Table 6.1 Varying Parameters Number of Floors Study

Variant	Stability	Frame (Beams + Columns)			Number of Floors
A	Bracing	Concrete (**1**)	Steel (**2**)	Timber (**3**)	1 to 18

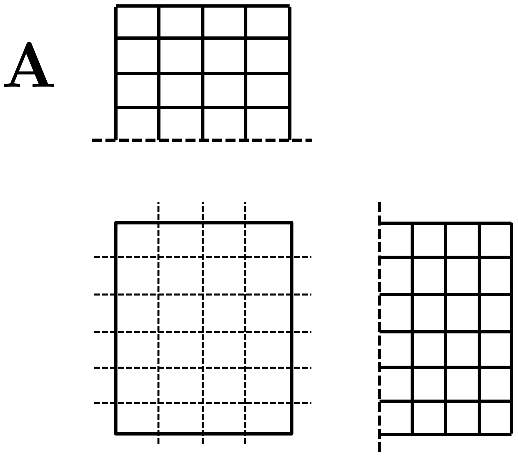

Figure 6.1 Design Variant A, 4 Floors

6.1.2 Results

Firstly, the total EC of each of the three variants is compared against the number of floors, Figure 6.2. The results show different behaviour for each of the three frame materials, where concrete and timber show similar linear behaviour from 7 floors or more. However, the steel frame variant shows a much steeper linear relation, resulting in much more EC than the other two variants. This behaviour was expected as it is similar to the results of the performed case study. The concrete frame has a plateau in total EC between 3 and 6 floors, which indicates that the elements are relatively over-dimensioned for the lower number of floors.

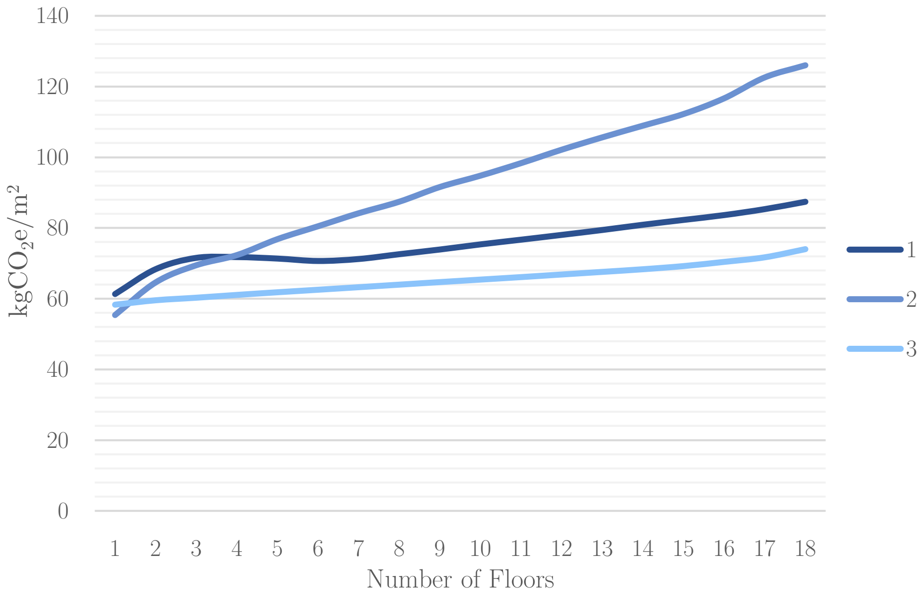

Figure 6.2 Total Embodied Carbon by Number of Floors

To find out what causes the different behaviour, the contribution of the elements is plotted, this time as a percentage of the total, as this gives a clearer indication of the contribution, and the total EC can already be seen in Figure 6.2. Figure 6.3 shows the distribution of the variant with a steel frame; steel is chosen as it was most sensitive to change in the case study. Like in the case study, the columns are the main reason for the increase in total EC when increasing the number of floors. The distribution of the concrete and timber frame variants can be seen in Figure E.1, and Figure E.2 of Appendix E. These figures show an increase in the contribution of the columns to the total EC, similar to the increase in total EC in Figure 6.2, thus also with these variants, the columns cause the increase.

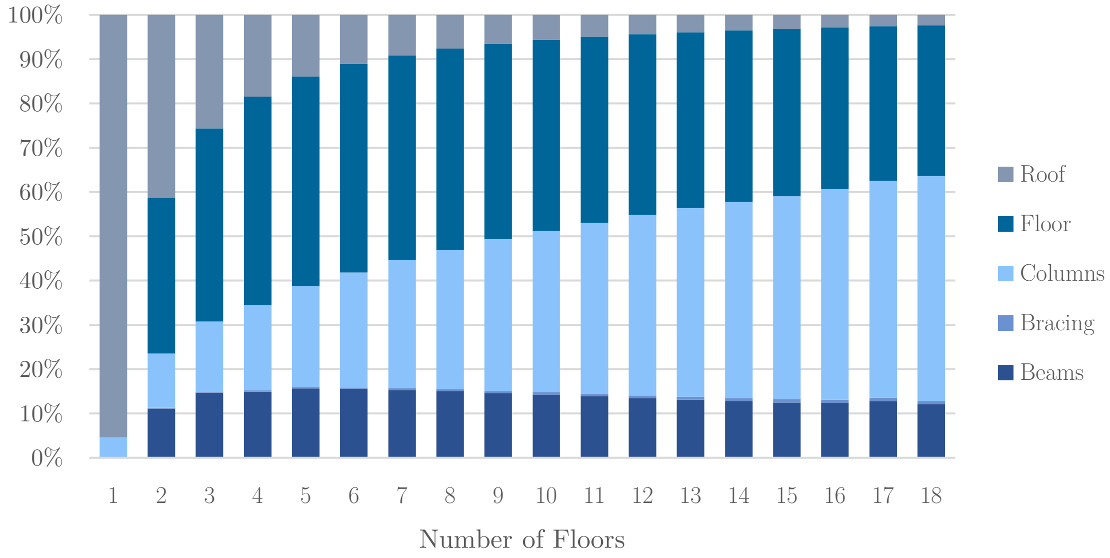

Figure 6.3 Embodied Carbon Distribution of Structural Elements, Steel Frame, Bar

The columns cause the increase in total EC; therefore, they are investigated further. In Figure 6.4, the column volume is plotted against the number of floors. It can be seen that the increase in volume for the timber and concrete columns is very similar and exponential. As discovered in the case study, the volume of steel is much lower, and therefore, the increase in volume is not as pronounced in this figure. However, by plotting the steel column volume against its own axis, the dotted line, it can be concluded that the steel volume follows the same exponential increase as the other two material volumes. This exponential increase in column volume is also necessary since the GIA increases linearly; thus, the volume must increase exponentially to result in a linear increase of total EC.

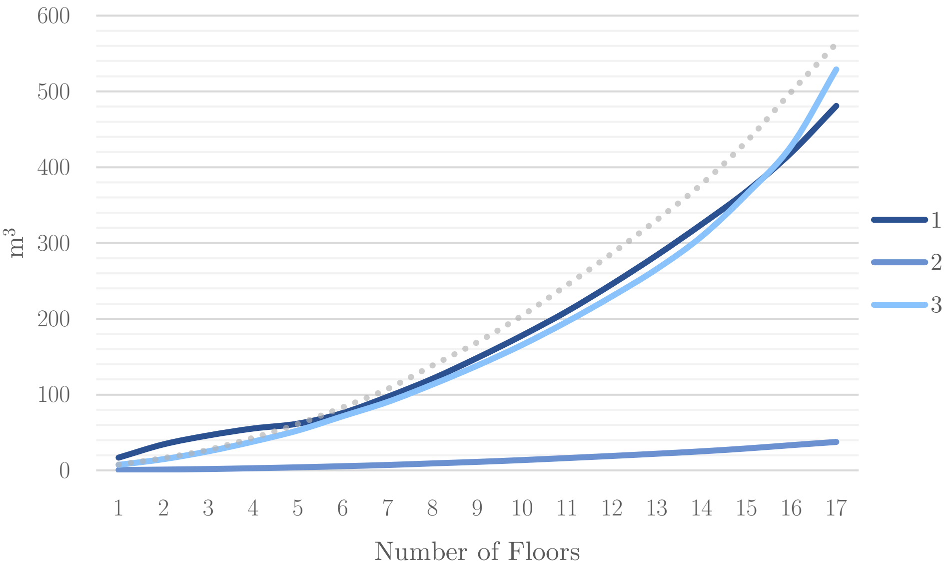

Figure 6.4 Column Volume by Number of Floors

With the increasing number of floors, the normal force in the columns will also increase. The normal force usually governs the column dimensions; therefore, increasing steel column volume can be related to this normal force increase. The added floor directly increases the normal force linearly. However, the columns must increase for this additional normal force and create another additional normal force themselves, resulting in the exponential increase of column material. In Figure 6.5, the normal force is plotted together with the volume of the steel columns. The figure shows that the relation between increasing normal force and the steel column volume is almost one to one.

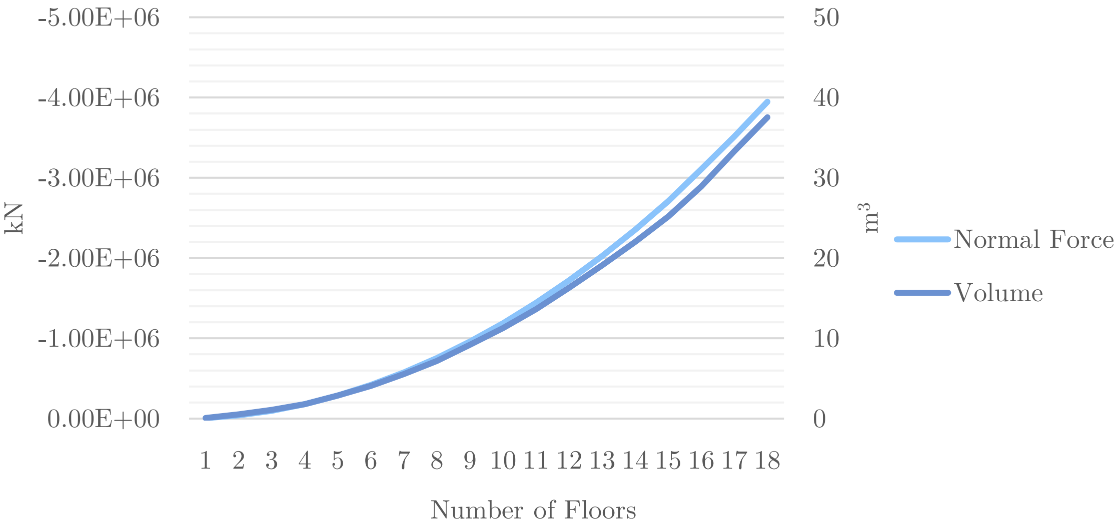

Figure 6.5 Normal Force in Columns versus Column Volume

If the contribution to the total EC is plotted in a line chart, the crossover points can be seen. Figure 6.6 shows the distribution of the steel frame variant, with each line representing an element type. The figure shows that up to 12 floors, the floor system contributes the most to the total EC; however, the columns will be the main contributor to the total EC from this crossover point onwards.

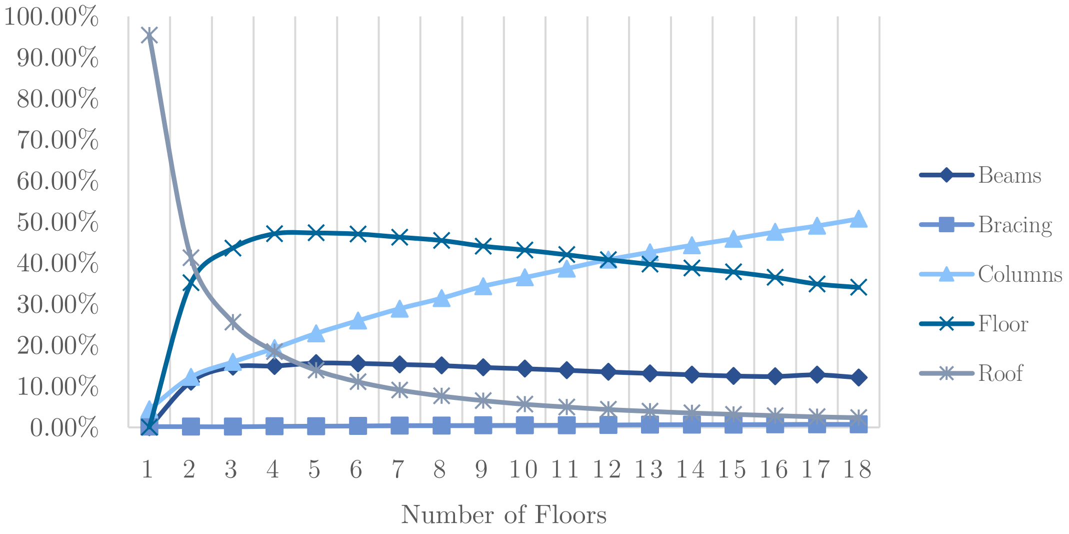

Figure 6.6 Embodied Carbon Distribution of Structural Elements, Steel Frame, Line

In Figure E.3 and Figure E.4 of Appendix E, the element contribution of the concrete and timber frame variants are plotted. For these two variants, the crossover point is not reached within 18 floors, and thus the floor will be the main contributor for most structures with these frames. This is further illustrated by Figure 6.7, which shows the volume and EC distribution of all three frame variants at 12 floors, the crossover point for the steel frame.

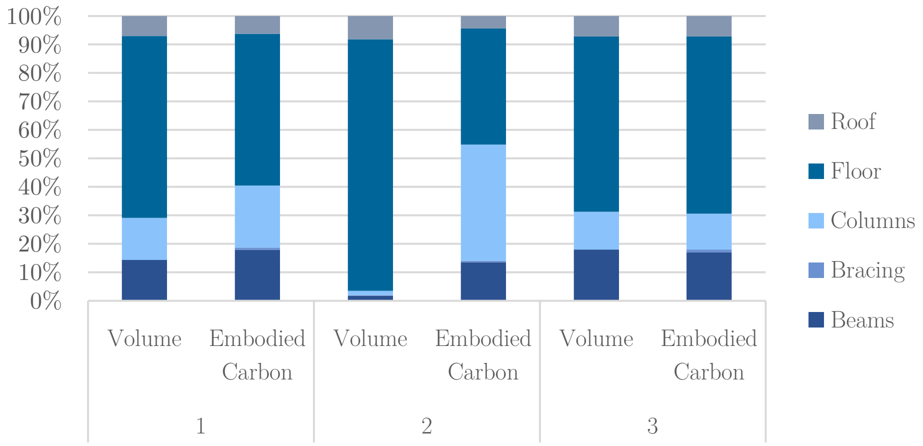

Figure 6.7 Volume vs Embodied Carbon Contribution by Element Type, 12 Floors

6.1.2.1 Variations

Design variant B is also investigated to validate the case study results, which showed that the building shape does not really influence the total EC if the number of floors stays the same. Next, the floor and beam span is increased for new variant D, which has the same design as variant A. All three variants are checked using a concrete frame structure as the behaviour of this frame was unique for the lower number of floors. The results are plotted in Figure 6.8 and show significant similarity between the design variants A and B, thus again showing that the building shape has little to no influence on the total EC. However, the increased spans of variant D clearly show an increase in EC. Therefore the floor and beam span will be the following parameter to be investigated.

