The Development of a Parametric Framework for Embodied Carbon Design

A master thesis supporting the integration of sustainability into the design process.

CIE5060-09: MSc Thesis

Martijn Verroen

The Development of a Parametric Framework for Embodied Carbon Design

A master thesis supporting the integration of sustainability into the design process.

by

Martijn Verroen

Student Name	Student Number
Martijn Verroen	4564235

Chair:	dr.ir. H.R. Schipper
Committee members:	ir. A.C.B. Schuurman, prof.dr. H.M. Jonkers, ir.C. Zha (DWA/ARUP)
Project Duration:	November, 2023 - December, 2024
Faculty:	Faculty of Civil Engineering and Geosciences, Delft

Style: TU Delft Report Style, with modifications by Martijn Verroen

TU Delft

Preface

This thesis marks the completion of my Master of Science in Civil Engineering at Delft University of Technology, specializing in Building Engineering. My passion for sustainability, timber structures, and parametric design inspired the research presented here, which integrates Embodied Carbon assessment into the early design phase of buildings.

I am deeply grateful to my committee members, R. Schipper, M. Schuurman, H. Jonkers and my company supervisor C. Zha, for their guidance and feedback throughout this process. Furthermore I would like to thank A. Muntinga and DWA for granting me this opportunity. Lastly, I thank my family, friends and girlfriend for their unwavering support during my studies and this project.

Martijn Verroen
Delft, December 2024

Summary

The building industry is the largest global contributor to carbon emissions. At the current rate of carbon emissions within this sector, the targets set by the Paris Agreement will not be achieved. Consequently, significant reductions in carbon emissions from the building industry are needed to align with global climate goals.

When discussing the carbon emission of a building two major type of carbon emissions can be distinguished: 1)operational 2)embodied. Operational carbon is all the CO_2 that is emitted during the use of the building and refers to the energy-related carbon emissions. Embodied carbon is all the CO_2 that was emitted to realize the construction of the building.

Historically, sustainable building design has focused on reducing operational carbon. However, as improvement in low-energy buildings continue to decrease operational emissions, the significance of Embodied Carbon has grown. Despite this, Embodied Carbon remains underrepresented in the design process, often addressed reactively at the end of the design, leading to unnecessarily high levels. Embodied Carbon must be integrated in the early design stages to create buildings with a low Embodied Carbon content, improving the sustainability of the building industry.

This master thesis introduces a parametric framework designed to embed Embodied Carbon assessment into the early building design process. Recognizing the uncertainties inherent in early design phases the framework prioritizes delivering ranges of values rather than precise figures, befitting of the dynamic and flexible nature of design exploration. By offering quick, clear results and transparent methodologies, the framework stimulates a multidisciplinary workflows, enabling accessible, efficient, and informed decision-making without requiring specialized expertise.

The framework consists of three tools; 1)Structure Generator Tool: Translates design parameters into structural systems and material quantities without requiring specialized engineering knowledge. 2)Embodied Carbon Material Factor Determination Tool: Converts material quantities into Embodied Carbon values using databases, with the flexibility to include or exclude biogenic carbon storage. 3)Iterator and Data Evaluation Tool: Supports iterative design exploration, comparing design alternatives and facilitating clear visualization and communication of results through tools like DesignExplorer.

The developed framework effectively supports the early design stage by providing actionable insights, enabling designers to quantify the impact of their choices with ease and efficiency. By integrating multidisciplinary variables, default settings, and automated element generation, the framework stimulates a multidisciplinary collaboration without requiring, but allowing the application of, specialist expertise. A range-based approach accounts for uncertainties in Environmental Product Declaration (EPD) selection, while sensitivity analyses helps distinguish robust conclusions from those sensitive to design changes and allowing the converging of the carbon assessment throughout the design process. Although future refinements,such as improved connection design and substructure integration, could enhance accuracy, the framework already delivers reliable estimates for Embodied Carbon assessment. Comparisons of databases show slightly conservative results for the Dutch building industry when using ICE V3.0 instead of NMD. Overall, the framework lays a strong foundation for integrating Embodied Carbon considerations into early design, proving its potential to significantly reduce carbon emissions in building practices.

Reader's Guide

This master's thesis presents the development of an Embodied Carbon Value Determination Framework. To ensure clarity, the thesis is structured into five main parts.

Part I: Introduction
Part I provides the context of the study, introduces the problem, and describes the methodology used in this thesis.

Part II: Analysis
Part II includes a literature review, an examination of the current state of the art of Embodied Carbon Value Determination tools and frameworks, and the formulation of requirements for the development of the framework.

Part III: Synthesis
Part III elaborates on the configuration of the framework, describing it in progressively increasing levels of detail. The framework is designed to address a complex process involving numerous variables and multiple interdependencies. To maintain a clear overview of the various processes and variables, these elements are introduced in a stepwise manner, beginning with a granularity befitting of a framework that is in the conceptual level of design, the primary processes, inputs and outputs of the workflow. Followed by a chapter which gradually increase in complexity. Starting with the various steps within the tools that are included, detailing what each step encompasses and its relationship to the other steps. To be concluded with a description of the detailed configuration of the tool, the specific variables and mechanisms within the components of the integrated tools. Some underlying formulas, pieces of the script and codes are included here. The rest can be found in the appendix.

Part IV: Simulation
In the simulation phase the created framework is verified and validated. Verification assesses the extent to which the framework's output is accurate, reliable, and correct, while identifying any limitations or considerations that should be taken into account when interpreting the results. The validation , given the results from the verification, evaluates the usefulness of the framework's output. It explores how the results can contribute to the design process and in what ways the framework can be effectively used.

Part V: Evaluation
This section presents the discussion, conclusions, and recommendations for future research and development.

Appendix
The appendix provides all relevant formulas, detailed material properties, Grasshopper scripts, Python code, and other supplementary materials necessary for a comprehensive understanding of the Embodied Carbon Value Determination Framework.

Contents

Nomenclature

Abbreviations and definitions

Abbreviation	Definition
Structural element category	Categories grouping the various structural elements used (Core, floors, columns, beams and joints).
Embodied Carbon Determination Framework	Developed Embodied Carbon framework in its entirety, Structure Generator Tool + Embodied Carbon Material Factor Determination Tool.
Structure Generator Tool	Tool of the Embodied Carbon Determination Framework focused on generating a structure.
Embodied Carbon Material Factor Determination Tool	Tool of the Embodied Carbon Determination Framework where Embodied Carbon factors are assigned and the mass of the structural materials is transformed into kg CO_2.
High rise	Building where the lateral loads are primary design loads.
Early design	Design phase where only rough sketches and a list of requirements are present.
Embodied Carbon Material Factor	Value that states the amount of kg CO_2 per kg of that material.

Part I: Introduction

1 Introduction

1.1. Carbon Footprint of buildings

A building design has several aspects in which it can be made more sustainable, but low-carbon design is considered to be one of the most important aspects[22]. The building industry is globally the most significant contributor to carbon emissions [27] and in general the largest sole contributor to GHG emissions[22].

When discussing the GHG(carbon) emission of a building two major type of carbon emissions can be distinguished: 1)operational 2)embodied. Operational carbon is all the CO_2 that is emitted during the use of the building and refers to the energy-related carbon emissions[66].Embodied carbon is all the CO_2 that was emitted to realize the construction of the building [66]. A common misconception is that embodied carbon of a building is limited to the sum of the CO_2 of all the material used in the building, but this is not correct. Al the CO_2 emitted when the structural elements were produced, transported and repaired or replaced could be included in the embodied carbon. The word 'could' is used since within academia, the concept of embodied carbon is defined in different ways. This is allowed as long as what is included is clearly defined. This is further elaborated in 3.1.

The reduction of operational carbon emissions is already a well-established practice in building design. Measures like double glass, higher insulation quantities and accompanying energy labels are present in most modern buildings.

In a paper written nearly 14 years ago the growing interest in embodied carbon is already noted. It is, however stated as well that at that time in general practice the embodied carbon value of the building is not taken into consideration during the design of the building [36]. EU legislation is presently still mostly focused on operational carbon[62], although the subject is receiving a further growing amount of attention from industry and the government. Presently only five EU countries have created legislation regarding whole life carbon (sum of operational and embodied carbon during the lifecyle of a building) [62]. One example is the Netherlands, where it is mandatory to include environmental impact calculations that account for whole life carbon[35]. However, the maximum allowable values set by these regulations are easily maintained below the limits, calling into question the effectiveness and overall usefulness of the legislation in this area.

The reduction of embodied carbon emissions is although less undervalued still underrepresented in the design process. During the life cycle of a building operational carbon is the most significant contributor to the carbon emission of a building. Seemingly justifying the before mentioned focus on operational carbon emission reduction.

With low energy buildings operational carbon emissions are getting relatively low. The more improvement and progress is made with operational carbon, the more relevant embodied carbon becomes[5]. As further emission reductions from operational carbon become limited due to already highly efficient buildings, embodied carbon arises as the most significant contributor to carbon emissions during the full lifetime of a building, despite being generated solely at the beginning of the building's life cycle[62].

1.2. Problem statement

Embodied Carbon is in general practice not sufficiently integrated in the design process. This insufficient integration leads to buildings with unnecessary high Embodied Carbon contents. The way Embodied Carbon is currently handled in the building design process is an end of design based approach. This place of 'integration' in the design makes that the current process requires detailed information as input. This requirement for detailed information makes it difficult to integrate it in the early design phase of the building. During the early design phase there is no design yet finished. The amount of materials needed, from where they will come and what their accompanying Embodied Carbon values will be is not known.

While some estimations can be made using standard estimates, this is still a phase characterized by significant changes, with nothing set in stone. This situation demands extensive communication between various disciplines, where delays due to waiting for responses and miscommunications pose significant obstacles. These challenges make it difficult to consistently assess the impact of decisions on the embodied carbon content of the building, as the process is cumbersome and discouraging. This leads to the conclusion that there are no suitable tools available to use in this stage of the design.

The problem with integrating Embodied Carbon in the early design is twofold: 1)The determination of the amount of material and 2)the determination of the Embodied Carbon material factors used for those materials.

A building design should be approached with the level of detail necessary to accurately assess the embodied carbon content of the structure. However, during early design stages, the design is highly susceptible to changes, necessitating that these assessments be generated quickly and efficiently. The generation of building designs requires extensive interdisciplinary knowledge, which is often challenging to utilize effectively due to efficiency constraints and communication barriers. A potential solution could involve integrating the various disciplines within a unified environment where the building design can be automatically generated based on inputs from these different fields.

Generating a structure however comes with multiple obstacles. Not all structural verification's can be performed due to time constraints, necessitating a selection of relevant verification's. The design process is also by nature an iterative process with a high interdependence between the different parts of the structure. To ensure the possibility of a easy design space exploration a parametric tool must produce swift results. For a parametric tool to be able to produce swift results a workflow has to be developed with as much as possible a linear workflow, reducing the iterative nature of the design process. To limit the use of heavy final element software, several dimensioning methods have to be developed and parameterised.

The second obstacle is with the Embodied Carbon material factors that are used. In the early design phase of the design process it is yet unknown from which producers materials and elements will be used. Depending on the producer you choose the Embodied Carbon values can vary greatly. Having to make assumptions and picking the wrong EPD can therefor insert significant deviations in the Embodied Carbon results. The public availability of trustworthy EPD's is also limited. There are several EPD's publicly available but they are quite scattered. This makes it hard to find and especially to compare EPD's and to judge them on their suitability for a specific project, leading to a higher likelihood of error when selecting an EPD. This in turn leads to a high Embodied Carbon value deviations. Non-product-specific, more generic values are available for use as well. These values are very coarse estimations and may deviate from the EPD value range. This can lead to discrepancies between the early and later stages of the design process. Using non-product-specific values can, just as with specific EPD use, cause high carbon value deviations.

In the Netherlands, the government has mandated the use of the National Environmental Database (NMD). This database faces however also several challenges relating to transparency and accuracy. The data provided by the NMD lacks full transparency and insufficient information regarding how the NMD's data sources correspond to the actual materials and processes utilized within the building industry is present. Furthermore, the NMD occasionally exhibits deficiencies in its data quality for structural materials. These discrepancies and inadequacies raise concerns about the applicability and accuracy of NMD data in environmental performance assessments.

With the rise of the importance of Embodied Carbon, tools are currently being developed that aim at the early design phase. These tools however work in a black box like manner with little room for customization's, making them sensitive for error and unverifiable. The tools give single values not befitting of the design stage and address none of the missing information issues for the input, failing to fill in important gaps, which might result in discrepancies between the early design stage and later stages. They do therefor not properly address the problems above and it is concluded that currently no tools exist in which it is possible for Embodied Carbon design to be integrated accurately in the early design process.

1.3. Aims and objectives

The aim of this master thesis is to develop a scientifically validated and transparent framework that enables both designers without structural expertise and structural engineers to gain insights into the embodied carbon content of a structure during the early design stages. To provide clarity and a quantification on how design choices impact the Embodied Carbon content of the structure, facilitating the integration of Embodied Carbon considerations into the early design process and promoting the creation of more sustainable buildings.

2
Research Structure

2.1. Scope

Akbarnezhad et al. analysed several office buildings stated that 59-66 % of the embodied carbon of those buildings consisted of the structural material[4]. Depending on the type of building materials used this can vary. Within this framework only the structural part of a building will be taken into account. Literature suggest that a big part of the total amount is still taken into consideration with this limitation, but even with the limitation to purely structure this however still leaves a wide variety of structural systems, therefor only one structural system will be evaluated. In section 5.2.2 a more in depth reasoning behind the minimization of structural variables is provided. The structural system that will be investigated is a timber-concrete hybrid structure with a vertical load bearing timber column-beam system and a concrete core for the lateral loads.

In figure 3.1 an overview is given of all the life cycle phases. Module A1-A3 will be taken into acount to determine the embodied carbon material factor. In 5.1 the reasoning behind this choice is further elaborated based on the literature research in section 3.1.

The tool that will be created will be made in grasshopper. Grasshopper is widely used by engineers and architects. Since engineers and architects alike understand grasshopper it is and environment in which collaboration is possible. DWA also extensively utilizes Grasshopper. Transparency is a cornerstone of this process, and using Python code could hinder comprehension for many users, which conflicts with the goal of ensuring verifiability.Some component might be coded with the help of the grasshopper integrated python component. But this will be limited.

The list of plug-in's used are;

- Karamba3D, Version=2.2.0.18
- Pufferfish, Version=3.0.0.0
- MetaHopper, Version=1.2.4.0
- CORE.Toolbox.Grasshopper, Version=2.0.3.0
- Sasquatch, Version=1.0.0.0
- Heteroptera, Version=0.7.3.0
- Colibri.Grasshopper, Version=0.2.6348.33183

2.2. Research questions

The research aim presented in chapter 1 is now formulated as a main research question. This main question will be divided into subquestions that will be investigated and answered in parts of this thesis. The main research question is:

How can a parametric framework be developed that integrates Embodied Carbon assessment effectively in the early design stages?