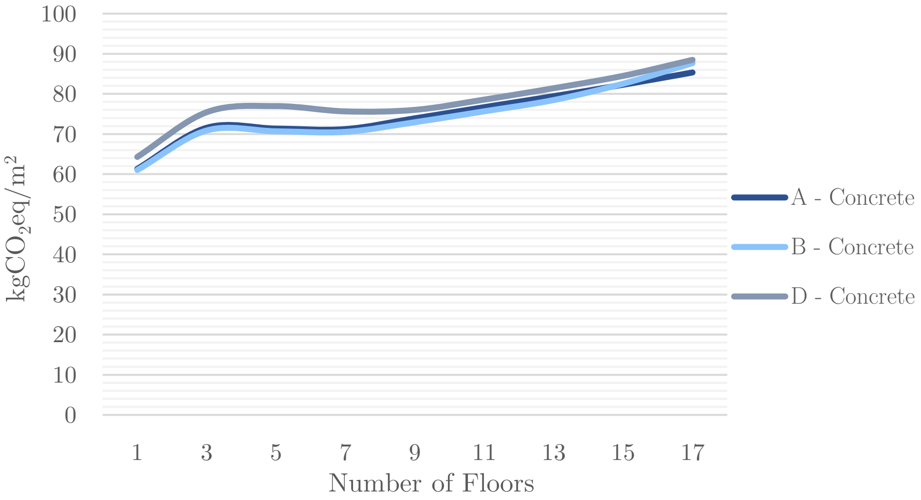

Figure 6.8 Embodied Carbon of Design Variations

6.1.3 Evaluation

The parameter study performed on the number of floors has shown multiple relations for the chosen variable design parameters. Performing this study also shows the method's potential for research purposes that could help define sustainable design guidelines. The first findings and careful conclusions are listed and discussed below.

- The increase in the number of floors results in a linear increase in total EC for all three different material variations. The slope of the linear increase is similar for a concrete and timber frame. The steel frame has a steeper slope showing a higher sensitivity to change. This is in line with the case study findings in Chapter 5.
- The increase in EC can be mainly attributed to the column elements, which are the most sensitive to the increase in the number of floors. The volumetric increase of material for the columns is exponential and similar for all three materials, with the steel columns in much lower quantities but the same exponential increase. As the increase is similar for all materials, the total EC increase is higher for steel due to its higher emissions per m^3.
- The increase in column volume is a result of the increase of the normal forces acting upon these columns. The normal force increases exponentially with the linear increase in the number of floors and has an almost one to one relation with the column material volume. As the normal force increases, the column dimension must as well, resulting in another increase in weight, and thus normal force resulting in the exponential increase.
- The increase in total EC of the floor elements is linear due to the linear increase in the number of floors and thus GIA. Due to the exponential increase in column material volume, the columns can become the largest contributor to the total EC. For the steel frame variant of this specific design, the cross over point is at 12 floors. Therefore, efficient column design is very relevant for taller buildings as this could save a lot of EC.
- The building shape was checked but showed very little influence on the total results, as was the case in the chapter 5 case study. The floor and beam span were also varied for variant D to see if the stability would be influenced. This variant shows a little increase in total EC and will be researched further in the following parameter study.

6.2 Floor Span

The previous studies have shown that the floors are the major contributor to the total EC due to their sheer volume. The span and loads dictate the floor's dimensions; therefore, it is investigated what influence the floor span has on the total EC. Variant D, Figure 6.8, also shows that increasing the floor span influences the total EC.

6.2.1 Case

To investigate the influence of the floor span, most parameters will be left fixed, and only the material and floor span are varied. The building design is based upon design variant A, Figure 6.1. The same three material variations are used as in the previous studies; however, the floor type is also varied to investigate any material-specific results for this study. Therefore, three combinations are made for the material variation, as shown in Table 6.2.

Table 6.2 Material Variation Floor Span Study

Variant	Beams	Columns	Floor
1	Concrete	Concrete	Hollow Core Slab
2	Steel	Steel	ComFlor
3	Timber	Timber	Lignatur

The floor span will be increased with steps of one meter, and the dimensions of the building are kept as similar as possible, as seen in Table 6.3. The width of the building, due to the floor span variations, will vary slightly among some of the steps. As most results are normalised with the GIA, the results will be comparable; however, the difference must be taken into consideration for some results that are not normalised.

Table 6.3 Floor Span Variation

Floor Span	Dimensions [m]	GIA [m^2]
15 x 2m	24 x 30	2880
10 x 3m	24 x 30	2880
7 x 4m	24 x 28	2688
6 x 5m	24 x 30	2880
5 x 6m	24 x 30	2880
4 x 7m	24 x 28	2688
4 x 8m	24 x 32	3072
3 x 9m	24 x 27	2592

6.2.2 Results

Figure 6.9 shows the total EC of the three different material variants across the increasing floor span. There is a clear difference in total EC between all three variants, with the concrete variant (1) causing double the amount of EC as the timber variant (3). The steel variant (2) is by far the most polluting variant, with up to double the EC of the concrete variant and quadruple that of the timber variant. In this figure, the dotted line represents the EC if the full recycling potential of the EPD data is used. This shows the same trend as in the previous studies, with steel and timber having a considerable recycling potential while concrete does not. However, it is also seen that even with this high potential, the steel variant still emits the most EC by a considerable amount.

However, the most important result of this figure is the relatively small influence of the floor span on the total EC. Only when the span reaches large values of eight or nine meters the increasing span causes an increase in EC. There are also clearly two bumps in the steel variant line, which, after some investigation, are the result of the floor span table provided for ComFlor design. The ComFlor suggested by these tables for the span of four and six meters are uneconomic when it comes to material use, thus causing a significant increase in EC.

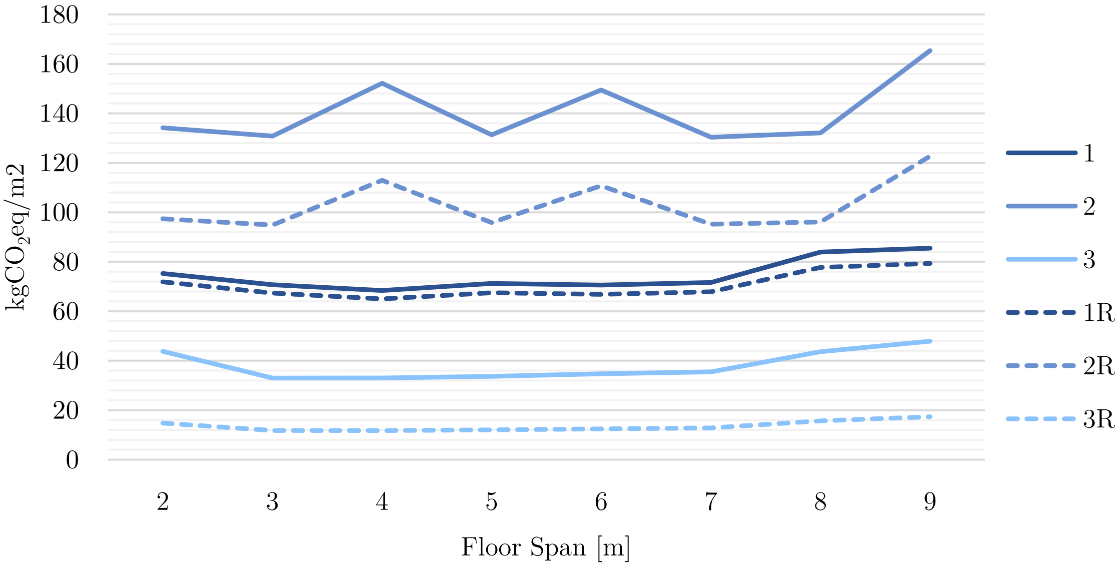

Figure 6.9 Total Embodied Carbon by Floor Span

The increasing floor span causes an increase in the floor height due to the moment capacity. It also creates a larger floor area with loads to be transferred to the supporting beams. Together with these beams, and the minimum free height requirement, the floor defines the height of each building level, or floor to floor height. The influence of the increasing floor span on the floor to floor height is illustrated in Figure 6.10. The figure shows a continuous increase for all three variants. The timber floor starts with a higher floor to floor height, mainly due to SLS deformation constraints resulting in relatively large dimensions for the beams. The governing SLS deformation constraints make the timber structure less sensitive to an increasing floor span as the beams are underutilized for their load capacity.

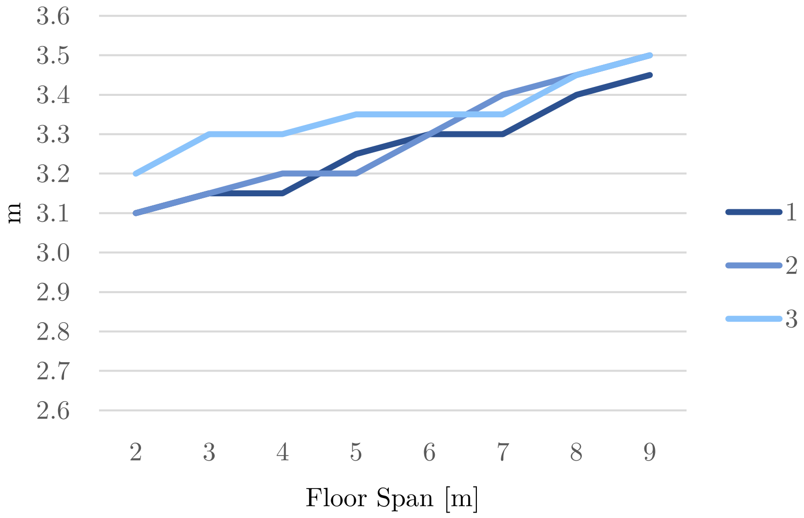

Figure 6.10 Floor to Floor Height by Floor Span

The increasing floor to floor height suggests that the size of the floors and beams increases with the increasing floor span. This increase in element size will also directly increase weight and thus normal forces acting upon the columns. Therefore the columns will increase in size as well. However, the total EC does not reflect this increase in element size. Looking at the volume of the beams and columns might explain why. By plotting the volume of the elements against the floor to floor(FtoF) height, it is possible to investigate a relation between these two results, as seen in Figure 6.11. All three variants show a similar trend in the volume of the beams and columns. In all variants, the total beam volume decreases, and the column volume stays relatively constant, while the floor to floor height and this element height increase. The initial large volume of timber beams due to the deformation constraints can also be seen.

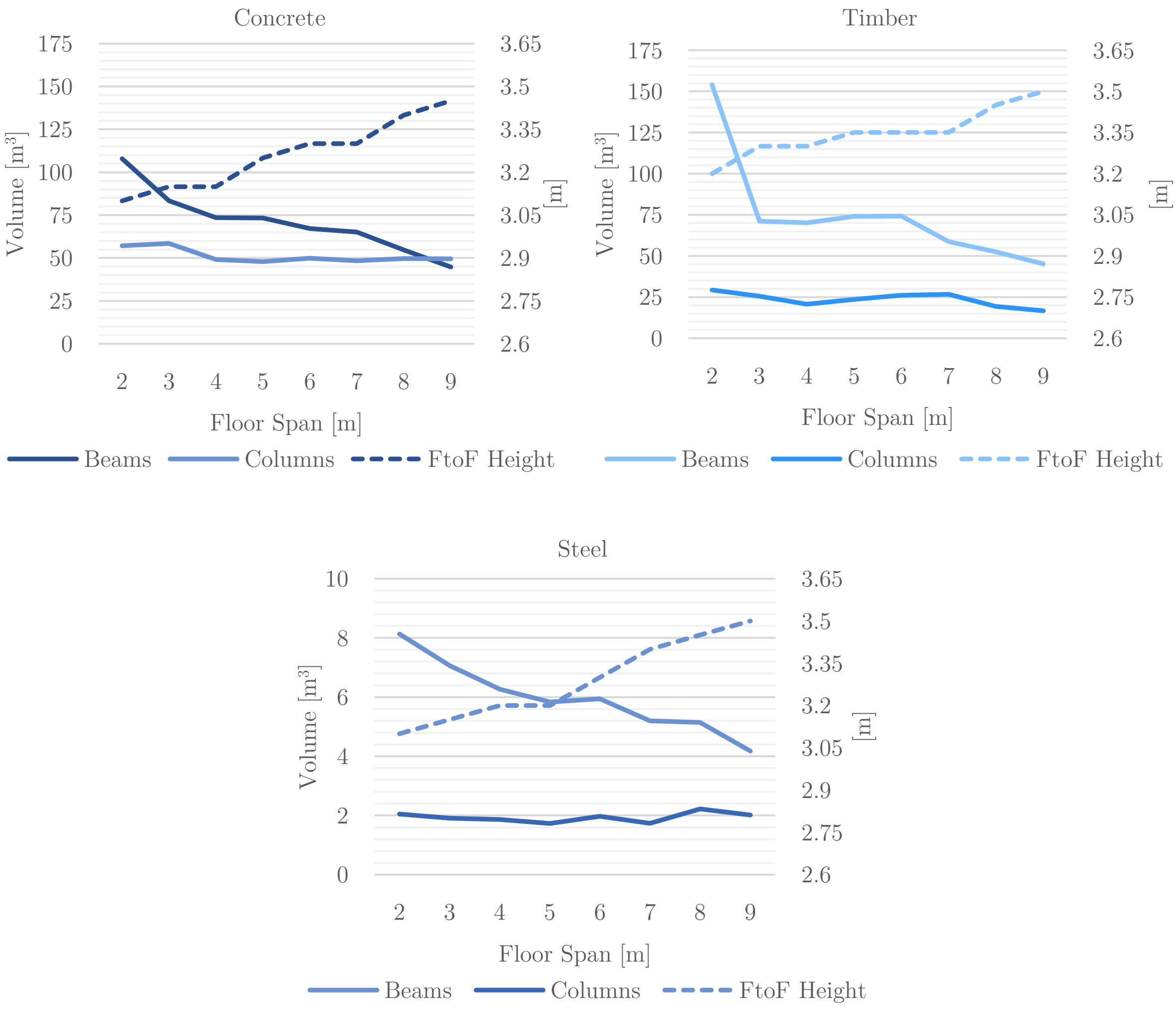

Figure 6.11 Volume vs Floor Height by Floor Span of Material Variations

A higher floor to floor height resulting in less volume is somewhat counterintuitive; however, the number of beams within the structure explains this relation. Because of the boundary conditions, the structure will be of similar size; thus, an increasing floor span decreases the number of beams and columns. Figure 6.12 shows the number of beams plotted with the EC of the beams. It is clearly visible that the number of beams decreases significantly in the first steps, causing the EC of the beams to go down rapidly as well. This decrease in the number of beams becomes smaller for larger spans, and the decrease in EC slows down as well. This shows that the decrease in the number of elements outweighs the increase in element size for the beams. Combining Figure 6.11 with Figure 6.12, a similar conclusion can be made for the columns, where the increase in column size and decrease in the number of columns balances out, resulting in a constant volume and EC.

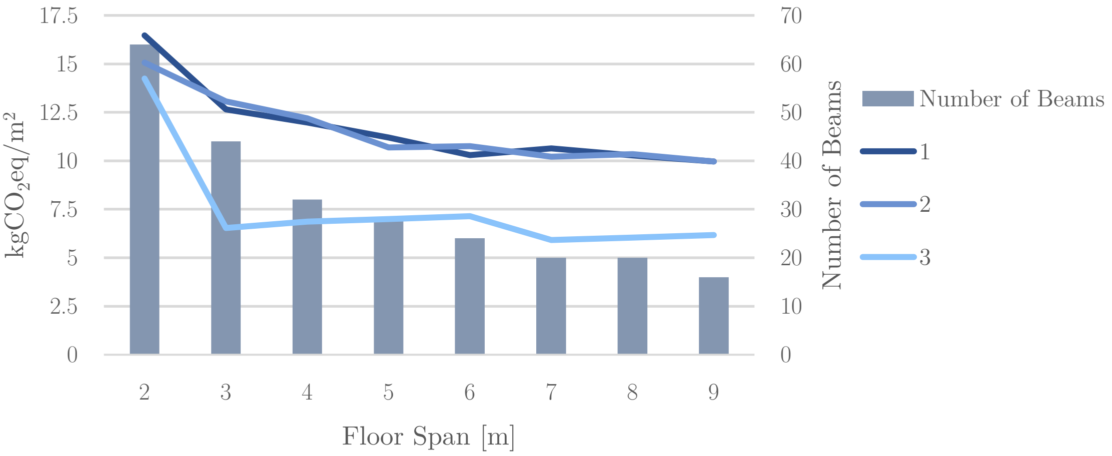

Figure 6.12 Column Embodied Carbon vs Number of Columns by Floor Span

6.2.3 Evaluation

The floor span was investigated as the floor elements often account for the majority of the material volume and would thus possibly have a significant influence on the EC of the structure. However, the parameter study has shown that this is not directly the case when boundary conditions are set. The most important results are listed and discussed below.

- The total EC is not sensitive to an increasing floor span up to 7 meters, after which the EC will increase slightly. The ComFlor- steel frame variant shows inconsistent results due to the uneconomic options given by the floor span provided for the ComFlor.
- The ComFlor- steel frame and Lignatur- timber frame variant have large recycling potential, whereas the Hollow Core- concrete frame variant does not. The ComFlor variant still results in the most EC but can save up to 27% with optimal recycling. The Lignatur variant becomes even more favourable and is by far the most sustainable.
- The increase in floor span leads to an increase in the element height of the floors and beams. Combined with the minimum height requirement, this increases floor to floor height. However, while this results in higher beams and longer columns, the volume of these elements decreases with an increasing floor span. The decrease results from a decrease in the number of beams and columns in the structure with an increasing floor span, as the boundary conditions limit the dimensions of the building. The decrease in the number of beams and columns outweighs the increase in element dimensions.
- The timber elements are primarily governed by the deformation limits when the floor span is small—suggesting that it is uneconomical to design timber structures when the deformation limits are largely governing. Larger spans can be more sustainable if that results in fewer elements with similar dimensions.
- The final results indicate that an increasing floor span has little effect on the total EC. However, this can only be said about the structure itself, as an increase in the floor to floor height would result in a larger façade and more interior finishing material. Therefore, for the entire building, the increase in the floor to floor height is unfavourable while structurally, it is neutral, and these results are only a part of the complete picture.

6.3 Reinforcement Ratio

As the previous case studies have shown, the floor to floor height can influence the total EC of the structure. The floor to floor height is determined by the element height of the beams and floor, which is mainly governed by the necessary bending resistance and deformation limits. Within concrete structures, most bending resistance is gained from the use of steel reinforcement. As the previous studies have shown, steel contributes significantly to the total EC, especially for its small volumes. However, using more reinforcement would result in higher bending resistance and more slender beams, resulting in a lower floor to floor height. This study will research what influence the reinforcement ratio will have on the total EC.

6.3.1 Case

For this case, design variant A, Figure 6.1, will be used with steel bracing and concrete beams and columns. All other parameters will stay fixed and are identical to the case study in chapter 5. The reinforcement ratio will be increased with 0,5% increments until 4% as this is the maximum reinforcement ratio according to NEN-EN 1992-1-1 (NEN, 2020).

6.3.2 Results

The total EC decreases when the reinforcement ratio increases, as seen in Figure 6.13. The EC decreases from 80 $kgCO_2eq/m^2$ to around 61 $kgCO_2eq/m^2$ which is a 24% decrease. This lowest total EC is already reached at a 3% reinforcement ratio and stays stable if the ratio is increased more. As expected, the floor to floor height decreases with an increasing reinforcement ratio as the elements become more slender. This increasing slenderness is likely the reason for the decrease in total EC. However, this must be investigated further.

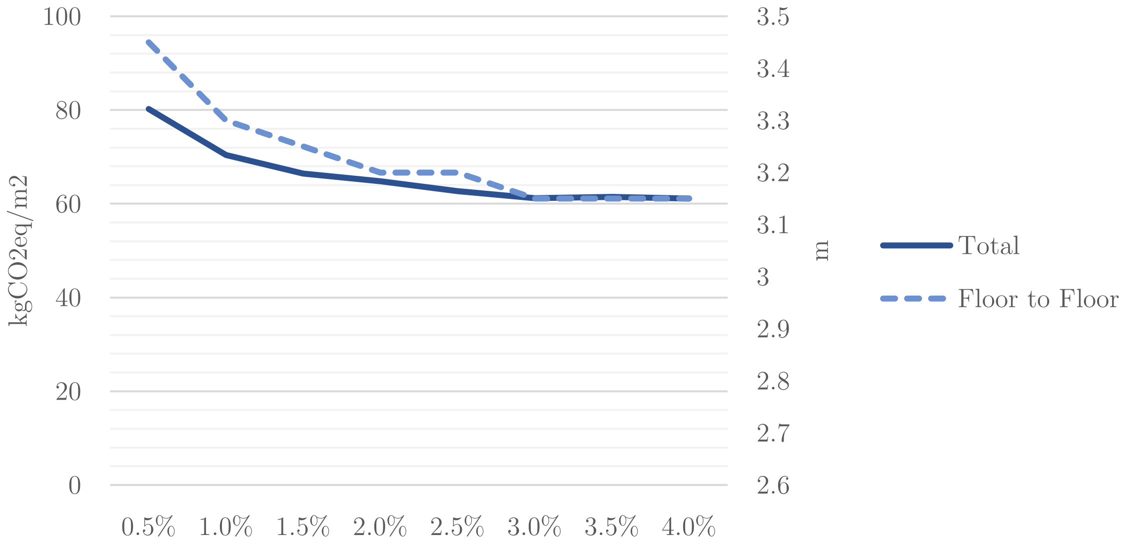

Figure 6.13 Total Embodied Carbon and Floor to Floor Height of Reinforcement Ratios

Plotting the volume of the three most relevant materials for this study gives an insight into the relationship between these elements. The steel reinforcement volume is plotted on its own axis as its significantly lower than the concrete volumes. Figure 6.14 shows that while the reinforcement volume increases up to 135%, the concrete volume of the beams decreases up to 71%. This decrease is especially large for the smaller reinforcement ratios, where a lot of concrete is saved by increasing the reinforcement ratio. This relation explains the decrease in total EC as the decrease in concrete volume outweighs the increase in reinforcement volume, as is illustrated in Figure 6.15, where the EC of the concrete beams decreases far more than the increase in EC of the steel reinforcement. The columns show little to no sensitivity to the changing reinforcement ratio and increasing slenderness of the beams. This is in line with the earlier case studies that showed concrete structures have a low sensitivity to changes when the number of floors does not exceed six.

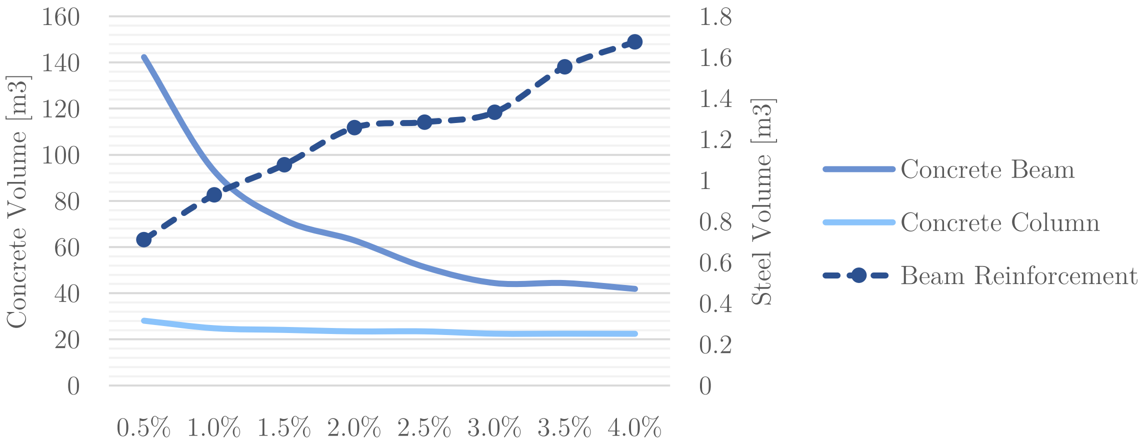

Figure 6.14 Volume of Concrete Beams, Columns, and Steel Beam Reinforcement

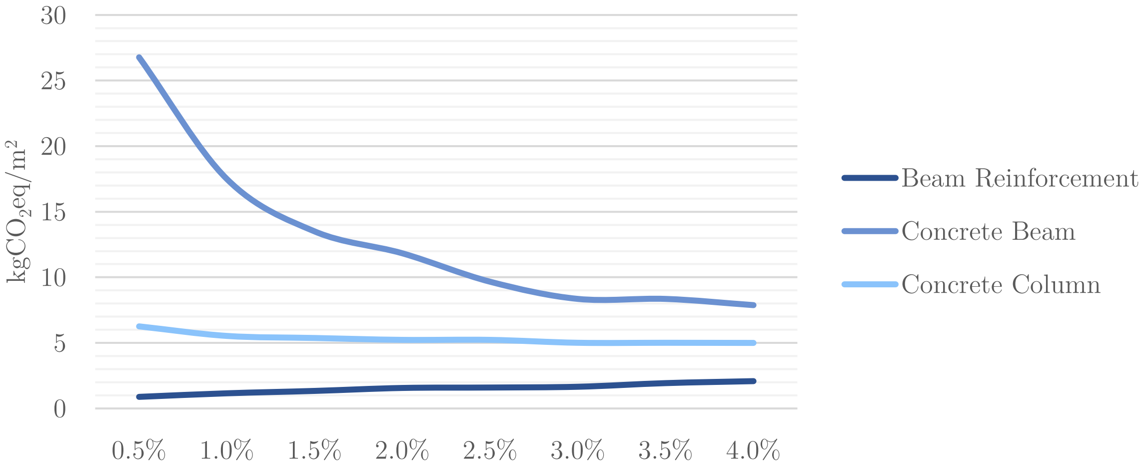

Figure 6.15 Embodied Carbon of Concrete Beams, Columns, and Steel Beam Reinforcement

The influence of increasing the reinforcement ratio can also be visualised by comparing the material volume, material weight, and EC in a bar chart, as seen in Figure 6.16. The figure shows that the reinforcement volume is almost insignificant to the total; however, the impact is clearly visible. The EC of the beam reinforcement increases, but the decrease in concrete volume, and its EC, decreases much more, which causes the total EC to drop. This indicates that an increased reinforcement ratio is favourably for reducing the total EC of the structure.

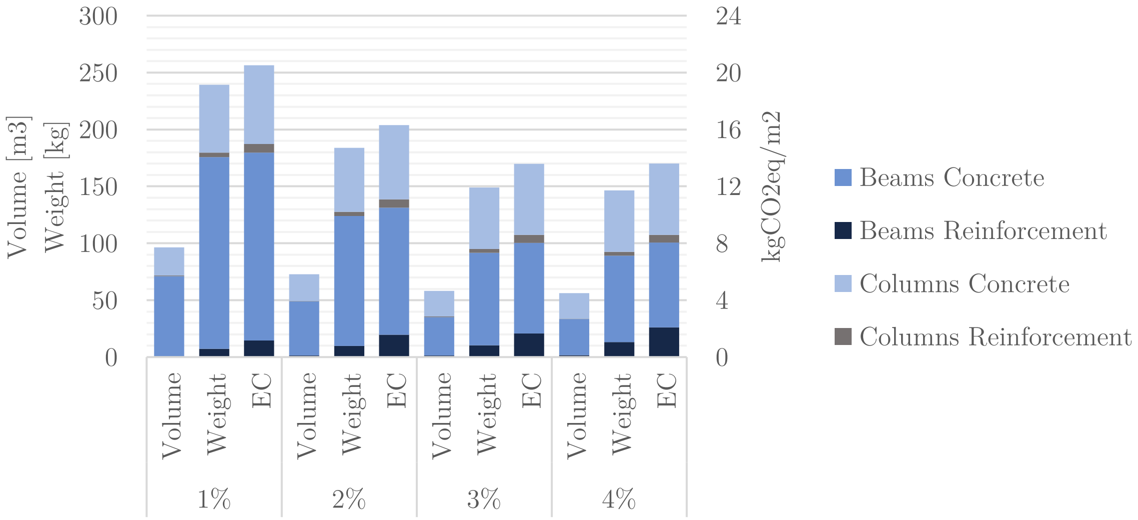

Figure 6.16 Volume vs Weight vs Embodied Carbon of Reinforcement Ratios

Lastly, recyclability can be of importance to the final result. The total recycling potential of stage D is plotted in Figure 6.17 for each reinforcement ratio. It can be seen that increasing the reinforcement ratio is unfavourable for the recycling potential. Steel reinforcement has a negative recycling value as it must be removed from the concrete, which requires more energy and thus emissions. However, Figure 6.14 shows that the material quantities of the concrete beams decrease significantly, resulting in less material to be recycled, thus lower recyclability potential but also resulting in a lower total EC. Therefore, the lower recyclability is actually a 'positive' result of the decrease in material volumes due to the increase in reinforcement ratio.

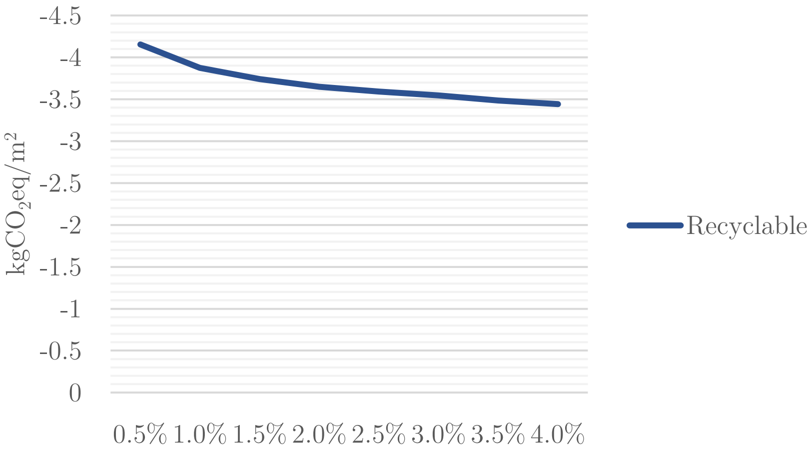

Figure 6.17 Recyclability of Structure by Reinforcement Ratio

6.3.3 Evaluation

The parameter study on the reinforcement ratio was performed to investigate the possible influence of a relatively material-specific parameter. The results have shown that the reinforcement ratio influences the total EC and should be taken into consideration for the early structural design. The most important results are listed and discussed below.

- Increasing the reinforcement ratio leads to a decrease in total EC up to a ratio of 3%, after which the EC remains constant. The increasing reinforcement ratio leads to more slender element designs, which in turn reduce the floor-to-floor height. As mentioned in the floor span study, the floor-to-floor height significantly influences the EC of the non-structural elements within a building; therefore, reducing the floor-to-floor height is a favourable property.
- The primary source for the decreasing EC is the decrease in concrete material used for the beams due to the increasing slenderness. While previous studies have shown that the small volume of steel has a significant impact, the decrease in concrete, -71%, outweighs the increase in steel reinforcement, +87%.
- All things considered, this study suggests that there is an optimal range for the reinforcement ratio for the chosen building design. A higher ratio is more favourable and would reduce the total EC structurally and non-structurally. However, this can only be said about a structure similar to the one used in the study, and more design variations must be investigated to validate this suggestion.

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7 Discussion

The goal of the project was to integrate BIM and LCA and find the possibilities to guide engineers in reducing the emissions related to the structure. The developed method shows that integrating these different tools can help make sustainable design decisions by using the design variations and the findings of the parameters research. However, simplifications were made for the project's feasibility, and boundaries were set. The implications of these limitations are discussed.

7.1 Parametric model

The parametric model is the core of the project and is used to generate a large variation of dimensioned concept structures. As the concepts are made for the early design stage, many factors and details are still unknown; therefore, a global design approach is taken. The generation of structural concepts comes with some simplifications that should be considered.

Firstly, the design parameters chosen allow for millions of variations but do still limit the scope of the study. The main limitations of the parameters are related to the geometry. For the purpose of this study, the geometry was limited to a rectangular floor plan, as this is the most common floor plan used in reality. The structural grid is also rectangular and uniform along the axis, limiting the optimisation of stability systems. The three material options, including many material grades, used in the model cover the large majority of the structures built in reality. Together, these parameters do not cause any inaccuracies and encompass most of the structures built; however, they create boundaries that limit the results' scope.

Secondly, there are also limitations within Grasshopper, and the plug-ins used should be noted as they cause inaccuracies. The geometry is generated using the parameters resulting in a line model where the elements are connected in a point node. This type of node causes the volumetric elements to overlap at these nodes resulting in more material used than necessary. This is acceptable but should be noted, as the model represents an early design stage where the detailed connections are made later in the design process.

The tool Karamba3D is used to define and assign cross-sections based on their optimal, minimal, cross-sectional area. A limitation of this tool is the lack of reinforced elements resulting in the external optimisation script made to bypass this limitation and assign concrete elements with reinforcement considered. This script is based on the method used by Karamba3D; however, it is less extensive than the tool itself, and therefore some consistency is lost in assigning the cross-section.