1. What is Embodied Carbon, and how can its levels be accurately measured and evaluated in the context of building design? [Sections 3.1 until 3.1.7]
2. What core functions must the framework include to effectively support Embodied Carbon assessment in early design stages? [Sections 3.1.8 , 3.2 and Chapter 3.4.4]
3. Which Tools need to be integrated into a single framework and how could they be individually build up and relate to one another in a manner that satisfies the requirement to effectively support Embodied Carbon assessment in early design stages? [Chapters 4, 5 and 6]
4. How effectively does the framework integrate embodied carbon assessment into the early design stages, and to what extent can it aid in reducing a building's embodied carbon content? [Chapters 6 and 7]

2.3. Methodology

To address the main research question, *How can parametric tools be used in the early design stage to predict the embodied carbon content of a structure?*, this master thesis developed a parametric framework designed for early-stage embodied carbon assessment of building structures.

The methodology follows four key phases as visualized in figure 2.1:

Analysis Phase: This phase begins with a literature review, evaluation of existing software, and discussions with DWA employees, along with reflections on previous experiences. These activities lead to the formulation of the problem statement and the development of a list of requirements for the framework.

Synthesis Phase: In this phase, the framework is constructed based on the list of requirements from the analysis phase. The components of each tool within the framework are further analyzed in this phase, and the relationships within and between these tools are investigated.

Simulation Phase: Once the framework is developed, it moves into the simulation phase, which includes two steps; 1)Verification: The coding and structural dimensioning methods are verified to ensure correctness. Based on these results, necessary adjustments are made to the framework components. 2)Validation: After verification, the framework is validated by assessing its usefulness in the early design stage. This involves analyzing the possible outputs the framework can generate and how these outputs can be used to evaluate the influence of various design variables. For select variables, data will be generated to demonstrate the framework's application.

Evaluation Phase: In the final phase, the framework as a whole is critically reviewed for accuracy, reliability, and overall capability. This evaluation assesses how effectively the framework meets its objectives and how well it can support early design decision-making.

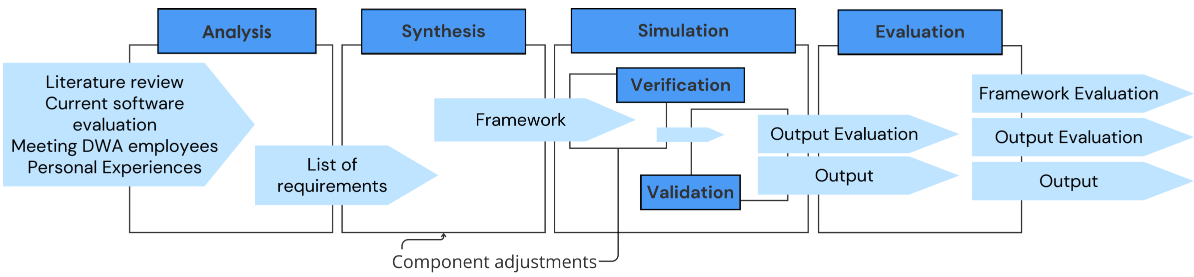

Figure 2.1: Methodology

Part II: Analysis

3
Literature and current state of the art

This chapter presents a literature review and an evaluation of currently available software tools. The first section focuses on the literature review, providing foundational knowledge on Embodied Carbon. This is followed by an evaluation of various existing Embodied Carbon-related software tools. The chapter concludes with an analysis of potential timber-based structural systems and their current applications, both globally and specifically within the Dutch building sector.

3.1. Whole life carbon

In the following section, the definition of Embodied Carbon is provided, including its composition, the various assumptions that can influence its calculation, and the relevant legislation governing its use in the building industry. Additionally, the section outlines how Embodied Carbon is communicated within the industry and discusses specific regulations related to its implementation in the Dutch building sector.

Embodied Carbon is a part of Whole Life Carbon. Whole Life Carbon is defined as the total sum of the carbon emission of a building during its full life cycle[62]. This includes embodied as well as operational carbon emissions. In figure 3.1 an overview is given of what is included in embodied carbon, pink/red, and operational carbon, orange.

The total whole life carbon life cycle is subdivided into three stages. The Product Stage encompasses emissions from the extraction of raw materials and the manufacturing of building elements. The Construction Stage includes emissions resulting from the transportation of materials from factory to site and the construction process. The In-Use Stage accounts for emissions associated with maintenance, repairs, and the replacement of building components. The End-of-Life Stage involves emissions related to the demolition and disposal of materials, with varying impacts depending on the disposal methods used. Emissions reductions through sustainable end-of-life strategies are considered separately in Module D, which addresses potential benefits but is not included in whole life carbon calculations. Each stage is further subdivided into modules to provide a detailed breakdown of emissions sources.

Depending on which modules are taken into account different terminology is used. In figure 3.1 some of these subcategories are shown. In the BSRIA-ICE guide the same definitions are used, with an additional term, cradle-to-site. Meaning module A1-A4 [23]. The Buildings Performance Institute Europe (BPIE) defines the sum of the carbon emission during module A1-A5 as upfront carbon. Contradictory with most academic literature the Dutch Green Building Councel(DGBC), defines the total embodied carbon emissions of a building as the sum of module A1-A5 [14].

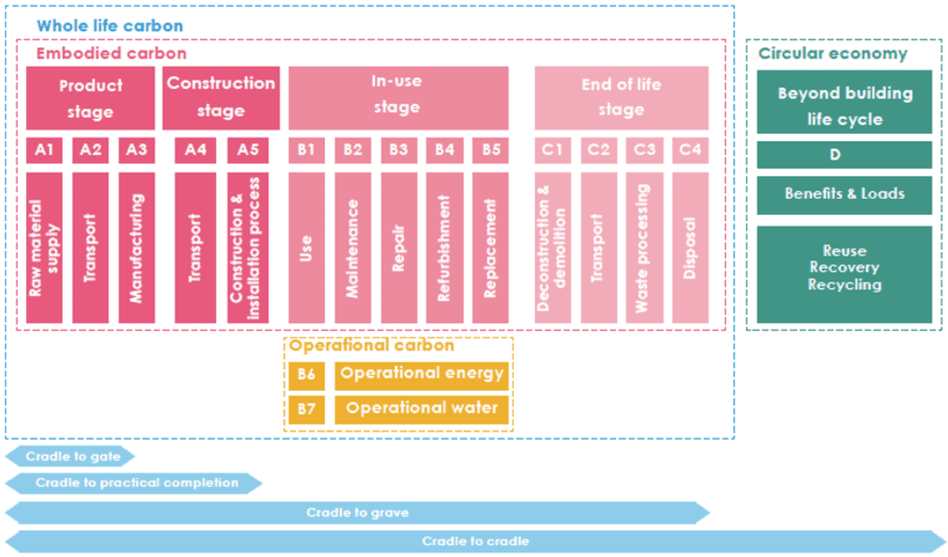

Figure 3.1: Whole life carbon life cycle phases

3.1.1. Embodied Carbon Contributions buildings parts and life cycles

Seven buildings were evaluated for their whole life carbon emissions. All buildings were located in the UK, were projects that aimed to create low embodied carbon buildings considering the whole life cycle and also measured operational carbon [64]. All projects are residential ultra-low energy buildings being completed between 2019 and 2022, with the exception of one which has not yet been completed [21][64].

Out of these seven case studies the following ratios were concluded; 50% located in the product stage (A1-A3), 5% in the construction stage (A4-A5), 20 % in the use stage (B1-B5), 2% in the end of life stage (C1-C5) and 23% in the operation stage (B6).

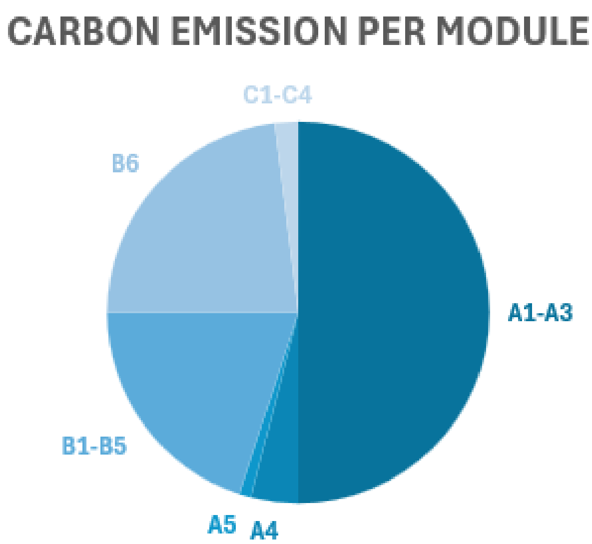

Figure 3.2: Carbon Emission Per Module Case Studies LETI

The emission of the operation stage is considerably lower than with most current buildings. As stated in section 1.1 operational carbon is becoming lower in newly constructed buildings, as is the case here. These value are however not applicable to current buildings. Buildings constructed earlier will have higher operational carbon emissions.

Dimoudi and Tompa (2008) analysed two office buildings consisting of respectively 3 and 5 levels with a main load bearing structure of concrete. In these two building 73.3-75.3 % of the embodied carbon consisted of the structural material. The building envelope was roughly one fourth of the embodied carbon content [4][15]. Building installations were not included in this study and finishes were applied in minimal capacity. LETI (2021) performed seven embodied carbon determination case studies. All building were ultra-low energy and consisted of a significiant amount of bio-based materials. In the seven case studies performed by LETI the sub-and, superstructure were responsible for on average 82% for the carbon emitted during A1-A5. The remaining 18% being of finishes, building installation and FF&E [64]. The superstructure definition used in the report from LETI includes the facade. The emission for solely the structure is lower, but not mentioned in this report.

3.1.2. Module A4: Transport

Module A4 of the construction life cycle stage concerns itself with all emmission due to the transport of materials from the factory to the building site. For building projects the contribution of module A4 to the total embodied carbon is most of the time quite minimal [21]. The carbon factor for the emission due to transportation is determined with equation 3.1

$$ECF_{A4,i} = \sum_{mode} (TD_{mode} \cdot TEF_{mode}) \tag{3.1}$$

$ECFA_{4,i}$ = embodied carbon factor for transport to site for the ith material
TD_{mode} = transport distance for each transport mode considered
TEF_{mode} = transport emission factor for each transport mode considered

Examples of emission factors for the UK ar shown in table 3.1. For more detailed calculations and for other emission factors a conversion excel can be downloaded from the United Kingdom Government website [17].

Mode	TEF_{mode} (gCO_2e/kg/km)	Source
Road transport emissions, average laden	0.10749	Ref [17]
Road transport emissions, fully laden	0.07375	Ref. [17]
Sea transport emissions	0.01614	Ref. [17]
Freight flight emissions	0.53867	Ref. [17]
Rail transport emission	0.02782	Ref. [17]

Table 3.1: Transport Emission Factors for Different Modes

a For HGVs (all diesel), average laden.
b For HGVs (all diesel), fully laden.
c For cargo ship/container ship, average.
d International, to/from non-UK (direct effects from CO_2, CH_4, and N_2O emissions only).
e Freight train.

If the transport distances are yet unknown the United Kingdom applies the following Embodied Carbon factors for transport;

A4 Transport Scenario	km by Road	km by Sea	$ECFA_{4,i}$ ($kgCO_2e$/kg)
Locally manufactured	50	–	0.005
Nationally manufactured	300	–	0.032
European manufactured	1,500	–	0.161
Globally manufactured	200	10,000	0.183

Table 3.2: A4 Transport Scenarios and Embodied Carbon Factors

3.1.3. Biogenic Carbon Storage

During the manufacturing of steel and concrete a significant amount of carbon is emitted. During the growing of timber CO_2 is sequestrated. CO_2 is taken from the atmosphere and is stored within the material. If the materials are eventually decomposed this biogenic carbon is returned to the atmosphere. In contract with concrete and steel, timber has a cyclical emission and absorption process [37].

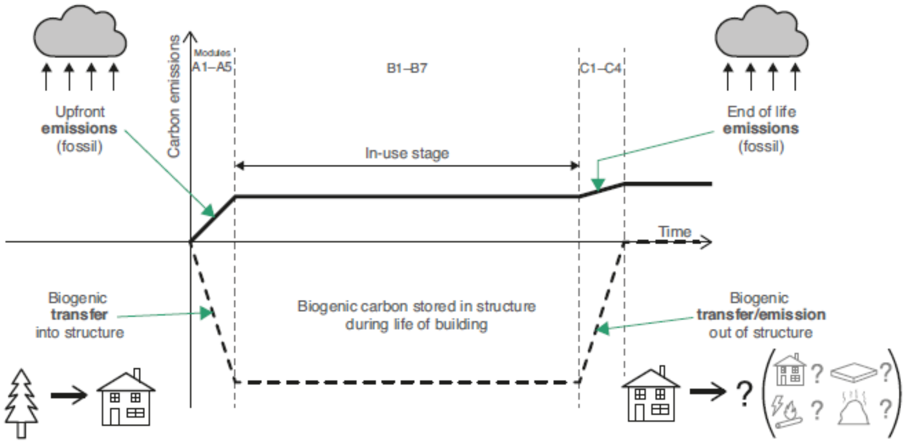

Figure 3.3: Biogenic carbon storage during the life cycle [21]

Literature research shows that in the academic world there is still a lot of ongoing debate about how to include biogenic carbon storage. Biogenic carbon can be integrated in an EPD as a negative amount substracted from module A1-A3. With timber this often results in a negative material factor. Meaning that if you use more timber, the more sustainable the building becomes. In EPD's written accourding to EN 15804+A2 biogenic carbon is reported separately for the carbon factors of modules A1-A3 [21]. EPD's written according to EN15804+A1 can include biogenic carbon storage in their A1-A3 module which would have to be extrapolated in order to compare them with EN 15804+A2 EPD's.

3.1.4. Legislation

Carbon emissions of the building industry can be reduced with the implementation of legislation concerning embodied carbon emissions during the full life cylce of the building. Current carbon emission related EU legislation and their scope regarding life cycle stages is shown in figure 3.4.

Lifecycle stages	Modules	EU policy instruments							
		EPBD	EED	CPR[6]	Ecodesign	WFD[7]	ETS[8]	Level(s)[9]	Taxonomy[10]
PRODUCTION	A1 Raw material supply	-	-	(*)	•	-	•	••	(*)
	A2 Transport	-	-	-	-	-	(*)	••	(*)
	A3 Manufacturing	-	-	(*)	-	-	•	••	(*)
CONSTRUCTION	A4 Transport	-	-	-	-	-	(*)	••	(*)
	A5 Construction installation process	-	-	(*)	-	-	-	••	(*)
USE	B2 Maintenance	-	-	(*)	-	-	-	••	(*)
	B3 Repair	-	-	(*)	-	-	-	••	(*)
	B4 Replacement	-	-	(*)	-	-	-	••	(*)
	B5 Refurbishment	-	-	(*)	-	-	-	••	(*)
	B6 Operational energy use	••	••	-	•	-	(*)	••	••
END-OF-LIFE	C1 Deconstruction	-	-	(*)	-	•	-	••	(*)
	C2 Transport	-	-	-	-	-	(*)	••	(*)
	C3 Waste processing	-	-	-	-	••	-	••	(*)
	C4 Disposal	-	-	-	•	••	-	••	(*)
BEYOND LIFE	D Reuse/recycle	-	-	(*)	•	•	-	••	(*)

Partially covered · Fully covered · Under revision

Figure 3.4: Scope of EU regulated and not-regulated measures during the building lifecyle [62]

EU legislation is mostly focused on operational carbon[62]. An exception is the Level(s) policy which targets all life cycle modules. Level(s) is however not a selfstanding policy but a framework for assessing and reporting the sustainability aspects. Despite the limited representation in current EU legislation the subject of embodied carbon is receiving a further growing amount of attention from industry and the government. Countries with the most well-developed operational carbon emission regulations are now also leading in embodied carbon regulations. Presently only five EU countries have created legislation regarding whole life carbon [62].