Lastly, the cross-section design is entirely based on satisfying basic structural requirements, loads and deformations resulting from the design parameters. In reality, the structure should also be checked on other building physical properties, such as acoustics, fire safety, and thermal bridges. This is especially the case for steel and timber elements which could require increased dimensions to satisfy the structural and non-structural requirements. Timber structures also often require steel connections with bolts and nails, which can have a significant impact even in their small quantities. Finally, the foundation of the structure is not considered for the scope of the study as there are many location-specific variables involved, such as soil, wind and climate. This simplification can be a significant influence, especially for larger structures and should be researched further.

7.2 Life-Cycle Analysis

The LCA performed in this project focuses on EC as this is the most important metric for the structure's environmental impact. Embodied carbon is a holistic approach; therefore, it does not include a detailed analysis of elements. The process of calculating EC is straightforward and relatively simple. However, this approach requires assumptions to be made for location-specific data and data availability.

The data used for the study focuses on northwestern countries; thus, the analysis performed can only be applied to this region of the world. The transportation stage A4 is a location-specific result and can influence the final result modestly. For this study, the data used for A4 is based on the average distance the manufacturer assumes to its customers, which is a simplification.

LCA data can often be found in databases, but many require licensing and are therefore unavailable for this study. This results in the LCA data being gathered from public EPDs published for the northwestern scope. Therefore the data can be skewed due to the limited amount of manufacturers represented in the data. However, averaging data is an inherent simplification in performing a global LCA study and should give a fair representation of the average emissions caused by the structure. If the manufacturers are known by the designer, the data used for the LCA should be adjusted accordingly.

7.3 Research

The studies done in this project show the potential of using the method as a design tool and a research tool. However, the early design stage does require simplifications and assumptions to generate design variations and perform quick LCAs. These simplifications and assumptions work their work down and apply to the studies performed and their results. This includes overlapping elements at the nodes, simplifications in cross-section assignment and generalised LCA data.

Therefore the results from the studies should always be looked at critically and need to be validated. The studies performed also limit themselves to a number of design variations for the project's feasibility. The results can only be applied to similar building designs and need to be validated or explored more extensively with different design variations. Because of the simplifications, assumptions and inaccuracies, the results of the research studies are an indication and cannot be used as final results without further research, comparisons and validation.

8 Conclusion

For this thesis, a parametric method was developed to investigate the potential of integrating BIM and LCA for design and research purposes. The goal is to help engineers make smart and sustainable design choices in the early, concept, structural design stage.

8.1 Research Sub-Questions

How can parametric design generate quick and structural valid early designs?

A parametric design tool was developed to generate different structural models using straightforward design parameters. The structure's geometry is wholly dependent on the design parameters allowing the user to define the exact geometry of the structure within the boundaries and limitations set for this project. All loads and connections are defined automatically based on the geometry and boundary conditions. Using a cross-section optimisation tool such as Karamba3D, the dimensioning and assigning of cross-sections will be automated and consistent. Integrating the parametric geometry, the load definition, and Karamba3D, the combined tool allows for the parametric design of structures sufficing the structural requirements set by the user and Eurocodes 1, 2, 3 and 5.

Which life cycle stages are relevant for embodied carbon in early design?

EC is used as the impact indicator for structures, which is a holistic approach. To determine the EC of a structure, manufacturers' environmental carbon data is often referred to as GWP. The majority of the EC is released during the product stage A1-A3, with timber structures also having high EC emissions for the end of life stages A2-A4 due to its carbon sequestration. The production stage accounts for up to 90% of the total EC of the structure. Therefore this stage itself should also be the focus of sustainable improvements. Therefore, the manufacturers also play a large role in reducing the EC of structures by optimising and reducing their production process emissions. This shows that reducing the carbon footprint is a collaborative process involving many different parties.

How can the embodied carbon and its feedback be visualised?

The SCT provides direct insights into the distribution of EC by element type and generates carbon scores. With the comparison sheet, the tool allows for a direct one to one comparison or a comparison of a collection of design variations. These insights can instantly help engineers make choices based on these graphical results. The visual feedback can also be done within the parametric environment by looping back the LCA results and highlighting the elements with colours representing EC results, as is done by some existing LCA tools. To gain fundamental insights into the design choices, they needed to be analysed and visualised into charts manually. This leaves an area for improvement in the efficiency of the method.

What assumptions and simplifications have to be made?

Integrating BIM, LCA, and a parametric design requires simplifications and assumptions across all levels. This is the result of EC's holistic approach and the goal to encompass many different design possibilities into a single method. The early design stage allows for the inaccuracies these simplifications and assumptions cause, as the goal is to indicate carbon hotspots and unfavourable design choices. Simplifications are made for the geometric model, geographical scope and transport data, and assumptions are made for load cases and stability elements. Together these make for the results to be only used as a guideline and indication, and furthermore, a detailed analysis must be done in more advanced design stages.

Can an integrated method be used to generate guidelines?
The integrated method has been shown to provide design choice impacts, and when combined with more detailed data analysis, specific parameters can be researched. This gives two ways of guiding engineers with their design choices. The method allows for parameter specific studies to be performed as done in the parameter studies in this thesis. Indicating that increasing building height always leads to an increase in EC, an increasing floor span has little influence on the EC of the structure, and an increasing reinforcement ratio is favourable for the total EC both structurally and non-structurally. Extensive studies on specific parameters can be done to draw conclusions on the influence of specific parameters. These conclusions can be used to set up guidelines for sustainable structural design decisions.

8.2 Research Question

How can Life Cycle Analysis, Building Information Modelling and Parametric Design be integrated to assist designers in reducing embodied carbon emissions in the early design stages?
The increasing development in digital tools for designing buildings brings the opportunity to integrate structural design with sustainable decision making. Sustainable decision making is most effective if used in the early stage of the design process where important global design choices are made. Using a parametric modelling environment such as Grasshopper makes it possible to generate geometric design variations with simple design parameters. Using a tool such as Karamba3D turns the geometric model into a cross-sectional optimised structural BIM model that contains the necessary information to perform an LCA. By exporting the data to the SCT, an LCA can instantly be performed with automated data filtering, and its results are visualized. This method allows for multiple design variations to be generated quickly, exported and analysed within the same two software environments. This will allow the engineer to gain quick insight into which design decision and concept is sustainable. The data can also be analysed more deeply to better understand the influences of design decisions on the EC of the structure. More extensive research could create design guidelines based on the parameter influence and allow engineers to make sustainable decisions without investigating each possible design variation.

To conclude, creating a live connection between two different software makes it possible to get instant LCA results for multiple structural concepts. With the possibility of comparing multiple designs, the engineer can make sustainable design choices and gain knowledge on the influence of the design variations. The project has shown the potential to integrate LCA into the digital design process with a relatively simplistic method. With better internal software integration, a broader spectrum of environmental data, increased sustainable knowledge, and the help of guidelines, engineers can be helped to reduce the EC of their structural designs.

9 Recommendations

9.1 Parametric model

The parametric model is limited to the feasibility of this master's thesis and the set time frame. The geometric model has been limited to rectangular floor plans and a regular grid. The geometric model should strive for complete freedom of, simplified, design concepts for further development. This can include the implementation of importing geometries from other software. The load cases and load values are determined for the case studies performed; adding more building functions, including the corresponding load cases and values, would necessitate implementation for broader use.

Another recommendation is to visualize the LCA result onto the geometric model, highlighting the hotspots. This would allow for even more direct feedback and information to help the engineer understand the impact of the different design concepts. Another improvement would be performing the LCA within the parametric design software, as the calculations are relatively simple and would not require additional computational power. Only then the BIM and LCA will be fully integrated.

9.2 Life-Cycle Analysis

LCA has been around for decades; however, the implementation of this method has been limited. Also, the interpretation of how to perform an LCA varies among studies and even among EPDs. Therefore, a consistent set of rules should be developed to ensure data quality and avoid discrepancies in the calculation. Next to that, the environmental data is often not publicly available, if available at all. This is caused by different regulations in each country. Because the data is often behind a paywall, it is another hurdle that can scare off potential users; thus, the aim of the built environment should be to create openness on this data.

The case studies and literature research indicated that the product stage A1-A3 account for the most EC by far. Therefore, the method of calculating embodied carbon for structures could also be simplified to only using product stage data A1-A3. This is already done for certain EPDs and would simplify the process. However, the implications of this simplification must be investigated to ensure the inaccuracy in results does not invalidate the method.

The results of this research entirely focus on the structure of a building. However, there is more to a building that can be influenced by the design parameters used for the structure. These non-structural elements, such as a façade or internal finishing, also have their own GWP and, therefore, play a role in the carbon footprint. The relation between the structural parameters and non-structural elements should be investigated to create a complete picture.

This project aimed to investigate and develop a method that could guide engineers in making sustainable designs. More extensive research on parameters and improving the quality of the structural model will make it possible to draw conclusions on the influence of structural design parameters. This could be achieved by using tools such as One Click LCA, which have developed integration of multiple BIM software over the past year, including Grasshopper. Sustainable design guidelines should be developed to help guide and educate engineers on their design decisions. In combination with this, the basic knowledge of engineers on the topics of LCA and sustainable design can be improved. This can help engineers start with more efficient and sustainable designs and streamline decision making. In general, the whole topic of LCA is still in development with much room for interpretation. More effort must be put into developing, legislating, and implementing a streamlined and consistent LCA to achieve the carbon goals.

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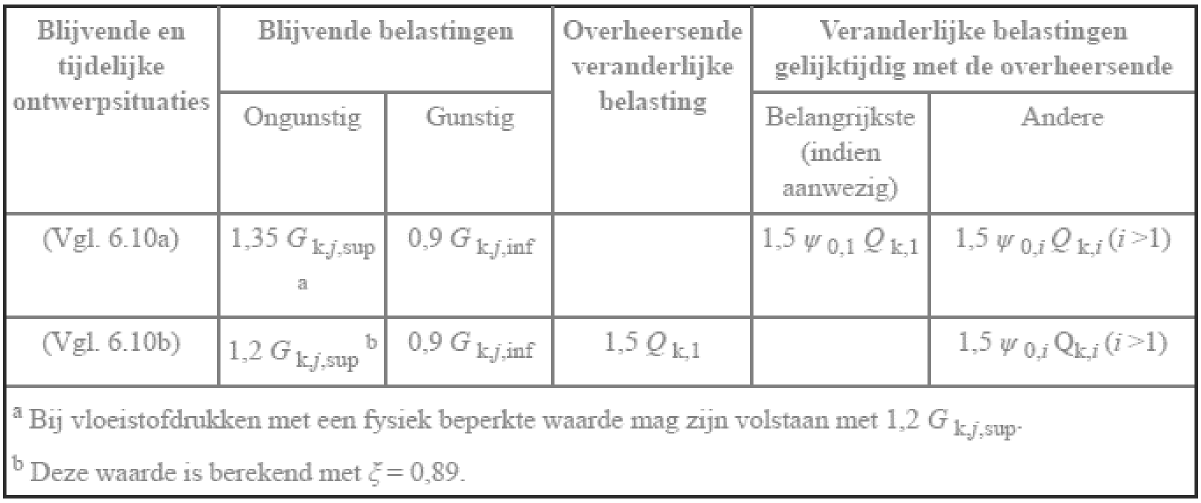
Appendix A

A.1 Eurocode – Basis of Structural Design

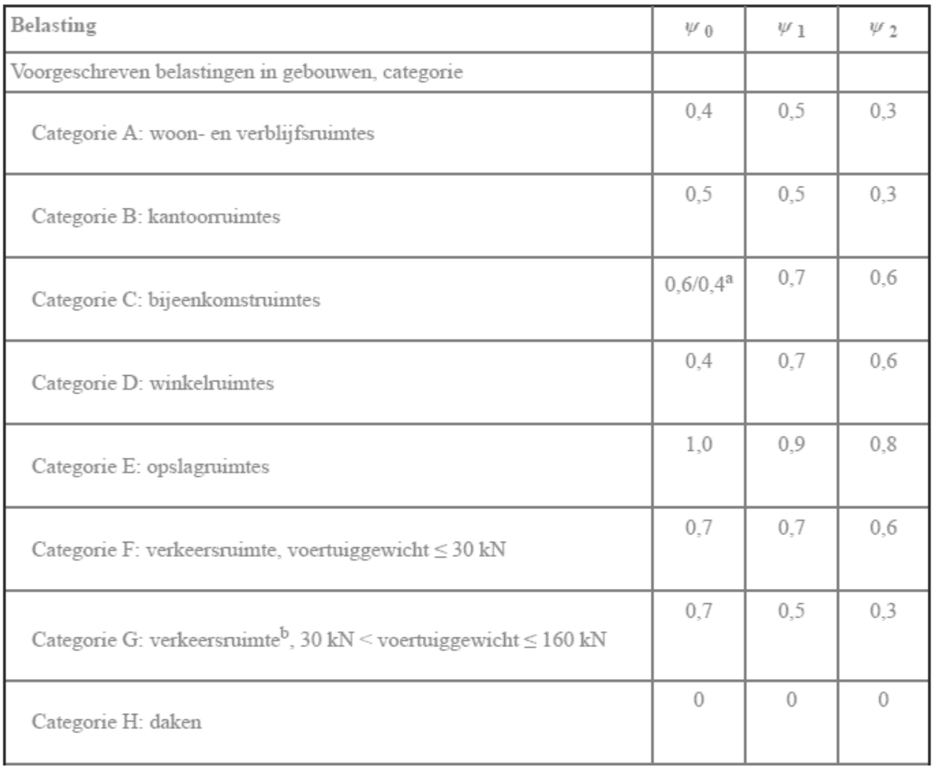


Blijvende en tijdelijke ontwerpsituaties	Blijvende belastingen		Overheersende veranderlijke belasting	Veranderlijke belastingen gelijktijdig met de overheersende	
	Ongunstig	Gunstig		Belangrijkste (indien aanwezig)	Andere
(Vgl. 6.10a)	$1{,}35\ G_{k,j,sup}$ [a]	$0{,}9\ G_{k,j,inf}$		$1{,}5\ \psi_{0,1}\ Q_{k,1}$	$1{,}5\ \psi_{0,i}\ Q_{k,i}\ (i > 1)$
(Vgl. 6.10b)	$1{,}2\ G_{k,j,sup}$ [b]	$0{,}9\ G_{k,j,inf}$	$1{,}5\ Q_{k,1}$		$1{,}5\ \psi_{0,i}\ Q_{k,i}\ (i > 1)$

[a] Bij vloeistofdrukken met een fysiek beperkte waarde mag zijn volstaan met $1{,}2\ G_{k,j,sup}$.

[b] Deze waarde is berekend met $\xi = 0{,}89$.

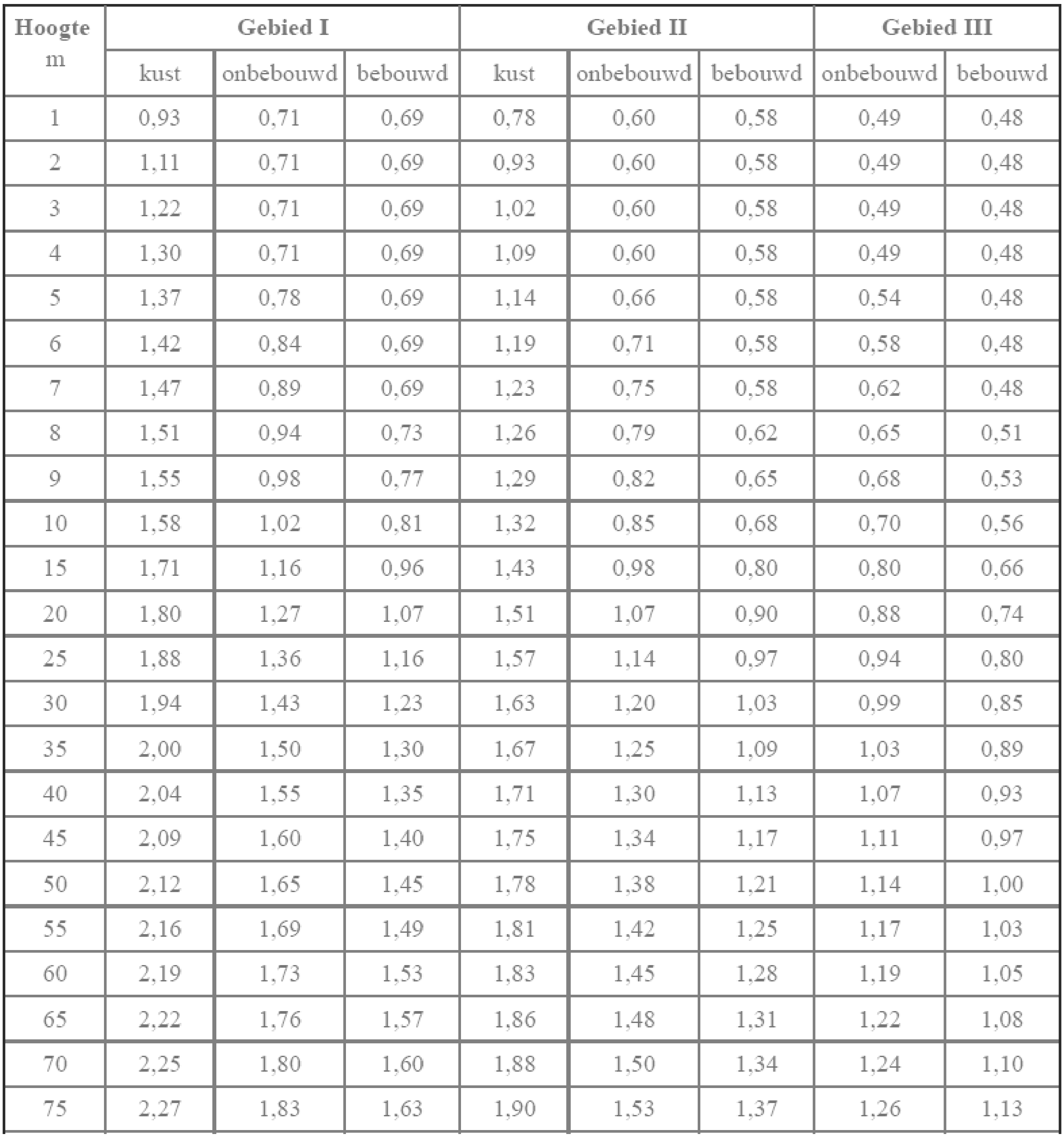
Table A.1 Load Combinations, Table NB.4 – A1.2 NEN-EN 1990_2002



Belasting	ψ_0	ψ_1	ψ_2
Voorgeschreven belastingen in gebouwen, categorie			
Categorie A: woon- en verblijfsruimtes	0,4	0,5	0,3
Categorie B: kantoorruimtes	0,5	0,5	0,3
Categorie C: bijeenkomstruimtes	0,6/0,4[a]	0,7	0,6
Categorie D: winkelruimtes	0,4	0,7	0,6
Categorie E: opslagruimtes	1,0	0,9	0,8
Categorie F: verkeersruimte, voertuiggewicht ≤ 30 kN	0,7	0,7	0,6
Categorie G: verkeersruimte[b], 30 kN < voertuiggewicht ≤ 160 kN	0,7	0,5	0,3
Categorie H: daken	0	0	0

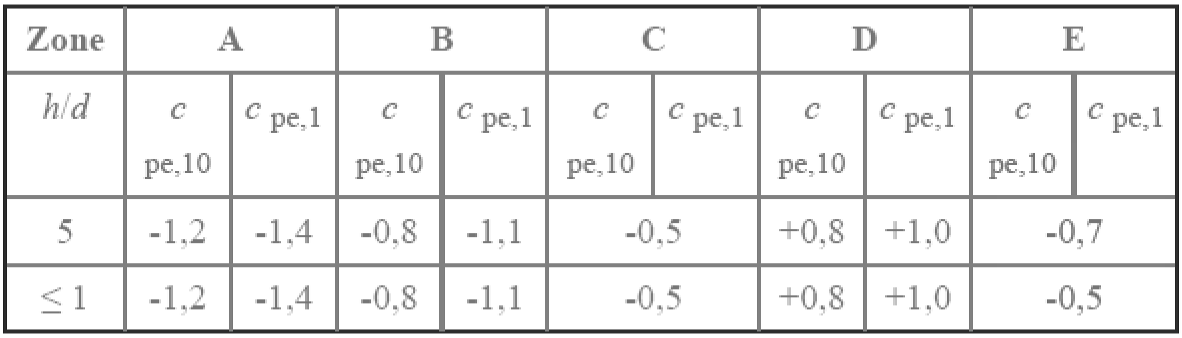
Table A.2 Combination Factors, Table NB.2 – A1.1 NEN-EN 1990_2002

A.2 Eurocode 1 – Loads



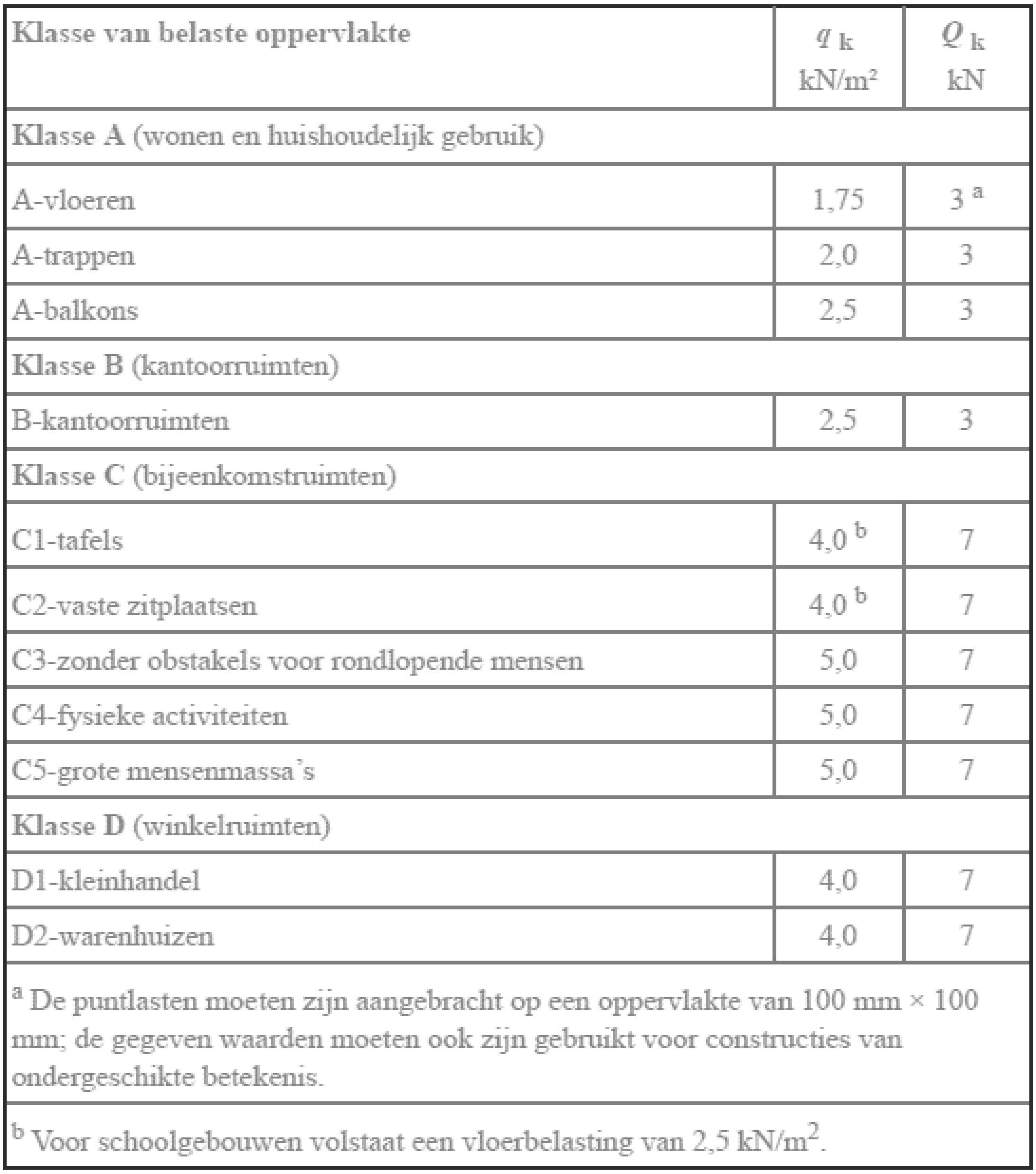
Hoogte m	Gebied I			Gebied II			Gebied III	
	kust	onbebouwd	bebouwd	kust	onbebouwd	bebouwd	onbebouwd	bebouwd
1	0,93	0,71	0,69	0,78	0,60	0,58	0,49	0,48
2	1,11	0,71	0,69	0,93	0,60	0,58	0,49	0,48
3	1,22	0,71	0,69	1,02	0,60	0,58	0,49	0,48
4	1,30	0,71	0,69	1,09	0,60	0,58	0,49	0,48
5	1,37	0,78	0,69	1,14	0,66	0,58	0,54	0,48
6	1,42	0,84	0,69	1,19	0,71	0,58	0,58	0,48
7	1,47	0,89	0,69	1,23	0,75	0,58	0,62	0,48
8	1,51	0,94	0,73	1,26	0,79	0,62	0,65	0,51
9	1,55	0,98	0,77	1,29	0,82	0,65	0,68	0,53
10	1,58	1,02	0,81	1,32	0,85	0,68	0,70	0,56
15	1,71	1,16	0,96	1,43	0,98	0,80	0,80	0,66
20	1,80	1,27	1,07	1,51	1,07	0,90	0,88	0,74
25	1,88	1,36	1,16	1,57	1,14	0,97	0,94	0,80
30	1,94	1,43	1,23	1,63	1,20	1,03	0,99	0,85
35	2,00	1,50	1,30	1,67	1,25	1,09	1,03	0,89
40	2,04	1,55	1,35	1,71	1,30	1,13	1,07	0,93
45	2,09	1,60	1,40	1,75	1,34	1,17	1,11	0,97
50	2,12	1,65	1,45	1,78	1,38	1,21	1,14	1,00
55	2,16	1,69	1,49	1,81	1,42	1,25	1,17	1,03
60	2,19	1,73	1,53	1,83	1,45	1,28	1,19	1,05
65	2,22	1,76	1,57	1,86	1,48	1,31	1,22	1,08
70	2,25	1,80	1,60	1,88	1,50	1,34	1,24	1,10
75	2,27	1,83	1,63	1,90	1,53	1,37	1,26	1,13

Table A.3 Extreme Wind Load, Table NB-1 NEN-EN 1991-1-4



Zone	A		B		C		D		E	
h/d	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$
5	-1,2	-1,4	-0,8	-1,1	-0,5		+0,8	+1,0	-0,7	
≤ 1	-1,2	-1,4	-0,8	-1,1	-0,5		+0,8	+1,0	-0,5	

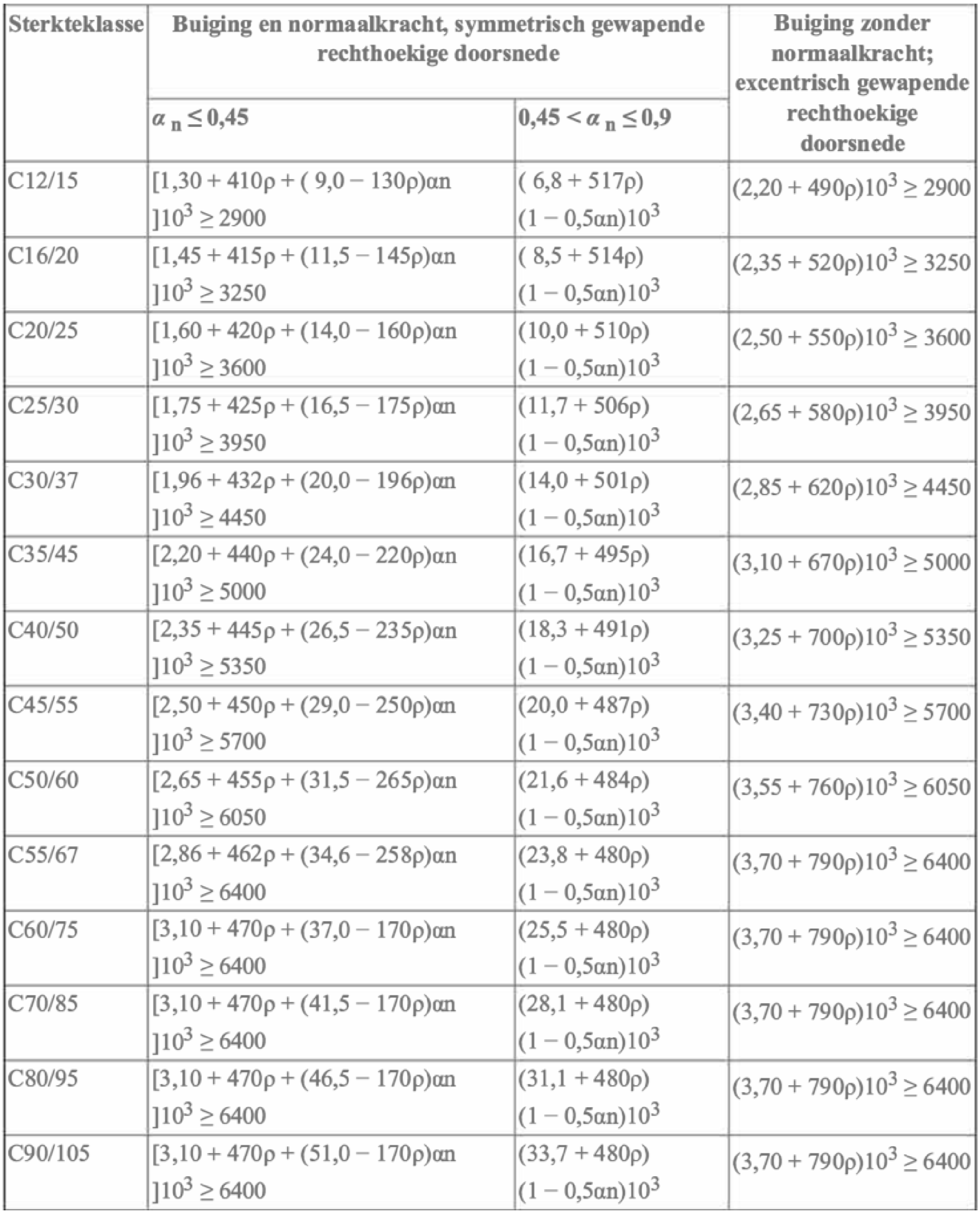
Table A.4 Pressure Coefficient C_{pe}, Table NB.6 – 7.1 NEN 1991-1-4



Klasse van belaste oppervlakte	q_k kN/m²	Q_k kN
Klasse A (wonen en huishoudelijk gebruik)		
A-vloeren	1,75	3 [a]
A-trappen	2,0	3
A-balkons	2,5	3
Klasse B (kantoorruimten)		
B-kantoorruimten	2,5	3
Klasse C (bijeenkomstruimten)		
C1-tafels	4,0 [b]	7
C2-vaste zitplaatsen	4,0 [b]	7
C3-zonder obstakels voor rondlopende mensen	5,0	7
C4-fysieke activiteiten	5,0	7
C5-grote mensenmassa's	5,0	7
Klasse D (winkelruimten)		
D1-kleinhandel	4,0	7
D2-warenhuizen	4,0	7
[a] De puntlasten moeten zijn aangebracht op een oppervlakte van 100 mm × 100 mm; de gegeven waarden moeten ook zijn gebruikt voor constructies van ondergeschikte betekenis.		
[b] Voor schoolgebouwen volstaat een vloerbelasting van 2,5 kN/m².		