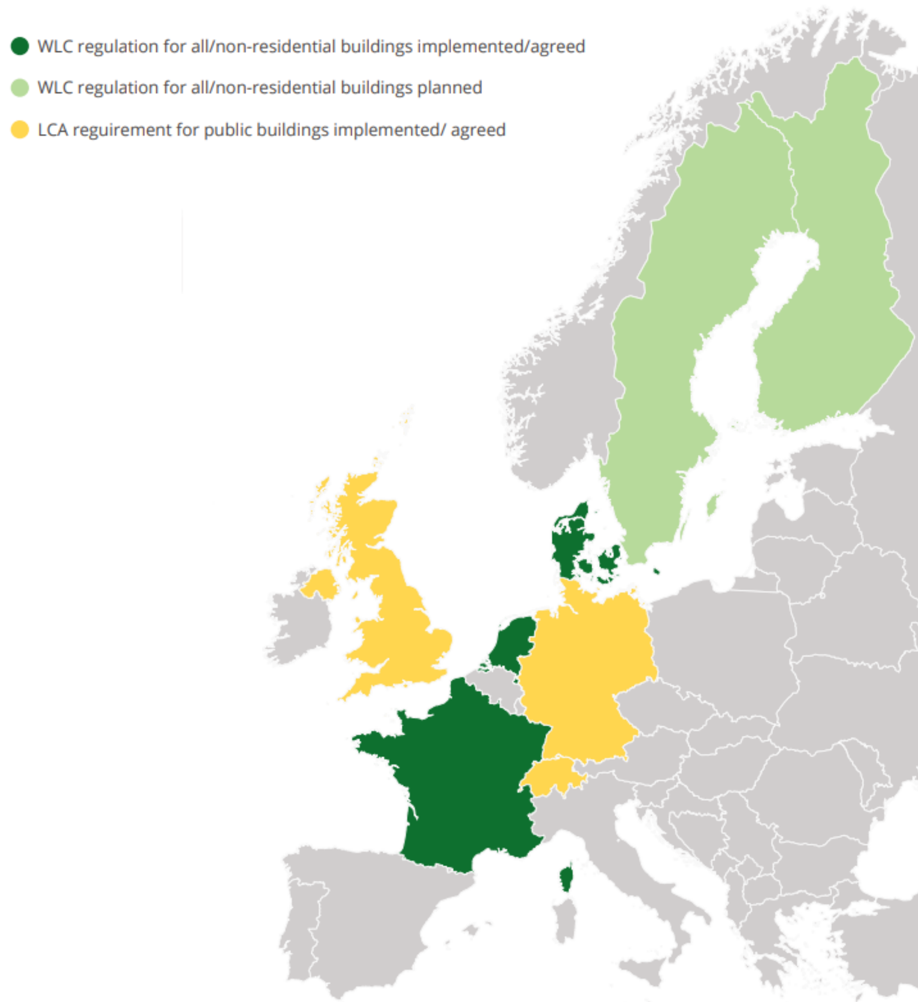

Figure 3.5: Map of the leading whole-life carbon regulations in Europe [62]

One example where legislation is being applied is in the Netherlands, where it is mandatory to include environmental impact calculations that account for whole life carbon[35]. However, the maximum allowable values set by these regulations are easily maintained below the limits, calling into question the effectiveness and overall usefulness of the legislation in this area. Increasing these demands is not as straightforward as one might believe. In the Netherlands, the government is bound by the public procurement rules of the EU that aim to ensure fair competition and prevent discrimination against companies in large building tenders. The government must avoid criteria that could inadvertently exclude smaller companies or those without specialized certifications, to maintain fair access for all businesses[40]. This can limit the ability to set high sustainability requirements since only specific companies could meet them[11].

3.1.5. Paris proof embodied carbon

On the 12th of December, 2015 in Paris 195 countries agreed to keep the rise in temperature due to global warming under 1.5 degrees [9]. Out of the maximum rise in temperature a worldwide greenhouse gas emission budget is determined of 400 Gt CO_2 with a probability of 67% [59]. In a report written by NIBE commissioned by DGBC a proposal is made for transforming this into a budget for the Dutch building industry. The world wide budget is first redistributed over the individual countries based on population. For the Netherlands this results in a budget of 909 million tons of CO_2, assuming 17.5 million people.According to research performed by the IEA in 2019 the building industry globally contribute 11% to greenhouse gas emissions. Taking this percentage of the budget results in a budget of 100 million tons of CO_2 for the Dutch building industry. Based on data from the CBS regarding the current building supply and demand multiple scenarios, varying in the level of sustainable design development, the expected usage of this CO_2 budget is plotted. Out of these graphs it can be concluded that with current trends, the Paris goals will not be attained and maximum emissions with which the climate goals can be attained are derived. In figure 3.7 these maximum values are given as kg CO_2 per m^2 for each building category [59]. An annual improvement rate of 5% is applied. This leads to a progressive reduction, asymptotically approaching zero. As a result, it is necessary to adjust the target values as the reference year nears 2050. In table 3.3 an analysis is shown of the embodied carbon values different type of buildings attain at this moment. Figure 3.6 shows the usage of the suggested Carbon Budget with current construction trends.

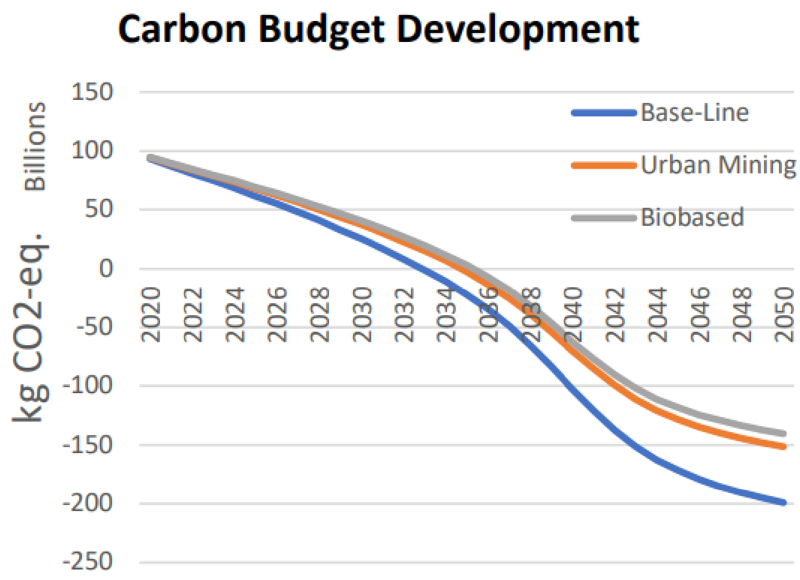

Figure 3.6: Carbon Budget usage following current construction emissions with 2% annual improvement included[59]

Code	Building Type	Low (kg CO_2/m^2)	Average (kg CO_2)	High (kg CO_2)
WE	Residence (single-family home)	190	286	373
WM	Residence (multi-family home)	190	286	373
KAN	Office	205	275	333
RV	Retail real estate	292	294	296
IND	Industry	228	253	271

Table 3.3: CO_2 Emission Ranges (A1-A5) for Various Building Types 2021[59]

Paris Proof target values	embodied carbon			
NEW CONSTRUCTION	kg CO_2-eq. per m^2			
	2021	2030	2040	2050
Residence (single-family home)	200	126	75	45
Residence (multi-family home)	220	139	83	50
Office	250	158	94	56
Retail real estate	260	164	98	59
Industry	240	151	91	54

Figure 3.7: NIBE Proposal for Upfront Embodied Carbon values (A1-A5) per square meter to achieve paris goals[59]

3.1.6. EPD Data types

EPD stands for Environmental Product Declaration. EPD's are created to objectively quantify the environmental impact of building materials. The rules and requirement for creating an EPD are determined by PCR's (Product Category Rules). A PCR is product specific and ensure the compatibility between different EPD's [39].

When following European standards for creating EPD's the data is subdivided into 3 category. Where the subdivision, just as with NMD categories, lies in the reliability and verifiability of the data. Type I and III are third party verified,while EPD's of type II are not. The difference between type I and type III EPD's is that type I EPD's provide an assessment of the data. An interpretation of the raw data simplifies the output and makes it more sensible for professional to client communication. EPD's from type III provide just the raw data giving a more detailed insight of the output and making it more suitable for professional to professional communication. The PCR's methodology for creating EPD's type III is written in NEN-EN-ISO 14025 [43][44] [42].

ISO 14025 however does not include how EPD's from specific building materials differ from each other. For the creation of building industry EPD's NEN-EN 15804+A2 gives detailed guidance.

EPD's from type III are used in the building industry. An EPD of type III consist of environmental impact of a product quantified in 19 impact categories and a text document describing all fundamental principles and assumptions made during the creation of the EPD. All 19 impact categories are shown in 3.4[1]. For embodied carbon the Climate Change impact category is relevant.

EPD's from the same product category rule can vary significantly. These differences can be allocated to two different reason; 1)Different methods applied 2)Different assumptions made. If a different method is applied which is more sustainable this directly translates to a more sustainable product. During the creation of a EPD it is however also allowed to make assumption to fill in missing information. When a producer consecutively makes the most sustainable assumption while another producer makes more conservative and possibly more realistic assumptions one product might unjustly get a higher sustainability grade than the other. An example might be with the drying of timber in kilns, producer 1 uses fossil fuels to dry it and producer 2 uses renewable fuels. Products from producer 2 will be more sustainable and this is reflected in the EPD. Both producers, however do not know what will happen at the end of life stage. Producer 2 assumes that the product will be incinerated, producer 1 assumes a 100% re-use. Even though there is no guarantee that the products from producer 1 will be re-used more than from producer 2, this product is now more sustainable on paper. Although in reality there is no difference between the two products. Another example might be when the raw materials are imported from different sources. In this case producers can make assumptions about average transport distances, modes of transport and fuel types.

3.1.7. MPG

In the Dutch building industry an MPG , Milieu prestatie gebouwen, calculation is mandated by the government for newly constructed residential and office buildings bigger than 100 m^2 . This calculation expresses in a monetary value the sustainability of a building. Currently 11 factors are taken into account, starting from the first of January 2025 19 factors will be taken into account. Every category gets its negative environmental influence expressed in a monetary value. This value is called 'the shadow price' ,the total sum of all shadow cost is then divided over the gross floor area and the life expectancy of a building. For residential buildings this is 75 year and for office buildings 50 years. This in the end result in a unitless MPG score of the building. The maximum value of the MPG score is for office building 1.0 and for residential buildings 0.8 [35]. Going into effect from the first of July in 2025 these maximum value will be reduced for both office and residential buildings. Buildings with other functions will also be included starting from July 2025. Which functions these are or to what amount the maximum MPG-scores will be lowered is not yet stated [55].

For these MPG calculation only the NMD, Nationale Milieu Database, may be used [35]. The NMD is a database containing shadow cost for building materials determined through life cycle analyses [35]. In the NMD there are three types of data. Data of category 1,2 and 3. Data of category 1 is brand-specific data which has been verified by a independent third party with the necessary qualifications according to the NMD assessment protocol. This is the same for Category 2 data, but now the data is brand-independent or 'brandless'. Category 3 is brandless data as well, but now the data has not been verified. When doing an MPG calculation it is allowed to use category 3 data but data of category 1 and 2 is preferred [34]. With category 3 data there is an additional surcharge factor, because data in this category tends to give optimistic values[34].

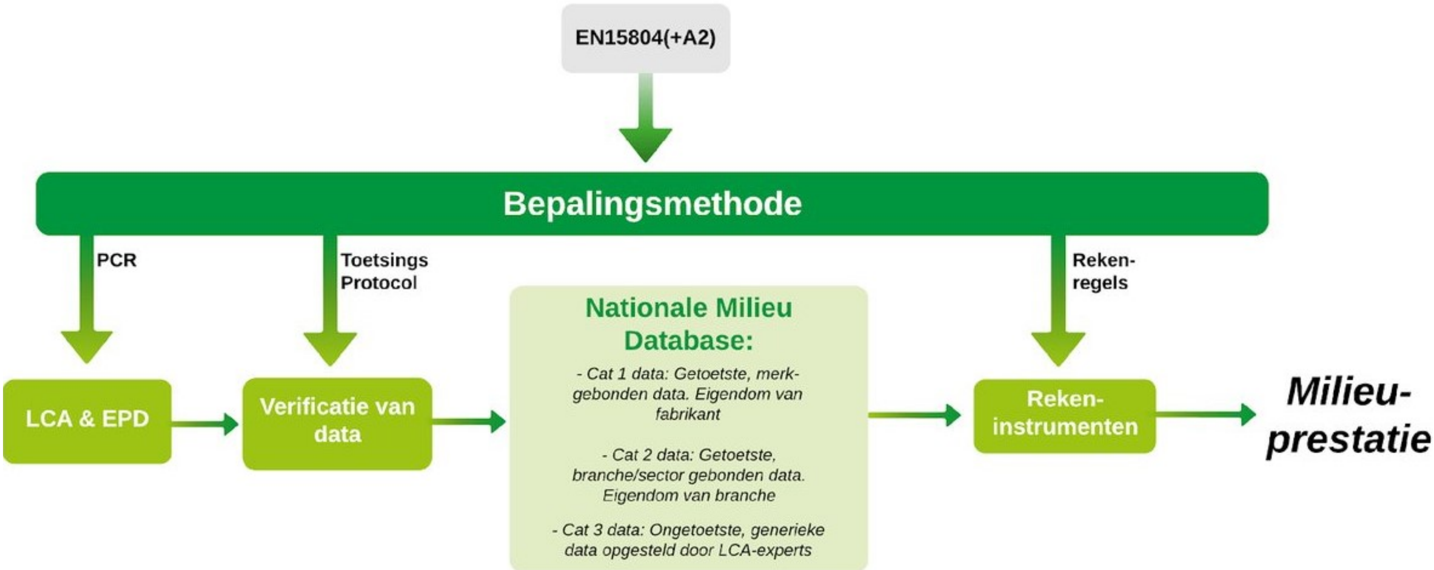

Figure 3.8: Dutch determination method [35].

3.1.8. Collaborative Embodied Carbon Design Process Integration

In a paper written in the journal of automation in construction it is discussed that for the way the building design process is currently developing itself an interdisciplinary collaboration is needed[28]. The role of the engineer during the design process is a widely discussed topic in many scientific papers. A traditional collaboration is described as a 'horizontal linear process'[38]. The problem with this type of collaboration is that the architect and engineer each have their own domain. All the building performance evaluation is done by the engineer who after analyzing than has to consult the architect for the possibility of design modifications [31]. This type of collaboration easily creates misunderstandings and another form of collaboration where the engineer functions as an acting assistant is described[38].According to Struck et al.an acting assistant engineer's role is to support the exploration of the design space. Thinking beyond analyzing a possible solution provided by the architect and thinking latterly with the architect and provide alternative design solutions [61]. The integration of several disciplines will result in an easier exploration of the design space with integrated solutions. This will make it easier to compare variants which has been shown is a highly effective method to lower the embodied carbon of a building [19]. With the sustainability concepts these integrated solutions are still lacking [28].