Table A.5 Imposed Loads, Table NB.1 – 6.2 NEN-EN 1991-1-1

A.3 Eurocode 2 – Concrete Structures

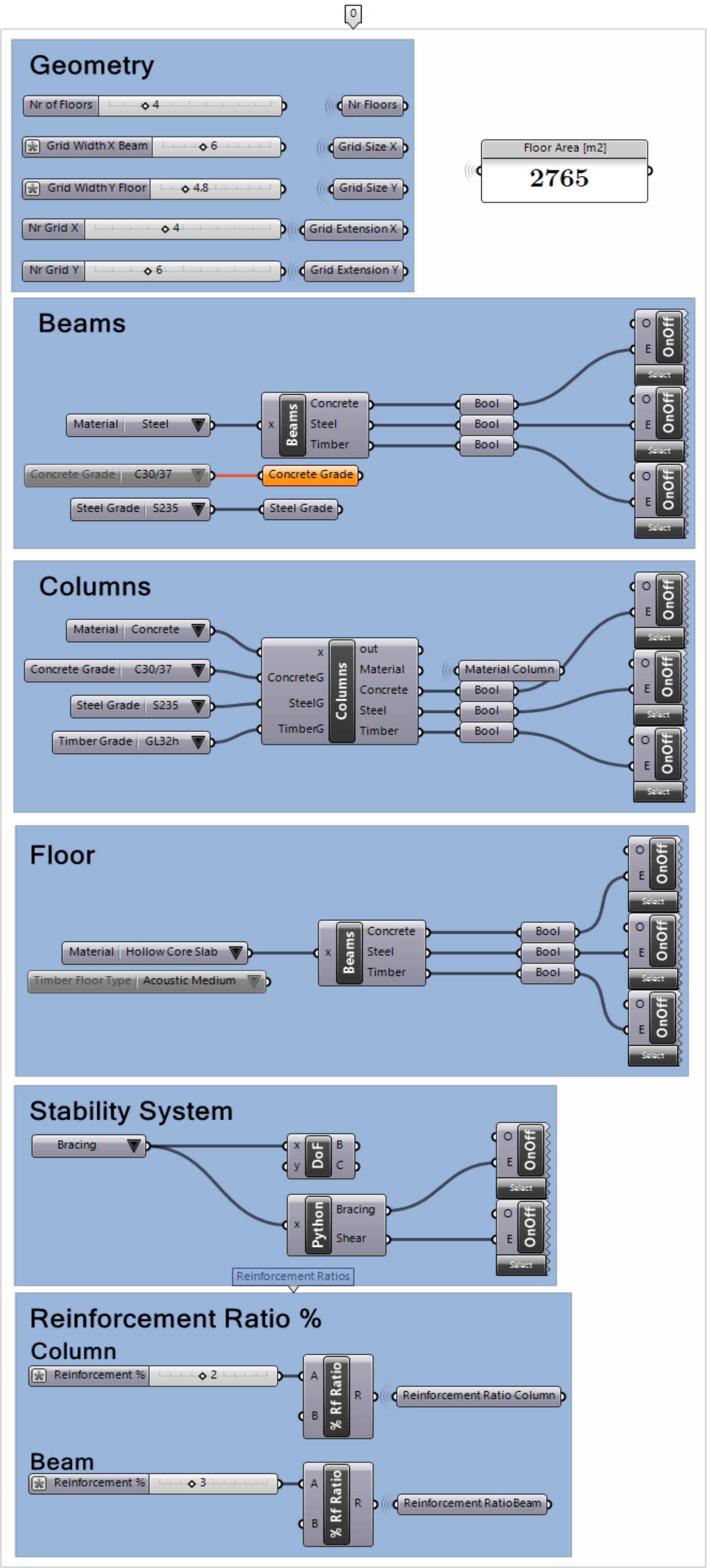


Sterkteklasse	Buiging en normaalkracht, symmetrisch gewapende rechthoekige doorsnede		Buiging zonder normaalkracht; excentrisch gewapende rechthoekige doorsnede
	$\alpha_n \leq 0{,}45$	$0{,}45 < \alpha_n \leq 0{,}9$	
C12/15	$[1{,}30 + 410\rho + (9{,}0 - 130\rho)\alpha n]10^3 \geq 2900$	$(6{,}8 + 517\rho)(1 - 0{,}5\alpha n)10^3$	$(2{,}20 + 490\rho)10^3 \geq 2900$
C16/20	$[1{,}45 + 415\rho + (11{,}5 - 145\rho)\alpha n]10^3 \geq 3250$	$(8{,}5 + 514\rho)(1 - 0{,}5\alpha n)10^3$	$(2{,}35 + 520\rho)10^3 \geq 3250$
C20/25	$[1{,}60 + 420\rho + (14{,}0 - 160\rho)\alpha n]10^3 \geq 3600$	$(10{,}0 + 510\rho)(1 - 0{,}5\alpha n)10^3$	$(2{,}50 + 550\rho)10^3 \geq 3600$
C25/30	$[1{,}75 + 425\rho + (16{,}5 - 175\rho)\alpha n]10^3 \geq 3950$	$(11{,}7 + 506\rho)(1 - 0{,}5\alpha n)10^3$	$(2{,}65 + 580\rho)10^3 \geq 3950$
C30/37	$[1{,}96 + 432\rho + (20{,}0 - 196\rho)\alpha n]10^3 \geq 4450$	$(14{,}0 + 501\rho)(1 - 0{,}5\alpha n)10^3$	$(2{,}85 + 620\rho)10^3 \geq 4450$
C35/45	$[2{,}20 + 440\rho + (24{,}0 - 220\rho)\alpha n]10^3 \geq 5000$	$(16{,}7 + 495\rho)(1 - 0{,}5\alpha n)10^3$	$(3{,}10 + 670\rho)10^3 \geq 5000$
C40/50	$[2{,}35 + 445\rho + (26{,}5 - 235\rho)\alpha n]10^3 \geq 5350$	$(18{,}3 + 491\rho)(1 - 0{,}5\alpha n)10^3$	$(3{,}25 + 700\rho)10^3 \geq 5350$
C45/55	$[2{,}50 + 450\rho + (29{,}0 - 250\rho)\alpha n]10^3 \geq 5700$	$(20{,}0 + 487\rho)(1 - 0{,}5\alpha n)10^3$	$(3{,}40 + 730\rho)10^3 \geq 5700$
C50/60	$[2{,}65 + 455\rho + (31{,}5 - 265\rho)\alpha n]10^3 \geq 6050$	$(21{,}6 + 484\rho)(1 - 0{,}5\alpha n)10^3$	$(3{,}55 + 760\rho)10^3 \geq 6050$
C55/67	$[2{,}86 + 462\rho + (34{,}6 - 258\rho)\alpha n]10^3 \geq 6400$	$(23{,}8 + 480\rho)(1 - 0{,}5\alpha n)10^3$	$(3{,}70 + 790\rho)10^3 \geq 6400$
C60/75	$[3{,}10 + 470\rho + (37{,}0 - 170\rho)\alpha n]10^3 \geq 6400$	$(25{,}5 + 480\rho)(1 - 0{,}5\alpha n)10^3$	$(3{,}70 + 790\rho)10^3 \geq 6400$
C70/85	$[3{,}10 + 470\rho + (41{,}5 - 170\rho)\alpha n]10^3 \geq 6400$	$(28{,}1 + 480\rho)(1 - 0{,}5\alpha n)10^3$	$(3{,}70 + 790\rho)10^3 \geq 6400$
C80/95	$[3{,}10 + 470\rho + (46{,}5 - 170\rho)\alpha n]10^3 \geq 6400$	$(31{,}1 + 480\rho)(1 - 0{,}5\alpha n)10^3$	$(3{,}70 + 790\rho)10^3 \geq 6400$
C90/105	$[3{,}10 + 470\rho + (51{,}0 - 170\rho)\alpha n]10^3 \geq 6400$	$(33{,}7 + 480\rho)(1 - 0{,}5\alpha n)10^3$	$(3{,}70 + 790\rho)10^3 \geq 6400$

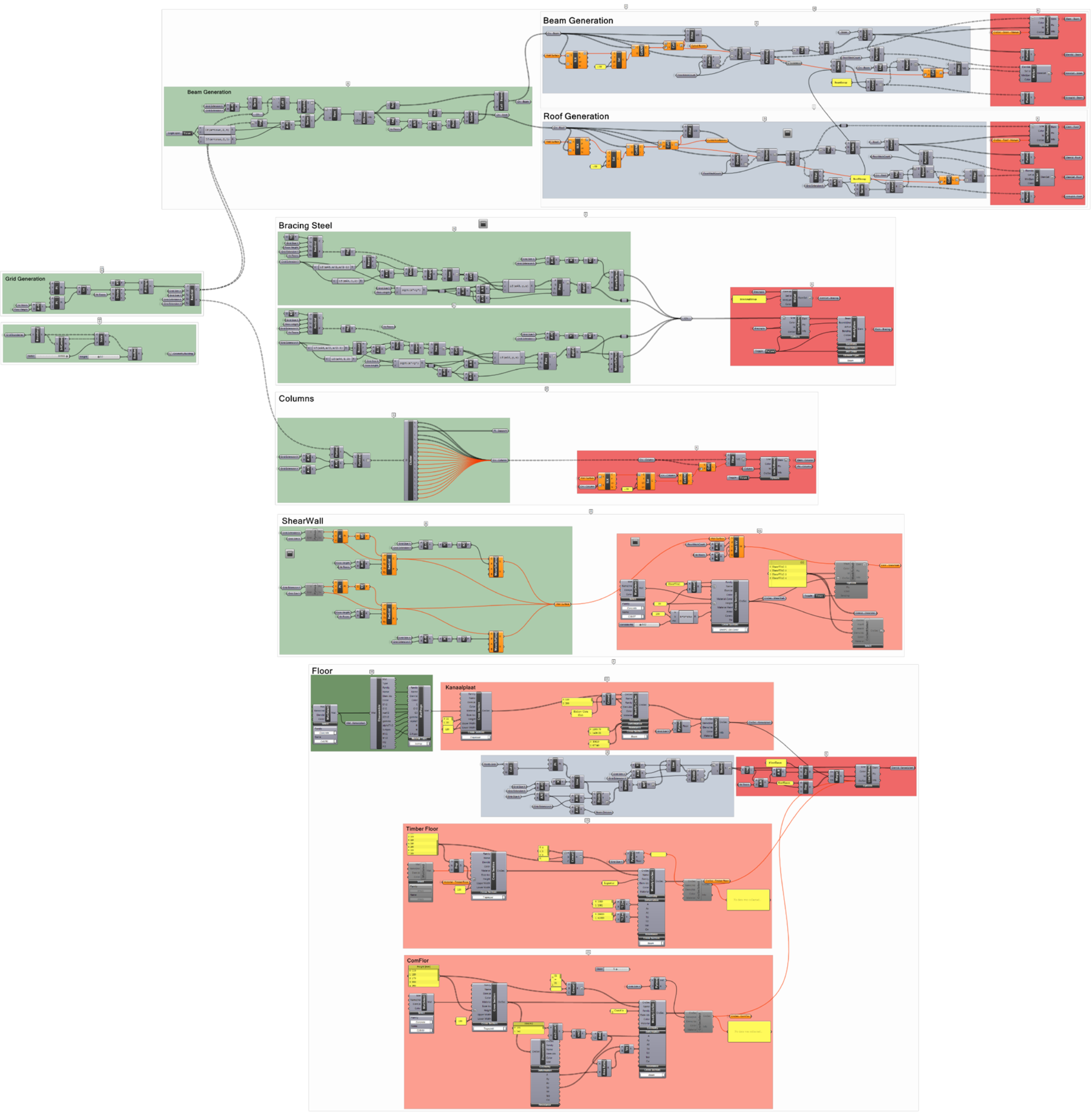
Table A.6 Fictive Modulus of Elasticity, Table NB-1 NEN-EN 1992-1-1 2005

Appendix B

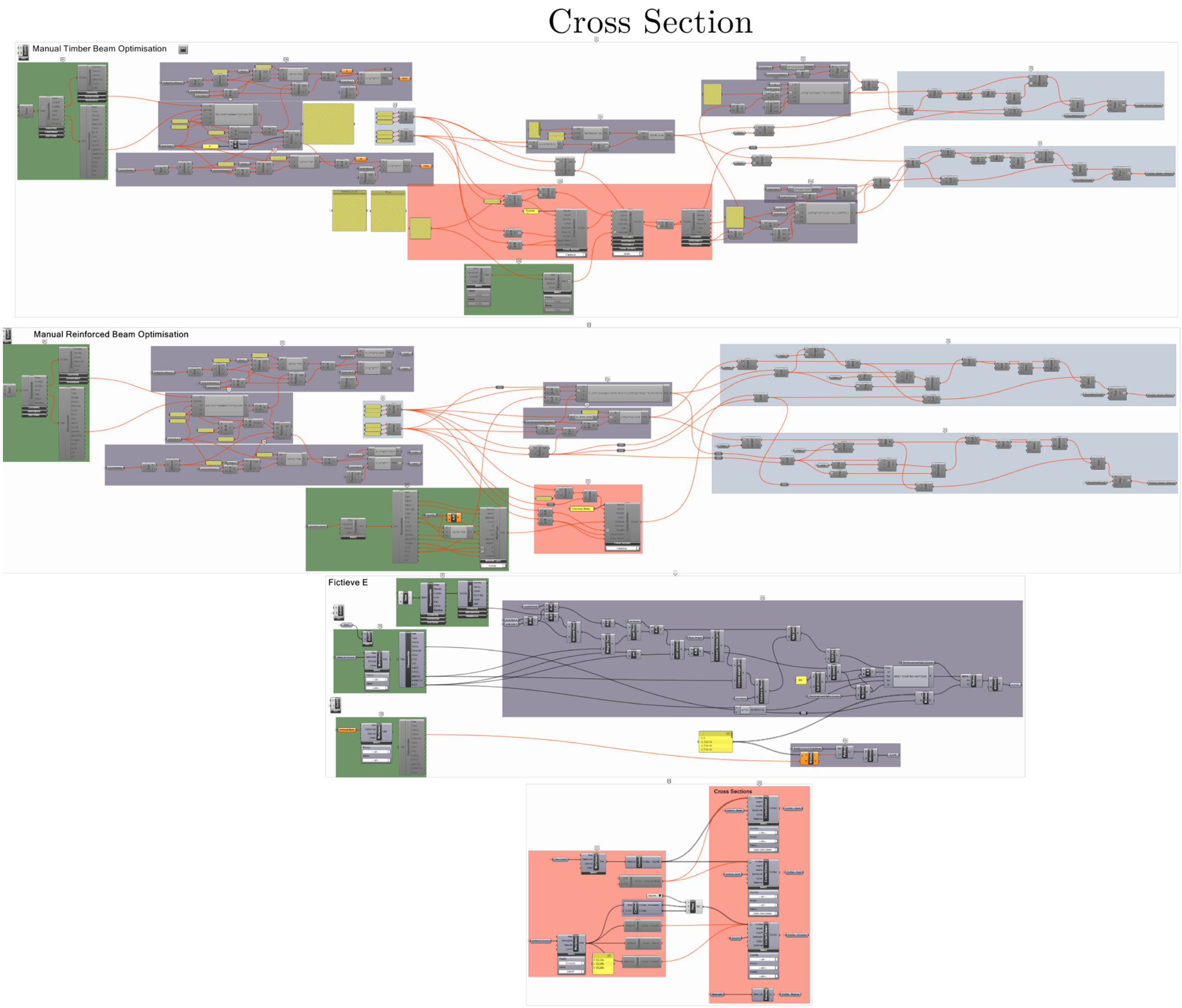
B.1 Parameters



B.2 Geometry

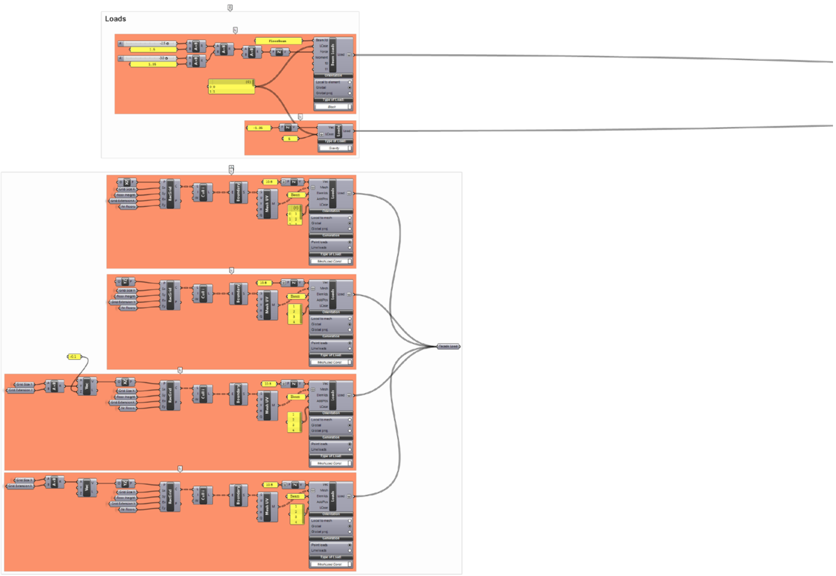

Beam Generation
Roof Generation
Beam Generation
Bracing Steel
Grid Generation
Columns
ShearWall
Floor
Kanaalplaat
Timber Floor
ComFlor

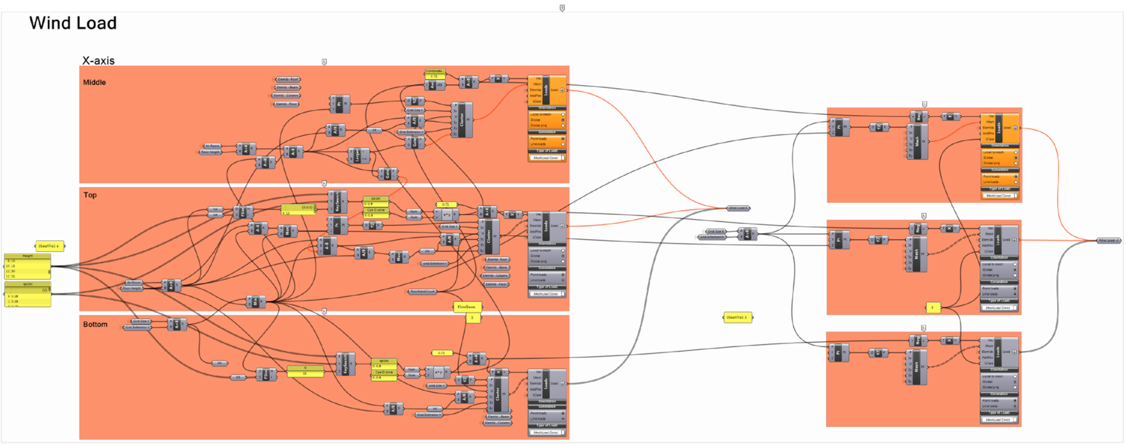
B.3 Cross-Sections

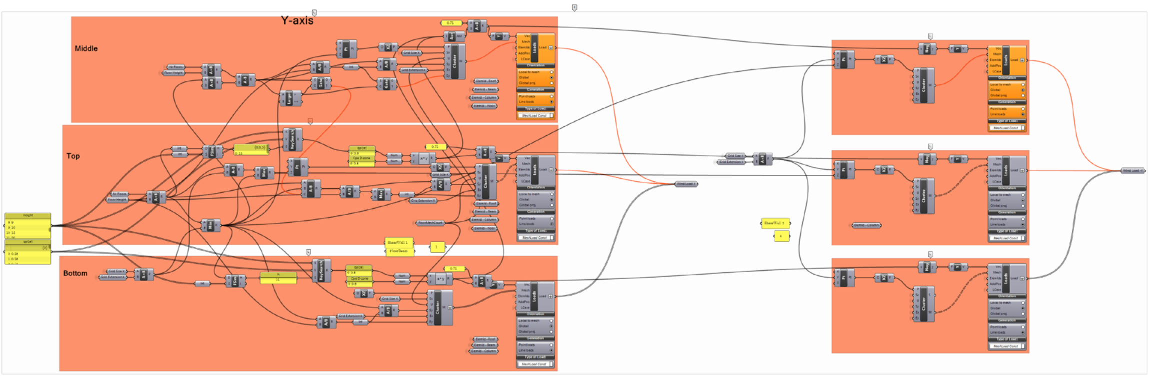


B.4 Optimisation

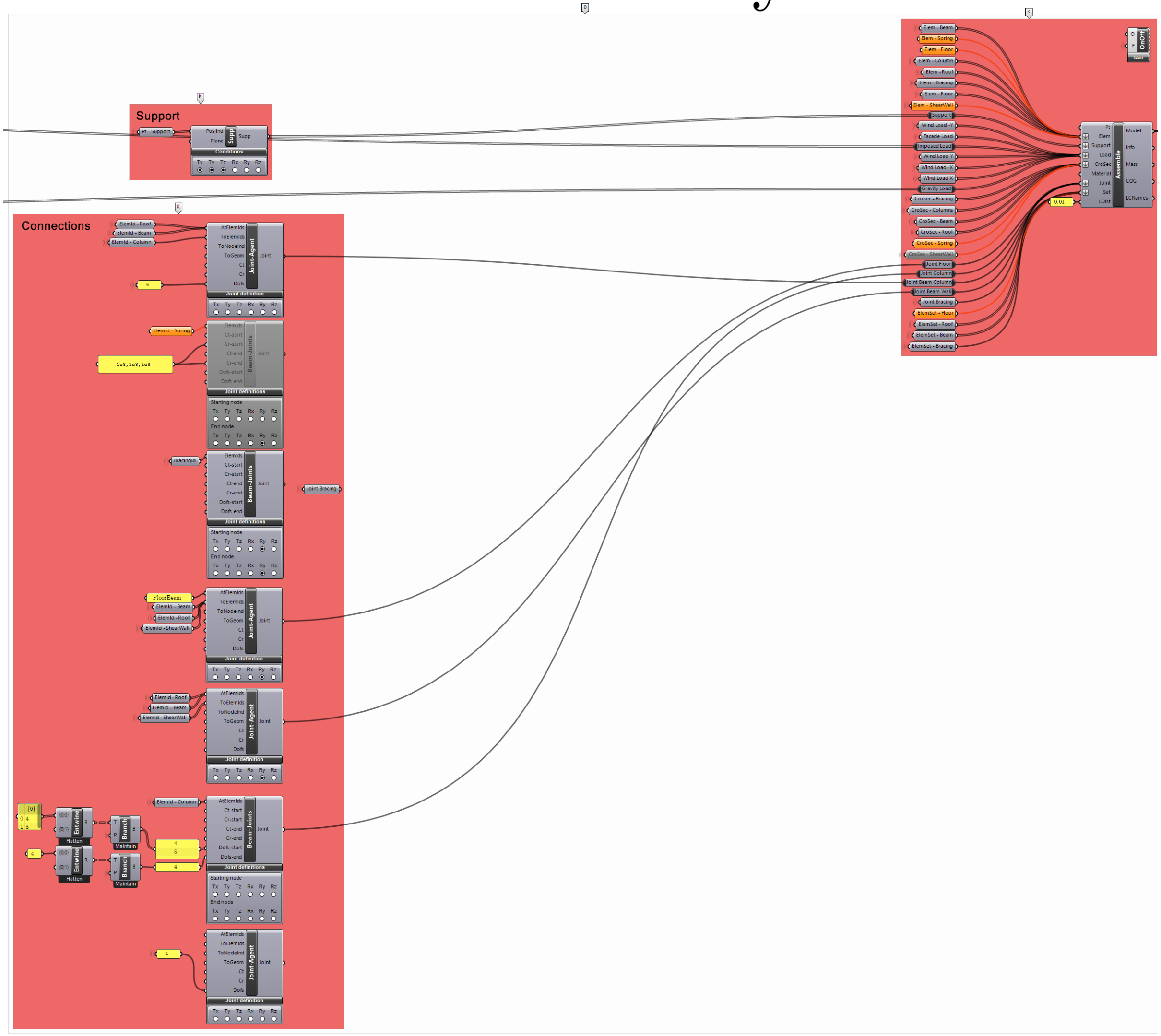
Loads







Assembly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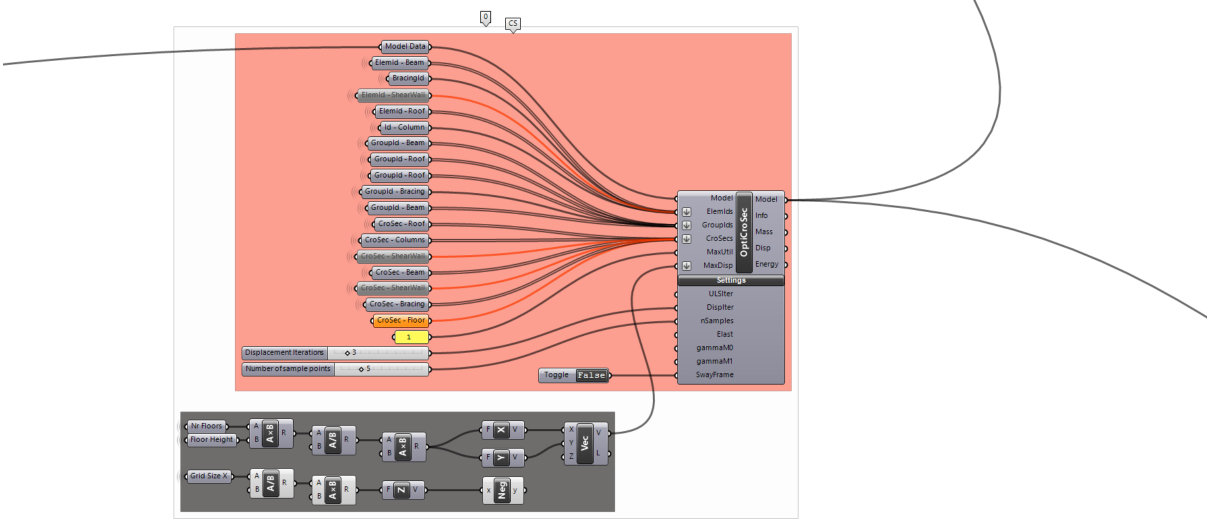
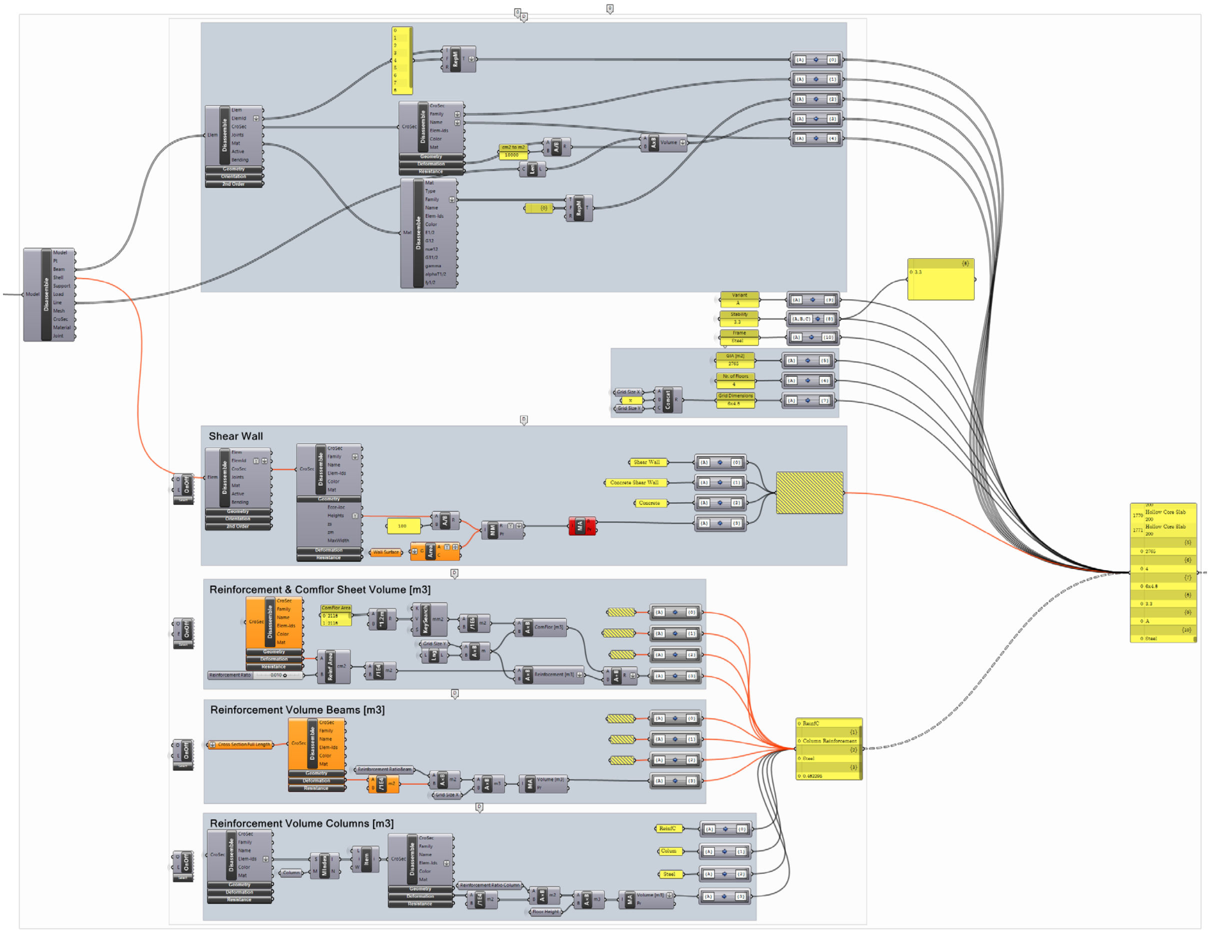
Pt - Support
Pos|Ind
Plane
Supp
Supp
Conditions
Tx Ty Tz Rx Ry Rz
Connections
ElemId - Roof
ElemId - Beam
ElemId - Column
4
AtElemIds
ToElemIds
ToNodeInd
ToGeom
Ct
Cr
Dofs
Joint-Agent
Joint
Joint definition
ElemId - Spring
1e3,1e3,1e3
ElemIds
Ct-start
Cr-start
Ct-end
Cr-end
Dofs-start
Dofs-end
Beam-Joints
Joint definitions
Starting node
End node
BracingId
Joint Bracing
FloorBeam
ElemId - ShearWall
{0}
0 4
1 5
{0;0}
{0;1}
Entwine
R
Flatten
T
P
Branch
B
Maintain
4
5
ElemId - Column
Elem - Beam
Elem - Spring
Elem - Floor
Elem - Column
Elem - Roof
Elem - Bracing
Elem - Floor
Elem - ShearWall
Support
Wind Load -Y
Facade Load
Imposed Load
Wind Load Y
Wind Load -X
Wind Load X
Gravity Load
CroSec - Bracing
CroSec - Columns
CroSec - Beam
CroSec - Roof
CroSec - Spring
CroSec - ShearWall
Joint Floor
Joint Column
Joint Beam Column
Joint Beam Wall
Joint Bracing
ElemSet - Floor
ElemSet - Roof
ElemSet - Beam
ElemSet - Bracing
Pt
Elem
Support
Load
CroSec
Material
Joint
Set
LDist
Assemble
Model
Info
Mass
COG
LCNames
0.01
O
E
OnOff
Select