In common practice in the Netherlands, embodied carbon is not adequately integrated into the design process; instead, the focus is mostly placed on assessing it only after the design is completed. This strongly limits the possibility for reducing the embodied carbon content of the building; “Once the building has been completed and the ‘as built’ embodied carbon is assessed there is no room for reducing it”[51]. To incorporate embodied carbon in the design of the building it has to be already integrated in the early design stage. Measuring embodied carbon in the early design phases makes it possible to prioritize low embodied carbon as a key design driver. This will result in more significant reductions [19]. Embodied carbon evaluation in the detailed-design stage is good for setting accurate benchmarks, but it offers very little flexibility in the design to make impactful design choices. Impactful design choices that could reduce the embodied carbon of the design [19].

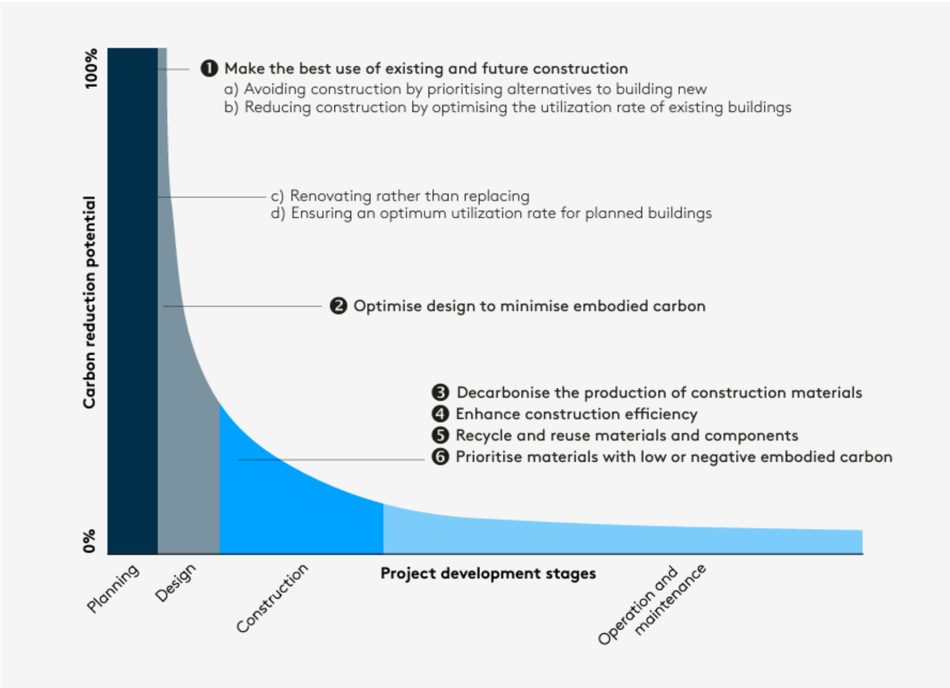

Figure 3.9: Embodied carbon reduction potential at different project development stages [26].

3.2. Current Software analysis

In this subsection the currently available software tools will be evaluated. This evaluation will be partly based on literature, partly on interviews performed with professionals and partly on own evaluations of these tools.

All Embodied Carbon calculator tools make use of the LCA methodology. The LCA methodology is seen as the best method for evaluating the environmental impacts of a building [47]. LCA is already present in the building sector, but methods to integrate it further with the building design process are pursued[10], since now LCA is mostly used to retroactively asses the environmental impacts of a building [49]. A promising way to integrate LCA more with the design process is to integrate LCA data of building components with a BIM platform[10]. LCA integrated in a BIM-based software has however still several obstacles regarding the data exchange and the smooth implementation in the BIM softwares [3].

LCA works on different scales. Various LCA tools are currently available, and they can be classified in three levels [46].

- Level 1: Product comparison tools.
  Gabi, SimaPro (NL), TEAM, LCAiT
- Level 2: Whole building design decision support tools
  LISA,Ecoquantum(NL), Envest, ATHENA, BEE.
- Level 3: Whole building assessment frame or systems
  This system uses methodologies as BREEAM, LEed, SEDA

Tools of level 1 aim to evaluate the environmental performance at a detailed level. They are used to evaluate and compare building products. Level 2 focuses on the whole building design scale and it takes into account the total assembly of the building and gives an output in the form of impact categories. Tools on level 3 work on the same scale as level 2, but they provide a scoring to the results [16].Tools like the Tally plug-in discussed in section 3.2.2 can be used for whole building life cycle assessments and to communicate the whole life embodied carbon[13].

3.2.1. Detailed LCA tools, Level 1

GaBi and SimaPro are stated as the leading software tools for life cycle assesments in a journal published in 2015 [25]. These tools are however only usable by experts and are not usable for early design phases. This is due to their complicated workflow and detailed granularity requirements for the input.

3.2.2. Approximation of level 1 tools; BIM-LCA plugins evaluation and comparison lv.1 GABI software results

Several BIM-LCA plug-in's are already available. In a paper written by Bueno and Fabricio an analysis is performed of several of these plugins, listing their features and limitations. An overview of the most important limitations of these plugins discussed in the paper are shown in table 3.5[10].From the analyzed BIM-LCA plug-ins, two stand out as having no evident limitations. These are the One Click LCA and the Tally plug-in. The Tally software was used to analyze several wall compositions and the same was done with the full LCA software Gabi 6. Out of a comparison between the results of the plug-in and the results from Gabi 6 big discrepancies arose. These discrepancies were attributed to the simplifications made in the BIM-LCA plug-in [10].

A major issue with the Tally plug-in is that it gives a 'black box' assessment. When using this plug-in there is no transparency in how the calculations are carried out. This means no interference is possible and finding the source of any discrepancies is difficult [10]. The One Click LCA plug-in was not compared in this study. One Click LCA however works with EPD's and has the same 'black box' issues as discussed in the paragraph above [10]. The problem with using EPD's in an early design stage is that the values can vary quite significantly depending on the producer [33] and during an early design stage the producer you are going to use is not yet known.

Tool name	Biggest limitations
Elodie Centre Scientifuqe et Technique du Bâtiment	Seperate software needed to import the data from BIM. Most information only in French.
eTool LCA international Team Effort	Seperate software needed to import the data from BIM.
Green building assessment tool (GBAT)	Seperate software needed to import the data from BIM.
Green Building Studio Autodesk	Seperate software needed to import the data from BIM. No full LCA studies
Impact Compliant Suite IESVE	Seperate software needed to import the data from BIM.
LCA Design (Ecospecifier)	Low transparency about used software, data and methods.
Lesosai	Seperate software needed to import the data from BIM.
One Click LCA	Difficult to find information.
Tally	Specific for Autodesk Revit software.

Table 3.5: Properties BIM-LCA integration tools [10]

3.2.3. Level 2 tools that stand out

Multiple Level 2 tools were examined in literature research. The most noteworthy tools are discussed here.

Institution of Structural Engineers - Structural carbon tool

This tool works on an excel basis. Data has to be typed in manually and the integration within the design process is limited. The tool is transparent in the data it uses and the assumptions it makes. The tool has the negative characteristic of using average value, but given the high level of expertise behind these values they are considered well founded.

Athena impact estimator

The Athena impact estimator is able to evaluate whole or sections of building. Users have to describe building assemblies through dialogue boxes. It can be used in any design stage. The data is customized to be regionally specific for North America. Any EPD's used in the tool can not be accessed and material values cannot be modified[13]. This tool has drawbacks; it relies on text input which can lead to misinterpretations, includes black box processes which limits transparency, offers minimal adaptability and primarily uses North American data.

OneClick LCA

Through DWA it was possible to get access to the OneClickLCA whole life carbon calculator for a short limited time. Observations I made during this short analyses are listed below. Categorized in Pro's and Con's.

The pro's are:

- Grouping of elements
- Visualization of results in 3D model including share per class options

The con's are:

- Black box LCA profiles
- Manual double input for material definition
- Unclear LCA profile selection

The biggest flaw of the OneClickLCA whole life carbon calculator is the lack of transparency. Confirming the black box issue stated in the literature research[10]. For timber specifically really coarse information and categorization are provided for the LCA profile selection.

GOEKO

GOEKO whas a quite new software at the moment of testing, being launched two months prior. It makes use of the Ökobaudat database which is the German equivalent of the NMD. No papers are published at this moment explaining the function of the tool and further user experience is needed to asses this tool. The data selection of the tool is very unclear. It functions also poorly with a lot of bugs and incoherence's occuring. In figure 3.10 the scripts is shown that was used to evaluate the plugin.

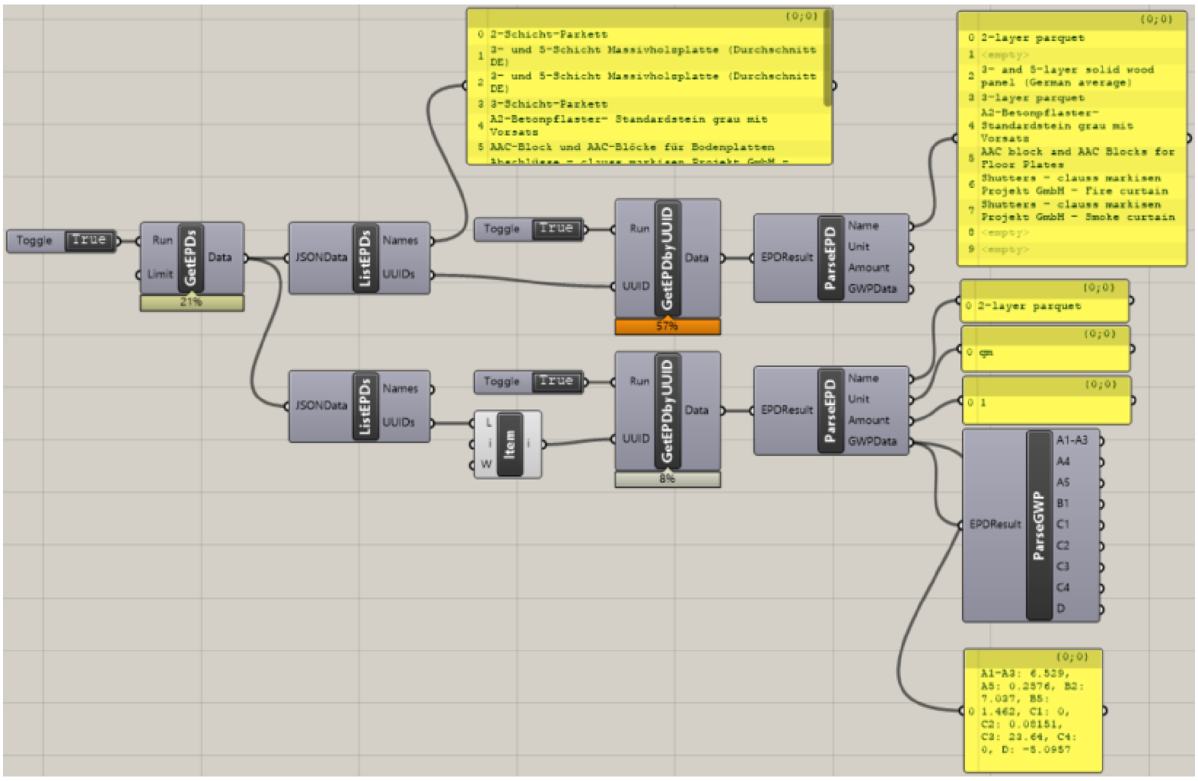

Figure 3.10: GOEKO plugin evaluation script

Bombyx

Bombyx makes use of the KBOB database [7],which is the Swiss equivalent of the NMD. This is viewed as a reliable source. Trusted users are however allowed to make changes to this database. There is no verification of these data changes however, since there is no clear definition provided of what a trusted user is and since there is nog verification of these data changes this results in some reliability issues. The embodied impact is determined by multiplying the mass of the material with its respective embodied impact factor. Where the volume is taken out of the grasshopper model and the density out of the bombyx database to attain the mass.Besides the initial embodied carbon of an element, the number of replacements are also taken into account. Equation 3.2.3 shows how the total embodied carbon of the structure is in the end determined. The KBOB database occasionally has products where the embodied carbon is expressed in surface area. If this is the case mass M_j is subsituted with area A_j[7].

$$I_E = \sum (M_j \cdot IF_{E,j} \cdot (1 + R_j)) \tag{3.2}$$

In the Dutch system the replacements are not included in the embodied carbon impact, since for the scope of this thesis only the structure is taken into account. This will not form a problem, since the structural elements considered have the same lifespan as the building. If the scope would however be expanded, differences will arise and the Bombyx tool will provide higher values. This is under the current assumption that the other included life cycle modules are the same. The determination of R_j is shown in equation 3.3

$$R_j = [\frac{RSP}{RSL_j}] - 1 \tag{3.3}$$

In figure 3.11 below an overview is given of the workflow of bombyx. Points of interest are the parameters 'stud period' and 'service life' as there are guidelines for these type of values these are mostly fixed. But inserting it as a parameter for further exploration might allow users to create more accurate service lifes for their specific project. This master thesis solely focuses on the structure of the building and the systems, marked in the figure with a purple colour, are left out of the scope.

Bombyx also includes the emissions due to transport which it has brought down to three parameters; weight, distance and mode of transportation[7]. It is however not clearly defined how these factors are derived an further research into this is necessary.

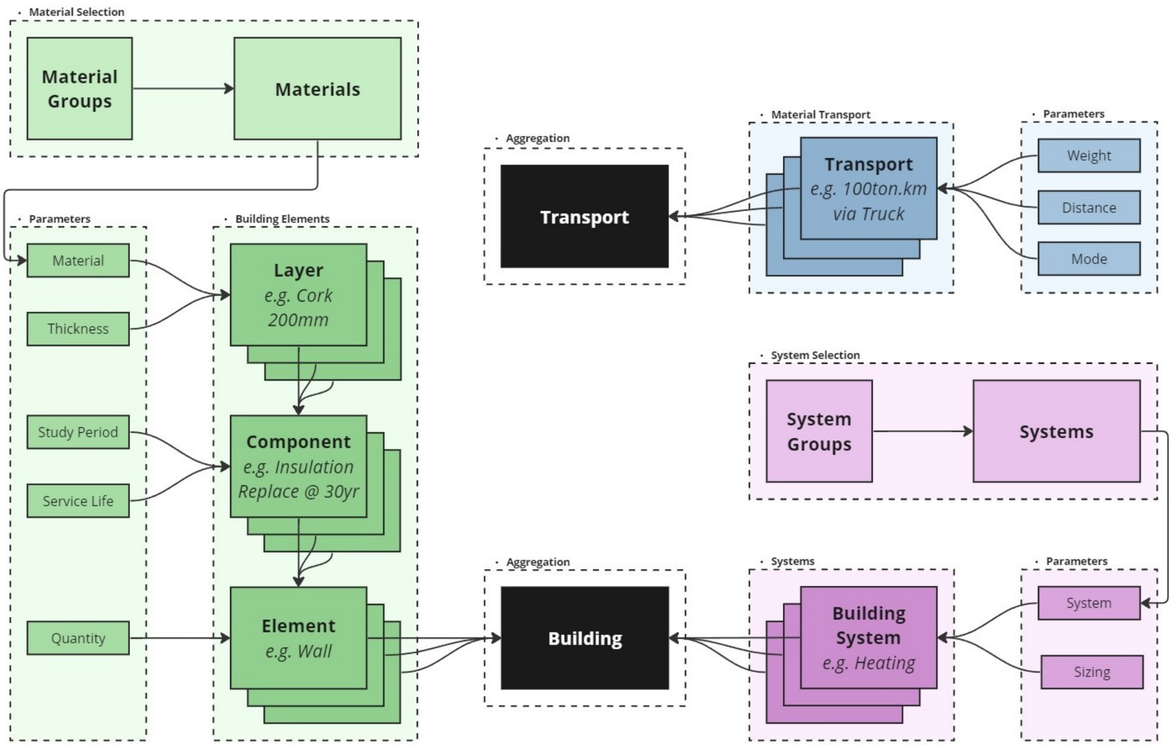

Figure 3.11: Bombyx workflow figure from food4rhino

3.3. Structural systems

A key requirement from DWA for this master thesis was the inclusion of timber structures. The following section examines various timber and timber-hybrid structural typologies, along with their applications in both the global context and specifically within the Dutch building industry. This includes an analysis of the types of systems used in buildings, categorized by height.

3.3.1. All-Timber structure typology's and their suitability

An all-timber structure is defined as a structure where the main vertical and lateral load bearing structure consists of timber. Connections and floor elements are allowed to be from a different building material for the building to be still defined as a all-timber structure since they are officially not part of the load bearing structure[56].

Most apartment buildings in the Netherlands are primarily made out of concrete and steel and do not exceed 10 levels[29]. A possible practical reason for using timber structure instead of traditional building materials like concrete or steel is the low self weight of timber. This allows for a lighter foundations and increases the ease of construction due to lower hoist capacity requirements[29].

Timber structures are often created out of mass timber. Mass timber structures can consist of wall, floor or frame elements. Mass timber elements are defined as engineered wood products where a more homogeneous product is created that optimizes the structural behavior of the wood [58].

Platform method vs Column-beam system for Timber Frame Multi-Storey buildings

In the platform method one layer of the timber structure is build upon the one below it. Leading to several elements being loaded perpendicular to their grains. Due to the limited capacity of timber perpendicular perpendicular to its grains, structures of this typology are limited to around four levels[29].

With a column-beam system the beams are connected to continuous columns and the beams are connected to the columns. This prevents loading perpendicular to the grain. Structures made with the column-beam system can be used for taller buildings [29].

Lateral load bearing structure

In column-beam systems some form of bracing is often applied to provide stability[29]. With structures higher than five stories timber engineered products like CLT or glulam are used [20]. The stability from frame structures is provided by high moment resisting connections [29]. The moment transfer of these glulam frames relies on the rotational stiffness of these connections. The variables that determine the global stiffness of these structures are the cross-sections of the structural elements, the rotational stiffness of the connections and the effective span [20]. For tall timber buildings a CLT core structure is theoretically possible. Core structure are in general made out of concrete and not CLT but due to the cross-lamination of CLT is has the potential to be used as well [20]. This is however very experimental. A study to determine the feasibility of using CLT cores for the UBC Brock Commons building in vancouver concluded that for this building it would not be feasible. This building stands 53 m in height and has a straight forward rectangular geometry supported by two cores [12]. Buildings that used CLT cores have also not been found within higher buildings during the inventory of timber structures world wide. A point to note when using a core structure is that additional lateral resistance can be provided by increased rotational stiffness in the column-beam system collaborating with the core. A glulam diagrid structure in the facade is also possible as a stability system. Here the stability is derived from a triangular construction in the facade. The efficiency of this facade is guided by the angle of the diagonal elements [20]. A master thesis evaluating the performance of frame, shear walls and diagrid stability systems in all-timber structures concluded that a diagrid system was superior[54]. This system is also used in the tallest all-timber structure in Europe, Mjostarnet.

General stability issues with multi-level timber frame structures

With multi-level timber frame structures stability is quite often an issue. The structures are relatively light and are therefore more easily pushed out of balance. A possible solution for this is the application of a timber-concrete hybrid structure. This is further discussed in 3.3.2. Within all-timber structure this problem can be minimized by optimizing the load distribution. An example of this method applied to a timber shear wall stability system is described in the paragraph below. In figure 3.12 two options are shown for the load distribution in this system. When situation B is occurring a higher force will be exerted on the stabilizing shear wall. This will help the overall stability of the building, the distribution over the elements is however less efficient[29]. In plane vertical deformation of the transversal wall contributes to the total horizontal deflections at the top of the structure. Research and experiments performed on 1:1 scale models have shown this to be the limiting factor for buildings designed with a load distribution as shown in situation A. As a result variable L has to be reduced. It is concluded that situation A is ideal for buildings up to three levels and B for buildings exceeding 3 levels [29].

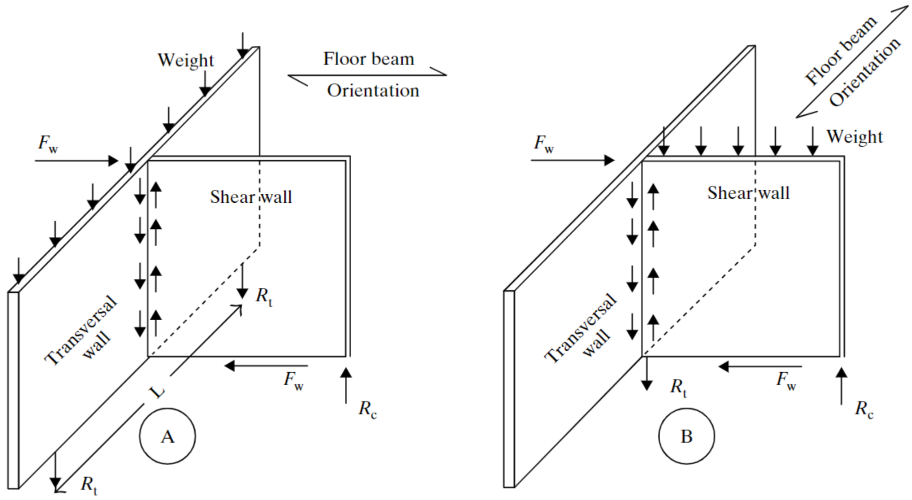

Figure 3.12: Influence beam orientation and following load distribution on overall stability [29].

3.3.2. Timber-hybrid structure typology's and their suitability

Beside all-timber structures several hybrid structure typologies are possible; 1)Timber-Concrete hybrid structures 2)Timber-Concrete steel hybrid structures 3)Timber-Steel hybrid structures. These are shortly discussed in the following sections.

Timber-concrete hybrid structures

A timber-concrete hybrid structure is a structure where a significant amount or element of the main load bearing structure, vertical or lateral, is made of concrete[56]. A timber-concrete hybrid structure is commonly a structure with a concrete core that resists the lateral loads, and a timber structure that carries the vertical loads. With a load transfer from the facade to the core through the floors making use of diaphragm action [67][56]. There are also examples where the beams and columns are made of concrete and timber is used for the floors and as partition walls [56]. According to the definition given in 3.3.1 these are however classified as concrete structures and are left outside of the scope of this thesis.

Research has shown that timber-concrete hybrid structures perform better under seismic loads, have an increased fire resistance and a higher bearing capacity than full timber structures [50]. Besides the stability system, concrete can also be used with the floors in a timber-concrete composite structure. These building elements are timber-concrete composites (TCC). With a TCC floor a timber base surface is connected with a concrete slab at the top of it [65]. The compressive strength of the concrete in the compression zone and the lightweight high-tensile strength timber in the bottom makes the best use of the properties of both materials [45].The increased weight of TCC flooring system, when placed correctly, contributes to minimizing wind-induced accelerations [60]. This added weight can also assist in the mitigating of tensile forces in the foundation. Supporting the overall stability of the structure

Timber-steel hybrid structures

A timber-steel hybrid structure is a structure where a significant amount or element of the main load bearing structure, vertical or lateral, is made of steel. In most cases this is a lateral force resisting system. Typical examples are steel-framed cores, exoskeleton steel bracing system or buckling-restrained braces. Often these systems also use a significant amount of steel in their vertical load bearing system in the form of steel columns and beams. Which is combined with a timber wall and floor system[56].

Timber-concrete-steel hybrid structures

Timber-concrete-steel structures are composed of all three building materials. A standard set-up of these structures would be a concrete core combined with a steel column and beam system and a timber floor and wall system[56].

3.3.3. Global Market Inventory Medium-High rise timber and timber hybrid structures

In a paper written at the Council of Tall Buildings and Urban Habitat (CTBUH) an inventory is made of the top 40 highest timber or timber hybrid buildings. With a minimum height of eight floors. Al included buildings have been completed or are under construction as of February 2022[56]. A notable building that is excluded from this list is therefor the SAWA building since the construction of that building started on November the 18th [24]. In figure 3.13 a classification of the structural materials as a function of the building height is shown. Out of this figure based on data from the CTBUH it is concluded that most buildings use a Timber-concrete hybrid systems and that the higher the structure becomes, the rarer the use of full timber structures becomes as well. In figures 3.14 and 3.15 pie charts are shown to further visualize this.

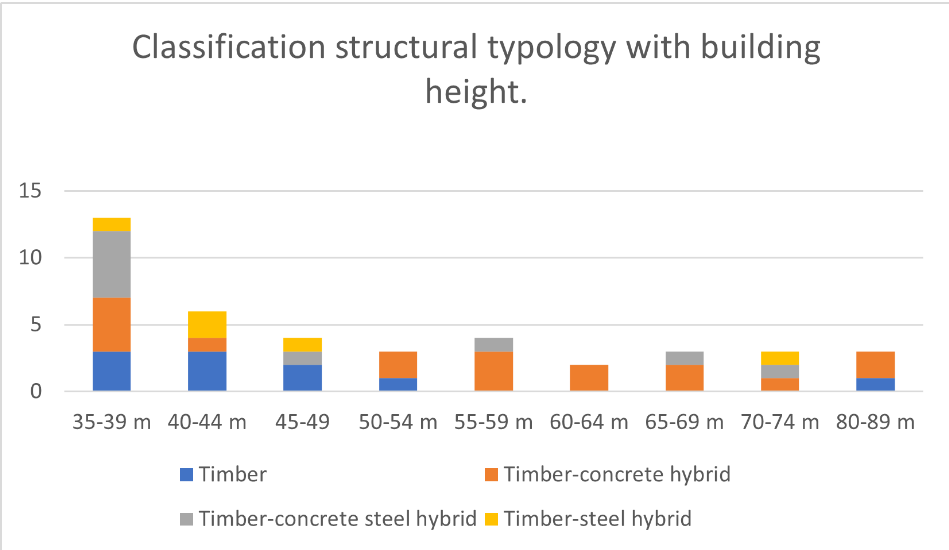

Figure 3.13: Classification structural typology with building height

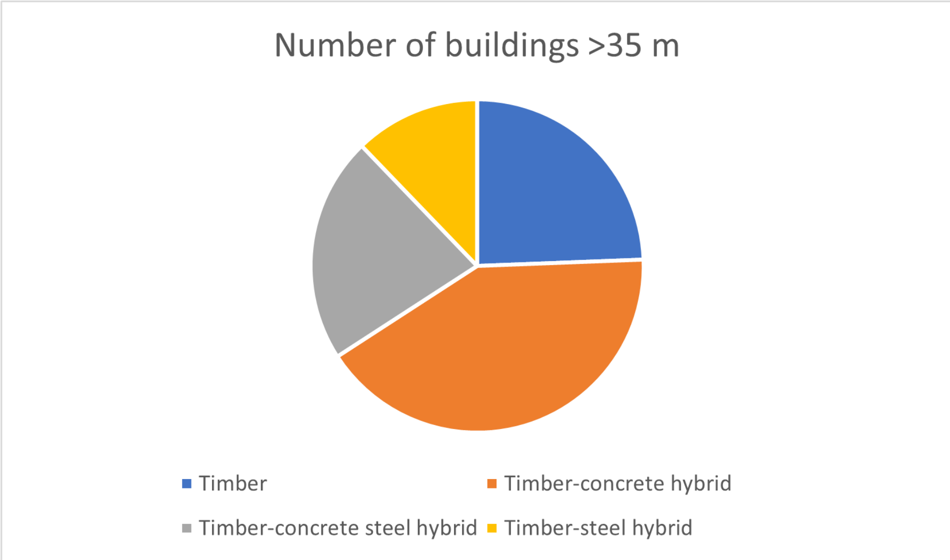

Figure 3.14: Classification structural typology with building height higher than 35 meter pie chart

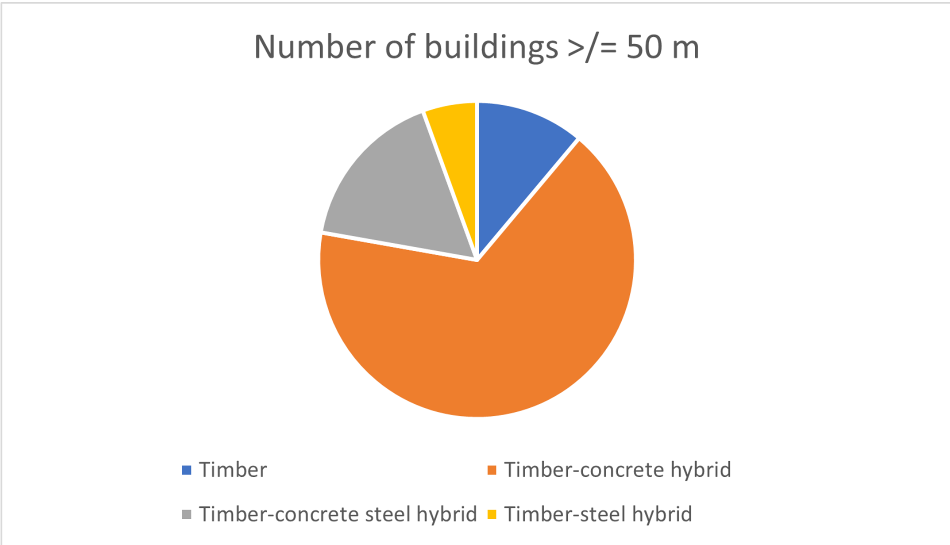

Figure 3.15: Classification structural typology with building height higher than 50 meter pie chart

3.4. Conclusions Literature and Current state of the art

In this section the conclusions of the Literature and Current state of the art chapter are given per section. The conclusions from the individual sections are than combined into a list of requirements for the Embodied Carbon Determination Framework.