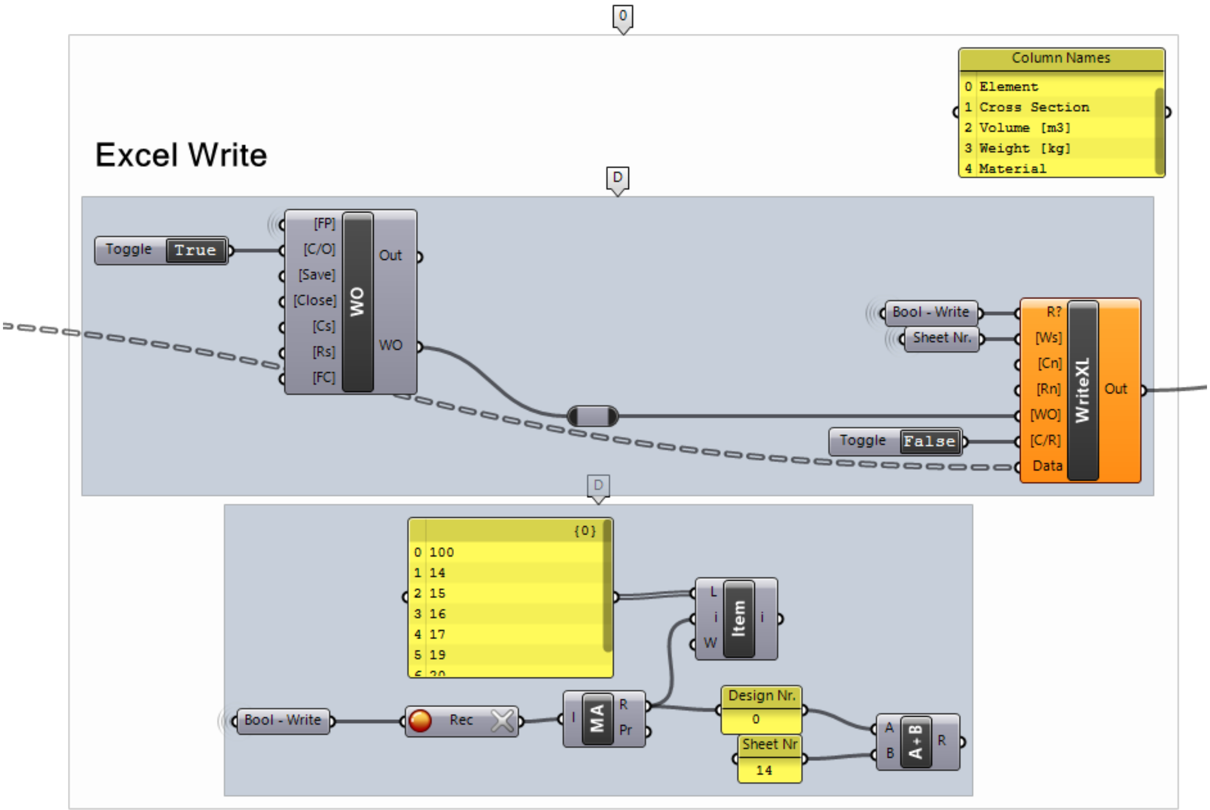
Karamba Optimisation



B.5 Export

Data Export

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1 Cross Section
2 Volume [m3]
3 Weight [kg]
4 Material
Toggle True
[FP]
[C/O]
[Save]
[Close]
[Cs]
[Rs]
[FC]
WO
Out
WO
Bool - Write
Sheet Nr.
R?
[Ws]
[Cn]
[Rn]
[WO]
[C/R]
Data
WriteXL
Out
Toggle False
{0}
0 100
1 14
2 15
3 16
4 17
5 19
L
i
W
Item
i
Bool - Write
Rec
I
MA
R
Pr
Design Nr.
0
Sheet Nr
14
A
B
A+B
R

Appendix C

C.1 Environmental Product Declarations

Table C.1 EPD Data for the Structural Carbon Tool, $kgCO_2eq/kg$

Element Type	Manu-facturer	A1-A3	A4	C2	C3-C4	D	Seque-stration
Reinforcement steel	BE Group	0.338	0.077	0.008	0.024	0.072	
	Celsa	0.370	0.014	0.018	0.000	0.120	
	Average	0.354	0.045	0.013	0.012	0.096	
Concrete C35/45	Lyrestad	0.141	0.000	0.005	0.006	-0.003	
	Markbygden	0.151	0.006	0.005	0.006	-0.003	
	Average	0.146	0.003	0.005	0.006	-0.003	
Precast Beam	Inhus	0.197	0.021	0.005	0.005	-0.005	
Hollow Core	Inhus	0.147	0.021	0.005	0.005	-0.006	
Precast Column	Inhus	0.214	0.021	0.005	0.006	-0.005	
Precast Slab	Inhus	0.202	0.021	0.005	0.006	-0.005	
Precast Wall	Inhus	0.165	0.021	0.005	0.005	-0.005	
Steel Beams	BE Group	0.712	0.065	0.008	0.003	-0.120	
	Smederna	0.741	0.006	0.002	0.023	-0.043	
	Average	0.727	0.035	0.005	0.013	-0.082	
Hollow Beams	Smederna	2.640	0.005	0.002	0.024	-1.160	
	Tibnor	2.580	0.046	0.007	0.003	-1.300	
	Average	2.610	0.026	0.004	0.013	-1.230	
Glulam Spruce	Zaza	0.673	0.017	0.065	1.543	-0.295	-1.516
Glulam Pine	Zaza	0.831	0.019	0.065	1.233	-0.269	-1.211
	Average	0.752	0.018	0.065	1.388	-0.282	-1.364
Sawn Timber	Svenskt Trä	0.270	0.018	0.014	1.583	-0.237	-1.791
ComFlor 80	TATA	0.314	0.032	0.022	0.012	-1.346	
Hollow Core Slab 150	VBI	0.147	0.004	0.0058	0.001	0.0164	
Hollow Core Slab 200	VBI	0.140	0.00444	0.005933	0.001532	0.012761	
Hollow Core Slab 260	VBI	0.138	0.004	0.005	0.001	0.012	
Hollow Core Slab 320	VBI	0.154	0.004	0.005	0.001	0.020	
Hollow Core Slab 400	VBI	0.160	0.004	0.005	0.001	0.022	

Appendix D

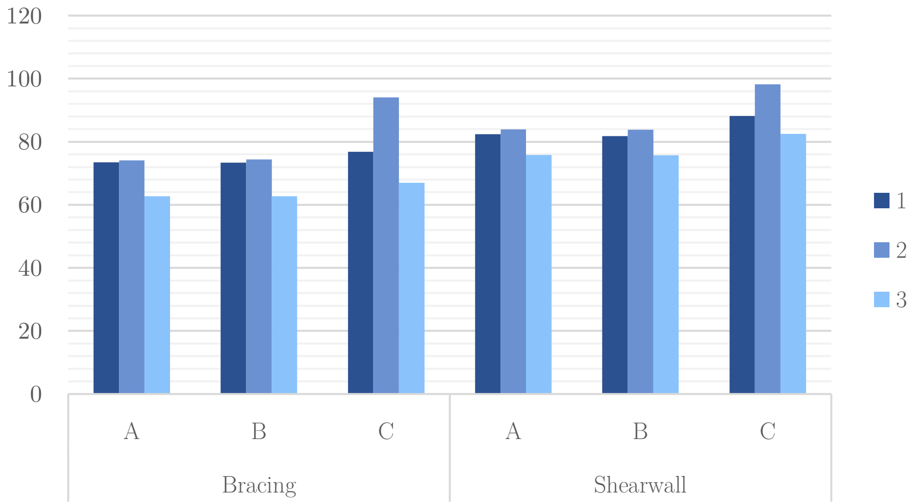

Figure D.1 Total Embodied Carbon Case Study Variants by Stability

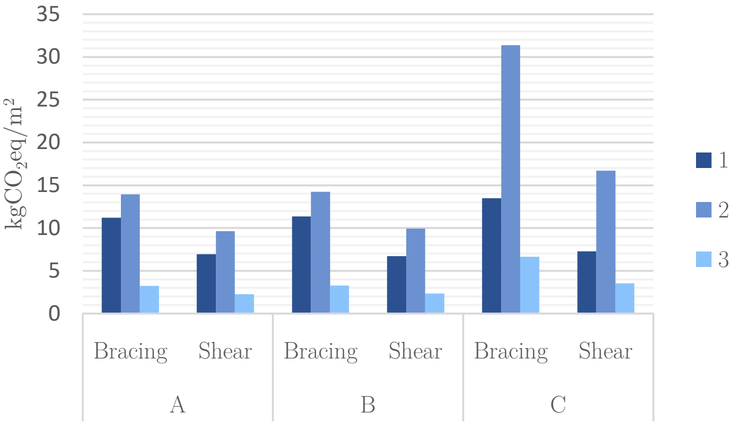

Figure D.2 Column Embodied Carbon

Appendix E

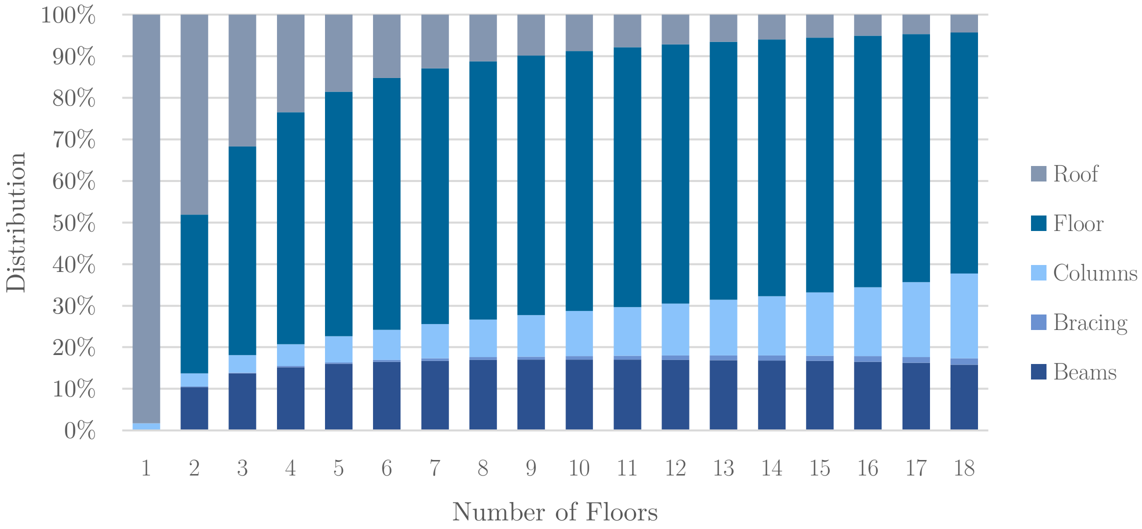

Figure E.1 Embodied Carbon Distribution of Structural Elements, Timber Frame, Bar

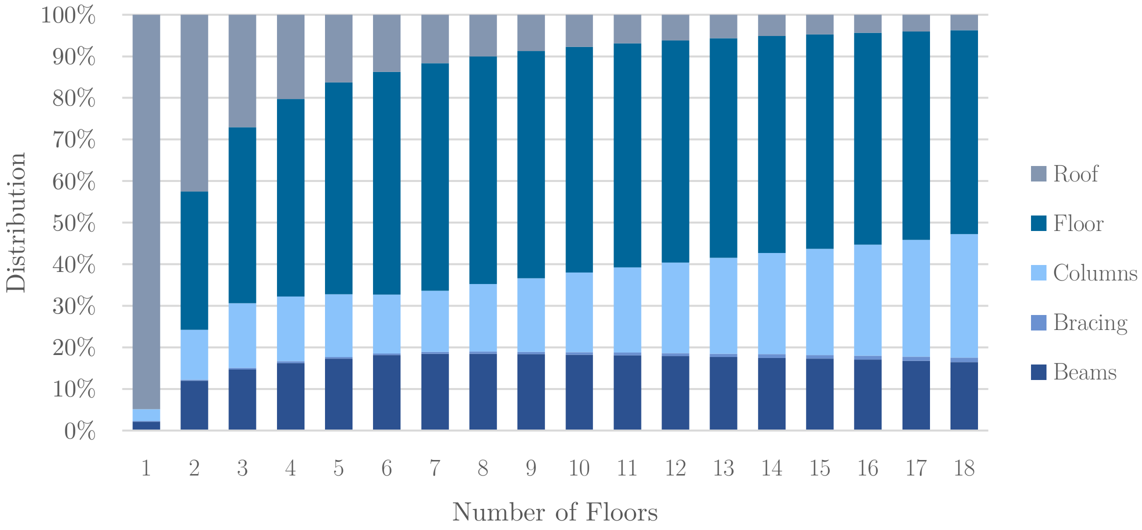

Figure E.2 Embodied Carbon Distribution of Structural Elements, Concrete Frame, Bar

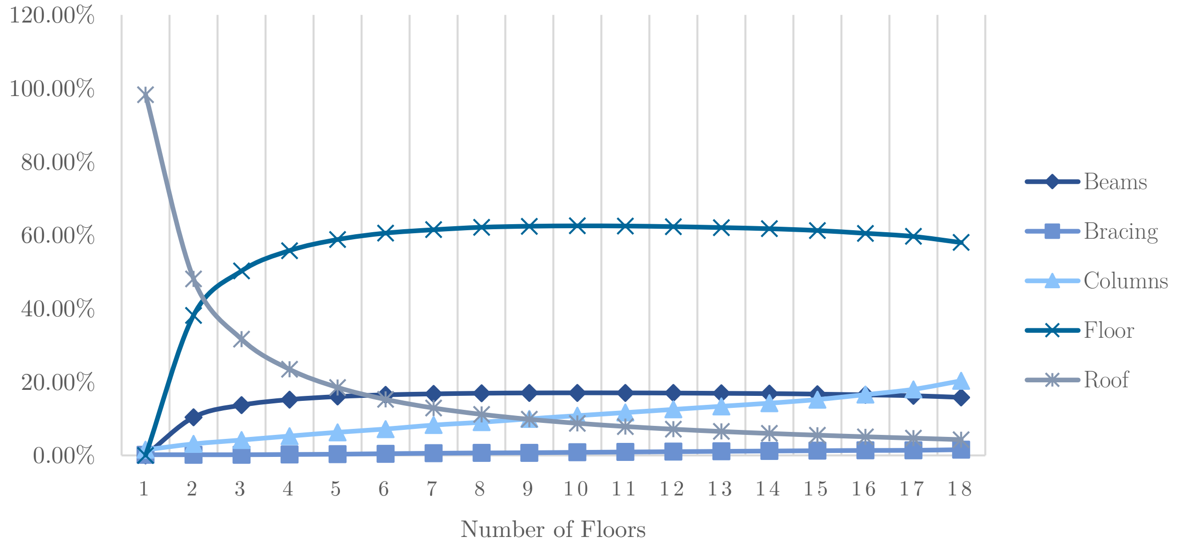

Figure E.3 Embodied Carbon Distribution of Structural Elements, Timber Frame, Line

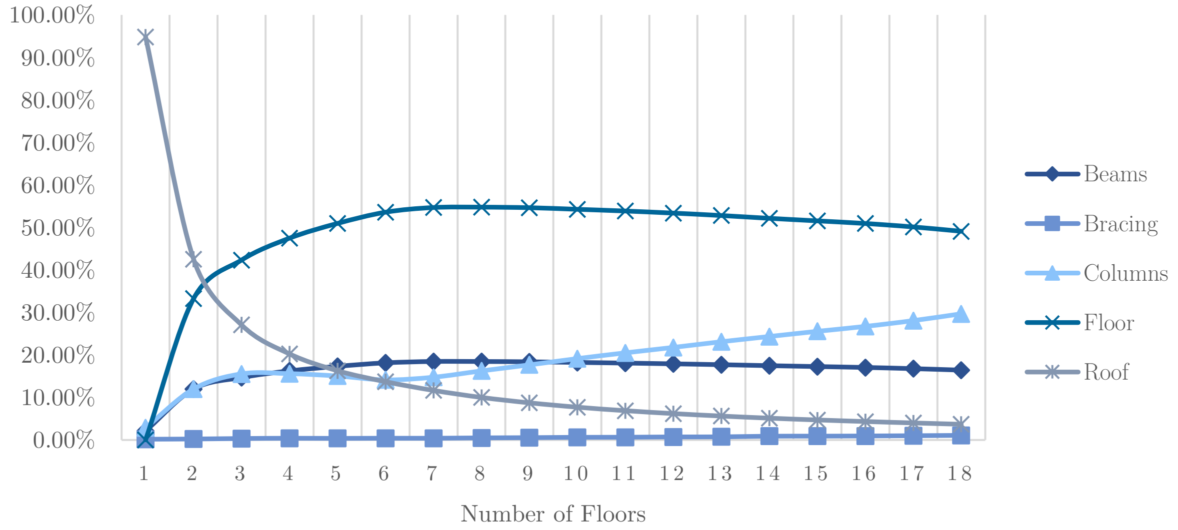

Figure E.4 Embodied Carbon Distribution of Structural Elements, Concrete Frame, Line