3.4.1. Conclusion Whole Life Carbon

Embodied Carbon is a part of Whole Life Carbon, which contains the total carbon emissions of a building throughout its entire life cycle, including both embodied and operational carbon emissions. Due to reduced Operational Carbon emissions Embodied Carbon now plays a critical role in minimizing the environmental impact of a building. By incorporating Embodied Carbon in the early design stages the biggest reductions can be made. Embodied Carbon is subdivided in two stages; 1)The Product Stage which contains emissions from the extraction of raw materials and the manufacturing of building elements, subdivided in module A1-A3 2)The Construction Stage includes emissions resulting from the transportation of materials from factory to site and the construction process, subdivided in module A4-

A5 . By focusing on life cycle modules A1–A3, which account for the largest portion of Embodied Carbon emissions, accurate evaluations can be made without introducing unnecessary complexity from project-specific variations in modules A4–A5. Environmental Product Declarations (EPDs), developed with Life Cycle Analysis in compliance with NEN-EN 15804+A2 standards, are used for quantification and communication of Embodied Carbon contents of structural elements. These can be found in databases like the ICE database and Nationale Milieu Database. Criteria like the MPG score and Paris Proof Carbon Budget provide benchmarks to assessing a design. The MPG criteria are, however easily met and the Paris Proof Carbon Budget is considered to be more representative of current societal needs regarding emission reduction.

3.4.2. Conclusion Current Software Analysis

Several tools are currently under development with the aim of being applicable during the early design stages. However, challenges such as black-box outputs, software bugs, and inefficient data input processes hinder their integration into these stages.

The Embodied Carbon Tool by IStructE features a large publicly available database, which could prove useful. Similarly, the Bombyx tool shows promise as a secondary software for result evaluation, provided it is integrated with an efficient data input and output evaluation framework.

3.4.3. Conclusion Structural Systems

Several structural systems and configurations are possible when building with timber. In addition to fully timber buildings, timber hybrid systems also exist, such as timber-concrete hybrids, timber-steel hybrids and timber-concrete-steel hybrids. An inventory of timber and timber hybrid buildings worldwide has shown that for structures higher than 35 meters timber-concrete hybrids are the most common. This structural system typically employs a concrete core to resist lateral loads, while timber elements are used for vertical load bearing. The added weight of the concrete core improves the stability of the otherwise lightweight timber structure, providing improved performance under dynamic and lateral forces.

3.4.4. Embodied Carbon Determination Framework requirements

Based on literature research and evaluation of currently available tools in table 3.7 and 3.6 a list of requirements has been formulated for the framework.

Three tools are identified as essential for supporting Embodied Carbon assessment in early design stages. The Structure Generator Tool focuses on structural modeling, the Embodied Carbon Material Factor Determination Tool calculates the Embodied Carbon content of created structures, and the Iterator and Data Evaluation Tool automates and guides data analysis and visualization. Combined they form the Embodied Carbon Determination Framework.

Tables 3.6 and 3.7 presented in this section translate the conclusions from this chapter into a list of framework requirements. They outline the key requirements for a framework capable of effectively supporting Embodied Carbon assessment, with a focus on transparency, usability, and multidisciplinary collaboration.

Tool	Input	Output
Structure Generator Tool	• Design variables (span, number of flors, floor height, width and length). • Structural parameters.	• Structural models. • Cross-sectional sizes of structural elements. • Mass of the structure per structural element. • Mass of the structure per structural material. • Post result structural verification results for further analysis. • Verifications.
Embodied Carbon Material Factor Determination Tool	• Mass of the structure from the Structure Generator Tool. • Embodied Carbon Material Factors.	• Average Embodied Carbon values for the structure. • Range of Embodied Carbon values for the structure. • Embodied Carbon values given different assumptions made in the Embodied Carbon Material Factor Determination. • Verifications.
Iterator and Data Evaluation Tool	• Design variants. • Different material factor choices. • Verification results from Structure Generator Tool and Embodied Carbon Material Factor Determination Tool.	• Evaluated data for each design variant. • Comparative analysis of different design choices. • Data visualization for stakeholders.

Table 3.6: Required input and output for each tool in the framework.

Tool	Requirements
Structure Generator Tool	• Able to generate high quantities of design variants in a automated process. • Creates reasonable structures that are acceptable for the early design stage. • Automatically determines required cross-sectional sizes based on governing calculations. • Uses a secondary software or method to verify the generated structures. • Limits the use of finite element software to reduce computational load. • Facilitates a linear workflow, minimizing iterative design cycles. • Takes only factors into account that significantly influence the mass of the structure.
Embodied Carbon Material Factor Determination Tool	• Converts the mass of the generated structure into Embodied Carbon values. • Integrates multiple databases. • Includes options to switch between different material factors to showcase their influence on results. • Includes options to switch between different material factor assumptions to showcase their influence on results. • Provides a range of embodied carbon values to account for uncertainty. • Transparent in used values and methods. • Capable of handling discrepancies between product-specific Environmental Product Declarations (EPDs) and generic values. • Includes a sufficient amount of life cycle modules.
Iterator and Data Evaluation Tool	• Automates the generation and evaluation of large amounts of data. • Separates data into relevant folders for each discipline. • Facilitates multi-disciplinary collaboration within a unified environment. • Provides tools for comparing different design variants and their embodied carbon impact. • Highlights correlations and the influence of design assumptions and simplifications. • Adaptable for specific design needs, allowing customizations.

Table 3.7: List of requirements per tool in the framework.

Impact Category	**Indicator**	**Unit**
Climate change – total	Global Warming Potential total (GWP-total)	kg CO_2 eq.
Climate change – fossil	Global Warming Potential fossil (GWP-fossil)	kg CO_2 eq.
Climate change – biogenic	Global Warming Potential biogenic (GWP-biogenic)	kg CO_2 eq.
Climate change – land use and LU change	Global Warming Potential land use and land use change (GWP-luluc)	kg CO_2 eq.
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11 eq.
Acidification	Acidification Potential (AP)	mol H^+ eq.
Eutrophication – freshwater	Eutrophication Potential freshwater (EP-freshwater)	kg P eq.
Eutrophication – marine	Eutrophication Potential marine (EP-marine)	kg N eq.
Eutrophication – terrestrial	Eutrophication Potential terrestrial (EP-terrestrial)	mol N eq.
Photochemical ozone formation	Photochemical Ozone Creation Potential (POCP)	kg NMVOC eq.
Depletion of abiotic resources – minerals and metals	Abiotic Depletion Potential for non-fossil resources (ADP-minerals and metals)	kg Sb eq.
Depletion of abiotic resources – fossil fuels	Abiotic Depletion Potential for fossil resources (ADP-fossil)	MJ
Water use	Water Deprivation Potential (WDP)	m^3 world eq. deprived
Land use	Land Use related impacts (LU)	Pt (dimensionless)
Particulate matter	Particulate Matter formation Potential (PM)	disease incidences
Ionizing radiation – human health	Ionizing Radiation Potential – human health (IR)	kBq U-235 eq.
Ecotoxicity – freshwater	Ecotoxicity Potential freshwater (ETP-freshwater)	Comparative Toxic Unit for ecosystems (CTUe)
Human toxicity – cancer effects	Human Toxicity Potential cancer (HTP-cancer)	Comparative Toxic Unit for humans (CTUh)
Human toxicity – non-cancer effects	Human Toxicity Potential non-cancer (HTP-non-cancer)	Comparative Toxic Unit for humans (CTUh)

Table 3.4: Environmental impact categories and indicators [1].

Part III: Synthesis

4 Conceptual framework

4.1. Embodied Carbon Determination Framework

The framework consists of three tools; 1)The structure Generator tool 2)The Embodied Carbon Material Factor Determination tool 3)The Iterator and Data Evaluation tool.

The structure generator will, given a set of design variables, generate a suitable structure. As output the masses of the building materials will be given categorised in various ways.

The Embodied Carbon Material Factor Determination tool assigns Embodied Carbon Material factors to the masses provided by the structure generator, transforming them to Embodied Carbon values.

The Iterator and Data Evaluation tool has three functions; 1)Connecting the design variables to an iterator facilitating easy variant creation 2)Collecting and putting relevant data to make variable correlation investigation possible 3)Exporting data to a format suitable for visualisation to make data insightful

These three tools put together form; The Embodied Carbon Determination Framework. A framework supporting an evidence based sustainable design.

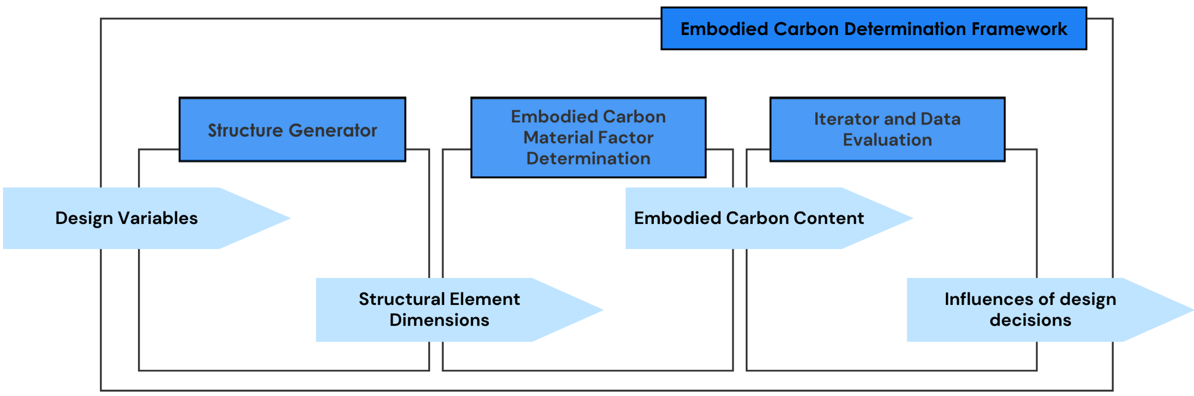

Figure 4.1: Diagram Concept Embodied Carbon Determination Framework

4.2. Embodied Carbon Material Factor Determination Tool

An Embodied Carbon Material Factor is a factor that states the amount of carbon emission per chosen unit of material. It is determined by taking the emission stated in the Environmental Product Declarations (EPD's) of the building materials used. The material factors for the same type of products can vary significantly. Material factors are created from EPD's from multiple database with the ability for adjustments based on key assumptions. This approach addresses the variability and differences between Environmental Product Declarations (EPDs) and between different databases, creating a clear and transparent range.

As stated in section 4.1 the Embodied Carbon Material Factor Determination Tool has to give different outputs depending on the purpose with which the tool is used. When comparing designs the absolute value of one design is less relevant. Its relations to the other designs is important. For comparing designs the embodied carbon results of the building will be made from average embodied carbon factors for the structural materials. When the final embodied carbon value of a specific design is wanted the Embodied Carbon content is given as a value range.

By employing a combination of average values and ranges, this methodology not only highlights the comparative relationships between different designs but also ensures that the final Embodied Carbon values are well-supported by a broad spectrum of data sources, thus enhancing the robustness and credibility of the analysis.

4.3. Structure Generator Tool

The structure generator tool is designed to fill in the structural design knowledge gap of the user if he or she is lacking of this or enhance the calculation speed for structural engineers. It creates a structure that aligns with the design variables input by the user. The tool is divided into two main components; 1) the Structural Karamba Model 2) the post-Karamba model mass addition. Not all elements are included in the Karamba model because extensive input into the 3D FEM model makes the operation of the structure generator tool demanding and slow. Additionally, some calculations depend on outputs from Karamba, which would require multiple iterations of running the 3D FEM analysis software which is an intensive and time-consuming process that significantly increases the calculation time and computational power required.

The structure of a building can be divided into two main parts; 1) the superstructure and 2) the substructure. As discussed in the scope of this thesis, the primary focus is on the superstructure, while the generated masses for the substructure are mainly intended for comparative analysis between different design variants, rather than providing precise final values for the substructure.

The superstructure is further divided into various structural element categories. The structure generator's output will provide the masses of these categories, which include:

- Column and beams
- Core
- Floors
- Joints

Ideally, all structural elements would be designed in strict accordance with Eurocode standards. However, incorporating every Eurocode verification step introduces a level of complexity that exceeds the intended purpose of the Structure Generator Tool. For each generated structure, the required cross-sectional sizes of structural elements are determined using simplified calculations believed to govern the design, based on prior experience and rough hand calculations. The level of detail in modeling each structural element category is adjusted based on its relative contribution to the building's total embodied carbon. Structural categories with higher embodied carbon contributions are modeled in greater detail, while those with lower contributions are simplified to optimize time and computational efficiency. In Section 6.2, the validity of these simplified calculations is verified. This guides the prioritization of taken into account only relevant structural element size influencing factors for the elements that significantly impact the overall embodied carbon of the structure.

4.4. Iterator and Data Evaluation Tool

The Iterator and Data Evaluation Tool is created to; 1) generate high amounts of data 2) evaluate high amounts of data.

The selected design variables are varied within a specified range defined by the user. This enables an easy exploration of the design space that meets criteria acceptable to the user. By automating this process, the tool significantly reduces the manual effort required for iterative testing and helps streamline the design evaluation workflow.

The evaluation of the data is threefold;

1)Inputs and outputs are combined into a visual representation to clarify the relationship between design choices and their impact on the embodied carbon content of the structure. 2)The results are organized into different folders to filter the data for various users, such as building designers and structural engineers, with the potential for structural engineers to investigate correlations. 3)A grading system is applied to the generated output, making the results less abstract and easier to interpret and assess.

Designing a structure involves a wide range of variables with many inter-dependencies. It is therefore not straightforward to observe the exact influence of each design choice on the final embodied carbon content of the structure. Visualizing these correlations clarifies for the user the impact of their choices.

To avoid information overload, the results are organized into separate folders to meet the specific needs of different users, recognizing that designers and engineers have distinct interests and requirements. By separating the data, each group can easily focus on the most relevant information for their role. This tailored approach ensures that users can investigate specific aspects of the design at any given time.

The grading form is applied by comparing a standardized to kg CO_2-eq per m^2 output to the threshold values stated in 3.1.5 for the year in which the structure is expected to be completed. This approach helps in providing a benchmark for evaluating the environmental impact of the design.

5

Detailed Configuration Embodied Carbon Determination framework

This chapter provides a detailed overview of the development and structure of the individual tools of which the framework is comprised. It begins with the Embodied Carbon Material Factor Determination Tool, which discusses topics relating life cycle module inclusion, databases and material specific factors to consider. This is followed by the Structure Generator Tool design covering building type and structural system selections, an evaluation of dimensioning methods, and the Level of Detail (LOD) of the output. The chapter is concluded with all small elaboration on the Iterator and Data Evaluation Tool.

5.1. Embodied Carbon Material Factor Determination Tool

In this section the detailed design of the Embodied Carbon Material Factor Determination Tool is given. This chapter addresses the argumentation behind life cycle module inclusion, biogenic carbon storage, the databases used, key properties of Embodied Carbon factors for specific materials, guidelines for developing a custom database, and methods to improve the accessibility of output data. In figure 5.1 a overview of the tool is given in the form of a flowchart.

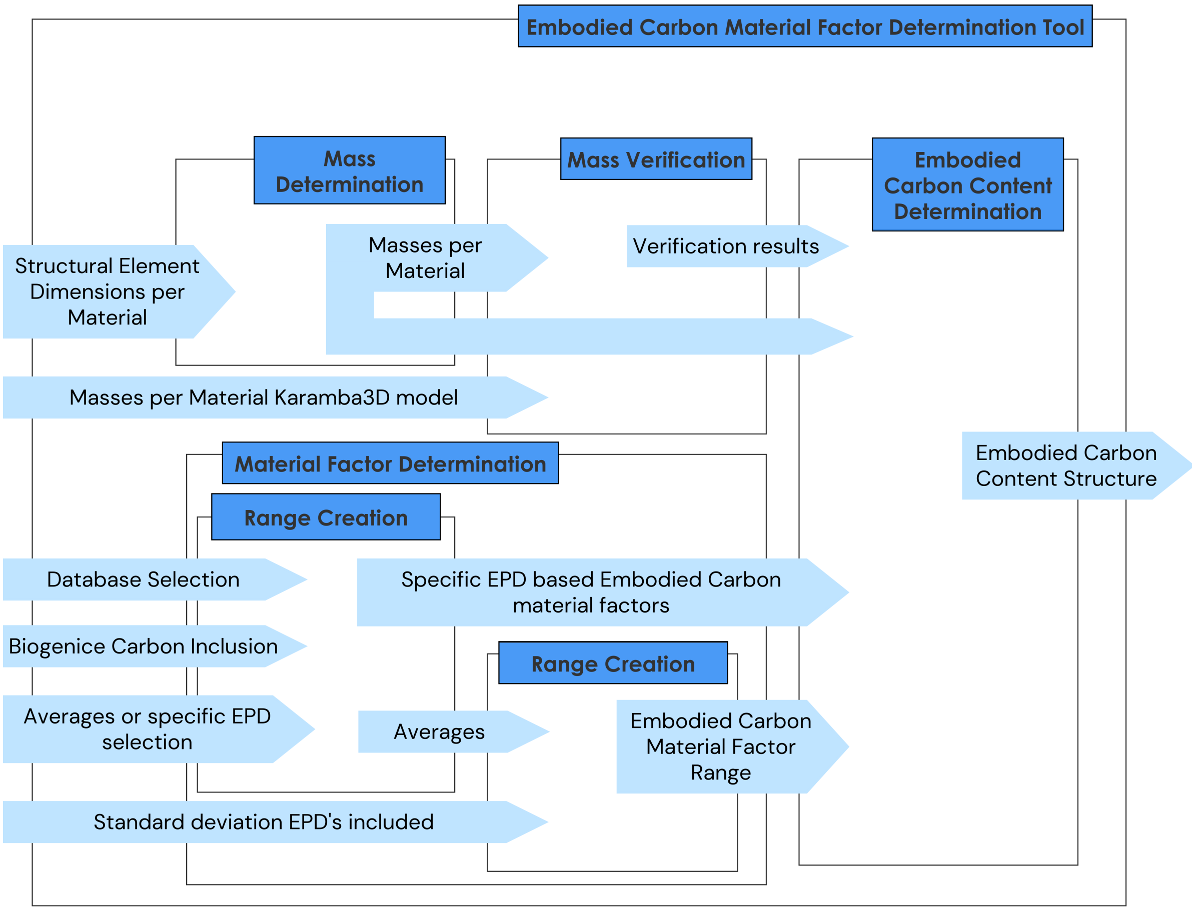

Figure 5.1: Embodied Carbon Material Factor Determination Tool Flowchart

5.1.1. Life Cycle stages and modules

In 3.1.1 it was discussed that in ultra-low energy residential buildings the whole life carbon emission is for 50% located in the product stage (A1-A3), 5% in the construction stage (A4-A5), 20 % in the use stage (B1-B5), 2% in the end of life stage (C1-C5) and 23% in the operation stage (B6). Adapting these percentages to only include embodied carbon with a cradle to grave scope (product stage, construction stage, use stage, end of life stage) leads to the following ratios;

- Product stage (A1-A3): 65%
- Construction stage (A4-A5): 6%
- Use stage (B1-B5):26%
- End of life stage (C1-C5): 3%

These ratios are derived from seven case studies, which is a relatively small sample group. The data includes categories such as finishes, façade elements, and installations, which generally require more frequent maintenance, repairs, and replacements compared to the main load-bearing structure. Most Environmental Product Declarations (EPDs) for structural elements exclude the use stage, which seems reasonable given that the lifespan of structural components typically is the same as the lifespan of the building, making replacements less relevant. Assuming the main load-bearing structure shares the same ratios for the construction and end-of-life stages, without having any emissions in the Use stage, the following ratios are derived:

- Product stage (A1-A3): 88%
- Construction stage (A4-A5): 8%
- End of life stage (C1-C5): 4%

These interpretations and adaptations are open to debate and should not be considered definitive figures. However, they clearly illustrate that for the main load-bearing structure of a building, the product stage is the dominant contributor to embodied carbon. The construction stage, module A4-A5, is mostly influenced by transport which accounts for 6-7% of the total 8%. The remaining 1% for module A5 is highly project-specific and of little contribution. The end-of-life stage is highly uncertain, as it is challenging to predict what scenarios will unfold in practice. As a result, the 4% contribution estimated for the end-of-life phase here can vary significantly based on the assumptions made about the disposal or reuse of materials.

The Embodied Carbon Material Factor in this thesis will entail solely contribution of the product stage (Module A1-A3). This is not in line with the DGBC definition of embodied carbon content which also includes the construction stage (Module A4-A5).

5.1.2. Biogenic Carbon Storage

The debate on how to account for carbon sequestration in timber is ongoing. On one hand, timber's sustainable benefits should be credited. However, the presence of negative material factors that arise due to the inclusion of carbon sequestration can paradoxically result in a situation where using more material appears more sustainable, which contradicts the core principle of minimizing material use for sustainability. This thesis does not aim to resolve this debate, but acknowledges its significant influence on the final embodied carbon value. In practice, these assumptions are not always clearly radiated outwards and are instead hidden within the details of reports, leaving users unclear about what is truly accounted for. It is crucial for users to understand how these assumptions impact results. Therefore, the tool developed in this thesis offers options to include or exclude biogenic carbon storage in the final output.

5.1.3. Source Databases

The Embodied Carbon Material Factor Determination Tool uses two databases: 1)ICE V3.0 database 2)NMD. The ICE database offers a broad range of Environmental Product Declarations (EPDs), providing a more comprehensive view of material carbon factors. The NMD is mandatory for use in the Dutch building industry, making its inclusion essential for regulatory compliance. By incorporating both databases, the tool enables users to compare the influence of different data sources, even though they follow the same standards. This comparison highlights areas where the NMD falls short, offering a critical review of its limitations.

ICE V3.0 Database

The University of Bath originally created the database, with Dr. Craig Jones leading the project. The version used in this tool is managed by a sustainability consultancy firm, Circular Ecology, which is founded by Dr. Jones. Most of its data entries follow the NEN-EN 15804 +A2 code. Entries are present that follow the BSI PAS 2050 code.

A critical point on the ICE database is its CLT Embodied Carbon Material Factor data quantity. The CLT values derived from the ICE V3.0 Database are based on only three EPD's, resulting in uncertainty due to the small dataset. While a comprehensive list of the EPDs used in the database is available, not all EPDs are accessible, limiting the true transparency of the database.

Nationale Milieu Database

Extracting data from the Nationale Milieu Database is problematic. The results indicate the total shadow cost of a product rather than its individual impact categories in specific units. Although a workaround enables the extraction of data from modules A1-A3 concerning Global Warming Potential, this is not possible for al NMD entries. Some entries are provided in kilograms, aligning with the output of the structure generator, while others are expressed as functions of area or length, often combined with thickness or cross-sectional area. While volumes can be derived, density information is not consistently available. Only EPD's from which the EPD file can be retrieved, the density's are provided or from which the density's can be accurately approached are included. As a result, the average values used in the tool may differ from the actual average from all the values in the NMD.

Concrete values are often given 'including reinforcement'. The amount of reinforcement this entails and its contribution to the embodied carbon is not always clarified. Even when clarified, depending on the load applied to the concrete element the amount of reinforcement can vary greatly. Combining these two materials into a singular element is therefore quite a significant simplification.

It is noteworthy that all data in the NMD from categories 1 and 2 have been verified and can be considered reliable. However, the lack of background information about these entries means that users cannot independently verify their validity. Since transparency is a cornerstone of sustainability calculations, this lack of clarity in the NMD represents a significant shortcoming.

5.1.4. Embodied Carbon Material Factors

This subsection discusses the configuration of material factors for various materials. It examines material-specific considerations and highlights differences in how these materials are treated depending on the database used. The materials are addressed in the following order: concrete, timber, reinforcement steel, and structural steel.

The classification of material factors for concrete is based on strength classes. Multiple factors influence concrete strength, a key factor is the water-cement ratio. Both the quantity and type of cement significantly impact the embodied carbon material factor of concrete. The ICE database uses solely CEM I as an input, while the NMD database uses a mix of 25% CEM I and 75% CEM II. All quantities per m^3 of concrete are specified in the database referenced in B.2. For a more precise calculation of the embodied carbon material factor of a specific concrete product, the exact concrete mixture should be obtained.

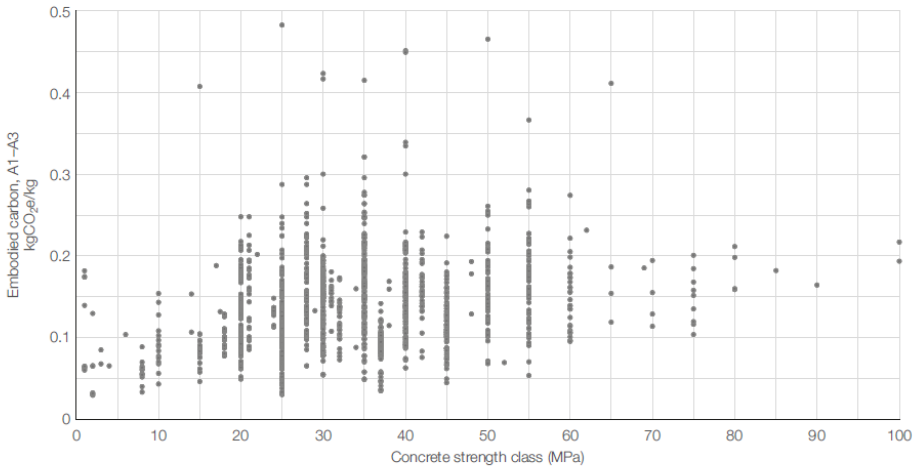

Figure 5.2: Embodied Carbon Variation for mixes in ICE Database V3.0 [21]

Two material options are considered for columns and beams: 1) solid softwood 2) glulam. Unlike concrete, the embodied carbon emissions of timber products do not increase with higher strength classes. For glulam and CLT, the type of adhesive used could significantly impact embodied carbon, however, this factor is beyond the scope of this thesis and warrants further research. Consequently, all softwoods, glulam, and CLT products are merged into a single material factor category within their respective structural classifications.

In the ICE database concrete and reinforcement amounts can be entered separately. In the NMD database it is a part of the concrete. From a structural point of view for the concrete used in the core a minimum of 80 kg per m^3 of concrete is maintained and for the foundation 150 kg of steel per m^3 of concrete. The NMD maintains a input of 10 kg of steel per m^3 of concrete if specified. Due to the high material factor of steel this difference is expected to have a significant influence on the end results.

Besides steel used in the reinforcement of the concrete elements, steel is also used in the joints of the timber elements. The NMD is seriously lacking on this area and has only one value for steel which is pretension steel, with a quite high factor. The ICE database has several options. Since the major contributor of the steel in the joints comes from the plates the average Steel Plate value is used. For the material factor determination of the steel plates, a system expansion was applied. Meaning that co products created during the process take up some of the emissions for their EPD. This results in 3 to 7 % lower GWP for the steel plates.

5.1.5. Development of a user-customized database with Dutch Market-Specific EPD's

For users who wish to create a customized database of EPD's tailored to their specific projects a methodology to guide that the selection of EPD's is applicable to the Dutch market is described in this section. It explains how to select and asses EPD data based on relevant market criteria.

Data quality index

The Institution of Structural Engineers has integrated a Data Quality Index (DQI) within their embodied carbon databases to assess the quality of individual EPDs across five key aspects. The DQI evaluates each EPD on these aspects and gives a rating per EPD. To get the final score for a category average the average is taken from all the individual EPD scores and then combined with the rating for data point quantity of that category. This combined score is then divided by the total achievable score to produce the final quality rating for that category.

The Institution of Structural Engineers (IstructE) has not provided scientific research to support the weighting of each category or the determination of subcategories and their assigned values within their Data Quality Index (DQI). The index is thus intended to serve as a quick indication of the quality of an EPD, rather than a precise tool for comparing individual EPD's. To make the DQI more applicable to the Dutch building industry, adaptations have been made to the category: Geographical Compatibility. The adapted DQI is presented in table 5.1.

Geographical compatibility

The Data Quality Index (DQI) is largely applicable to the Dutch building sector, with the exception of geographical compatibility, which has been adjusted to better align with Dutch industry practices. For each material, the likely countries of origin are analyzed to ensure the selected EPD's are relevant to the Dutch market. This makes it more probable that the embodied carbon values accurately reflect the embodied carbon values of materials used in Dutch construction projects.

The majority of timber used in the Netherlands is imported from within Europe . figure 5.3 [41] illustrates the distribution of import values by country, illustrating that countries like Germany, Belgium, and Sweden are key timber suppliers .

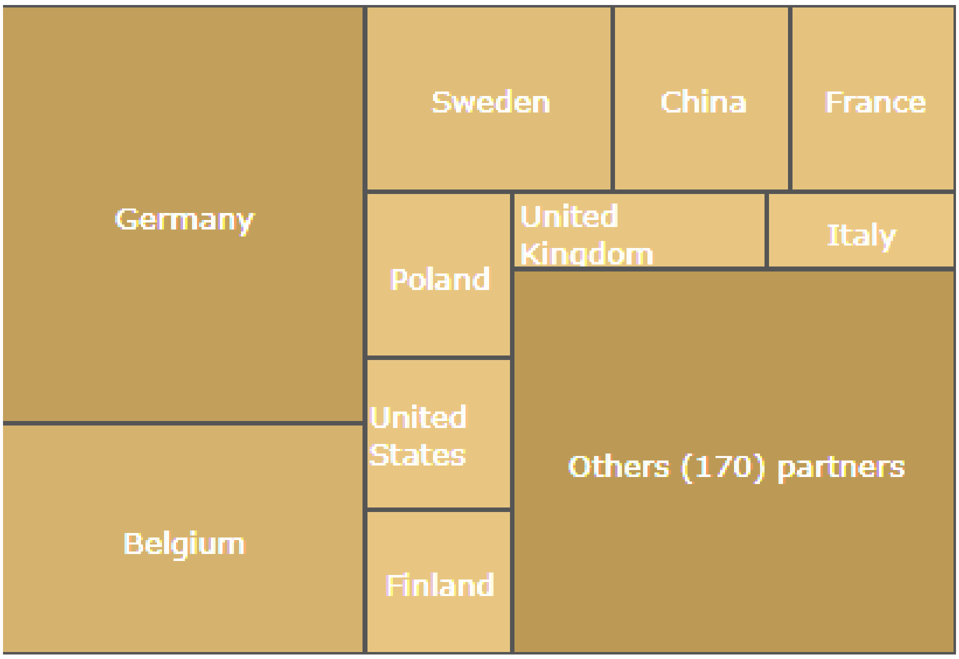

Figure 5.3: Import Partner share Wood products Netherlands [41].

The raw materials required for concrete have always been readily available in the Netherlands, leading to an abundance of concrete production domestically. As a result, only EPD's originating from the Netherlands are accepted for concrete products.

Similarly, while raw materials for reinforcement steel are sourced from regions such as Australia, South America, India, and Scandinavia, the production of steel products occurs on a large scale in the Netherlands, notably by companies like Tata Steel. Therefore, for reinforcement steel, as with concrete, only Dutch-origin EPDs are considered.

Score	10	9	8	7	6	5	4	3	2	1
Sample size (data points)	>=250 d.p.	>=150 d.p.	>=100 d.p.	>=75 d.p.	>=50 d.p.	>=25 d.p.	>=10 d.p.	>=5 d.p.	<5d.p.	1 d.p.

Table 5.2: Data quantity rating

Score	5	4	3	2	1
Method compatibility	EN 15804+A2	ISO 14067 or ISO 21930 or PAS 2050 or GHG Protocol for Products (not including any of the other GHG Protocol standards)	Other standardised method recognised nationally or internationally	Recognised method, but not standardised, e.g. ISO 14040/44 only, which is not a prescriptive method.	No recognised or standardised method
Assurance	External panel review (e.g. ISO 14040 panel review with 3 or more people)	2 External reviewers (e.g. academic papers often have two reviewer)	1 external reviewer (e.g. EPDs)	Internal review	No review process stated
Age of study	<= 5 years	<= 6 years	<= 7 years	< 10 years	>= 10 years
Geographical compatibility	• Timber: Germany or Belgium • Concrete and steel: The Netherlands	Sweden	Other European countries	-	All other countries and regions
Transparency	Full calculation model and detailed report available (very rare)	Detailed report (e.g. full LCA report, documenting assumptions in detail), but no calculation model. Or transparent calculation model, but no detailed report.	-	Summary report covering an overview of method inc key data (most EPDs will be this rating)	Limited details on method, or key information missing

Table 5.1: DQI Dutch build environment

5.1.6. Output Assessment

To make the tool's output less abstract and better interpretable, emissions are converted to a per m^2 basis and displayed alongside the maximum allowable emissions per m^2, as defined by the Paris carbon budget for 2025, discussed in 3.1.5. Additionally, current emissions for office buildings, categorized as low, medium, or high, are added to provide context regarding typical emissions of office buildings. These emissions per square meter represent the total building's emissions. If the result from the tool is substracted from these the remaining CO_2 value indicates the budget available for other building components beyond the structure.

The findings from Dimoudi and Tompa indicate that approximately 73.3–75.3% (rounded to 74% for further evaluation) of the total embodied carbon emissions in a building are attributed to the structure. By comparing this to the LETI studies, which report 82% of total emissions for the superstructure, the facade's contribution in the LETI study can be estimated. Subtracting the 74% structural contribution identified by Dimoudi and Tompa from LETI's 82% leaves 6.5–8.7% as the total carbon emission attributed to the facade. This is notably lower than the 25% facade contribution found in Dimoudi and Tompa's study. Since the initial study included minimal embodied carbon emissions for finishes and installations, we can slightly adjust the output. If we apply the 18% from LETI to Dimoudi and Tompa's findings, we achieve a distribution of 64% for the structure, 21% for the facade, and 15% for installations and finishes. Consequently, using the revised structure percentage and subtracting it from LETI's superstructure total, we arrive at an 18% allocation for the facade. This coarse scope alignment of both studies shows that a percentage of 65% is a valid estimate for the contribution of the structure to the total embodied carbon emission of the structure, although this may vary depending on the sustainability of structural materials compared to finishes and facade elements. As a starting benchmark, maintaining structural emissions at approximately 65% of the Paris-aligned carbon emissions per square meter is a good start.

5.2. Structure Generator tool

5.2.1. Building type choice

The primary objective of the Embodied Carbon tool developed in this thesis is to enhance the sustainability of the Dutch construction industry. To achieve the greatest possible impact, the tool must target a building type where it can have the most significant effect. This is determined by two main factors:

- The environmental impact per individual building of that type
- The number of buildings constructed of that type

Starting with the first factor, large-scale buildings typically consist of numerous structural elements. Due to the sheer size of these projects, even small improvements in individual elements can result in substantial overall reductions in embodied carbon. Achieving similar reductions with smaller buildings would either require much larger improvements per element or necessitate improvements across a larger number of different projects. Therefore, the focus of the tool should be on larger-scale buildings, where the potential for impact is greater.

However, the definition of a large-scale building can vary. In 2018, 55% of the global population resided in urban areas, and by 2050, this figure is expected to rise to 68%. This trend of urbanization leads to increased urban density, which often necessitates a more vertical, high-rise building approach as a solution to space constraints [53]. For this reason, a high-rise building is selected as the representative large-scale building type for this tool.

Additionally, the tool will focus on office buildings. This choice is based on the flexibility of office spaces, which can be adapted to various other functions over time. By focusing on office buildings, the tool can potentially be applied to a wider range of building projects, thereby increasing its overall utility and impact.

5.2.2. Structural System Design flow and selection

Two design flows are considered;1)A design flow that creates multiple structural system types and materialization from a single structure generator tool 2)A design flow where each structural system and materialization option has its separate workflow.

Approach one intertwines multiple system and material choices into one environment. When the structural system and material choices are intertwined problems arise with the design process. Each system and material choice necessitates a specific design process, with unique properties that dictate its optimal application in design. The complexity of this workflow escalates noticeably. This complexity may necessitate a reduction in granularity. While maintaining shallow analyses may increase the number of options evaluated, it risks producing mediocre results.

In design flow two, the process begins with a specific structural system and material combination. This approach tailors the generation of structural systems specifically to suit the characteristics of the chosen material. This specialization enhances efficiency, accuracy, and the overall straightforwardness of the design process.

Design flow number two is used in the Structure Generator Tool. In the tool one specific structural system and material choice is worked out. In further research this process can be repeated for different systems and material choices. By repeating the process for different configurations, the results can be integrated into a single tool, which would broaden the tool's applicability.

A timber-concrete hybrid structure is chosen as the structure for the Structure Generator Tool. It is an applicable building system for the Dutch building industry based on the market research performed of the buildings build in the Netherlands. Using a timber-concrete hybrid structure tackles several of the major challenges concerning multi-storey mid to high-rise timber structures. Making the most efficient use of the building materials. The selected timber vertical load bearing system is a column-beam system. This meets the open floor requirements of an office building and has a high flexibility in use. Which potentially could increase the lifespan of the building and for the lateral loads a concrete core will be used.

The Structure Generator is designed to create structural systems for buildings that fit within a volume of 40x40x70 m^3, with a minimum height of 6 floors. The maximum height is constrained to keep the building within consequence class 2, while the minimum height of 6 floor ensures the practical inclusion of a stabilizing core. The width and length dimensions were initially restricted to account for daylight entry limitations but were increased to meet the requirements set by DWA. The structural design assumes symmetry, which simplifies the implementation of a symmetric core and helps to avoid challenges such as torsion and coding complexity.

Column-Beam vertical load bearing

Within a column-beam system, multiple design choices can be made. Two primary beam systems are typically used: one-way spanning beams and two-way spanning beams. A one-way spanning system is efficient when there is a significant difference between the span lengths in one direction compared to the other. In contrast, a two-way spanning system requires fewer columns and is compatible with a two-way spanning CLT (Cross-Laminated Timber) floor. However, in a two-way system, the difference in stiffness between the two directions of the CLT floor must be considered.

Additionally, beams within these systems can either be singular, running directly between columns, or continuous, spanning multiple columns. Continuous beams, when correctly applied, can result in reduced moments and deflections.

For the sake of simplicity, the design will focus solely on one-way singular spanning beams running from column to column. Furthermore, to avoid stresses perpendicular to the grain in the columns, the columns will be continuous throughout the structure.

Flooring system

Single spanning CLT floors will be used. Due to vibrations or acoustic reasons concrete might be added on the floors. Early design calculations have shown that the thickness of this added concrete layer will be minimal. Timber Concrete Composite floors are therefore not further explored since the amount of concrete will not be sufficient to fulfill any structural function and it is striven to use as little concrete as possible.

Lateral load bearing

The main lateral load bearing system will be a concrete core. The lateral loads will be transferred to the core by CLT floors.

Connection design

For the connections of the beams and columns three design variants for slotted-in steel plates with dowels are generated. The schematic drawings of the connection and the location of each variant are shown in appendix H.

5.2.3. Structure Generator Tool Component Configuration

The Structure Generator Tool consists of three main sections; 1) Structural Design Configuration 2) Karamba3D Analysis 3) Final Element Development and Future Enhancements Assessment.

In the Structural Design Configuration section, the initial design is created. This design is then verified in the Karamba3D Analysis section. In the Final Element Development and Future Enhancements Assessment section, data from the Karamba3D analysis is used to create a foundation design, connection design and provide recommendations for further design improvements.

The Structural Design Configuration section includes two subparts; 1) Element Cross-Section Size Determination 2) Geometry and Grid Definition. In the first subpart, the cross-sectional sizes of the structural elements are defined, while in the second subpart, the placement of these elements and their interactions are considered.

Figure 5.4 visualizes the workflow of the Structure Generator Tool.

In this subsection all the individual components and methodologies of the Structure Generator Tool are discussed. Starting with the Geometry and Grid Definition section followed by the Element Cross-Section Size Determination section and ending with the Final Element Development and Future Enhancements Assessment section. Specific formulas, grasshopper scripts/python codes for the components can be found in respectively appendix C & D and A.

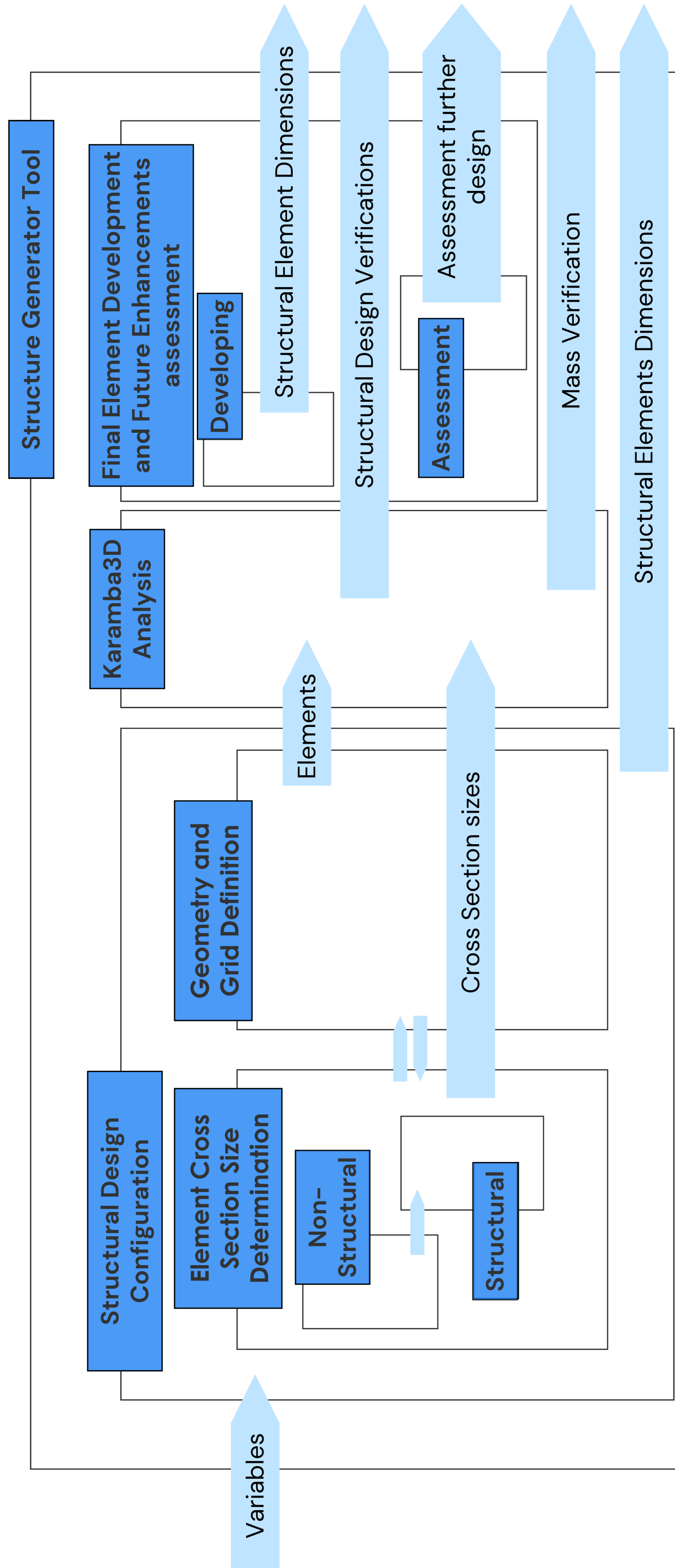

Figure 5.4: Structure Generator Tool Flowchart

Geometry and Grid Definition

An important part of a good structural design is the use of a efficient grid. Within this thesis an efficient grid is defined as a grid that;

- Has no unnecessary deviation of the grid standard measures.
- Has no deviations of the standard grid to such amount that it results in significantly higher dimensions of affected structural elements.
- Has no unnecessary structural elements.
- Is measured in efficiency by m^3 of material needed per m^2 of usable floor plan.

The building footprint and accompanying grid can be generated in two ways. The first method creates the footprint as a function of the grid, meaning the footprint dimensions are determined by multiplying an integer value by the given grid sizes. With this approach, deviations from the structural grid occur only near the core. The second method starts with a predefined footprint, into which the grid is fitted. In this approach, the grid is generated from the center of the building to better integrate the core. However, this method introduces additional deviations near the facade, in addition to the existing deviations around the core.

Two main factors were evaluated: design flexibility and alignment with the principles of an efficient grid. The first method, where the footprint is a direct function of the grid, reduces deviations from the standard grid dimensions and helps meet the criteria of an efficient grid. However, this method limits the flexibility to explore varying spanning distances within a predetermined footprint.

On the other hand, the second method, where the grid is fitted within a predefined footprint, offers greater design freedom, particularly architectural requirement, by allowing different spanning distances without altering the floor plan dimensions. While this approach leads to more deviations from the standard grid—violating one of the efficiency criteria—the trade-off for increased design freedom is considered more beneficial. Therefor the second method is used in the Geometry and Grid Definition part of the Structure Generator Tool.

Initially, columns and beams may be generated too close to the core or facade, resulting in unnecessary structural elements. These extra columns not only become redundant but can also increase the required core dimensions, as they detract from the compression stresses that would otherwise benefit the core. The tool addresses this by automatically removing or repositioning such columns to better fit the grid.

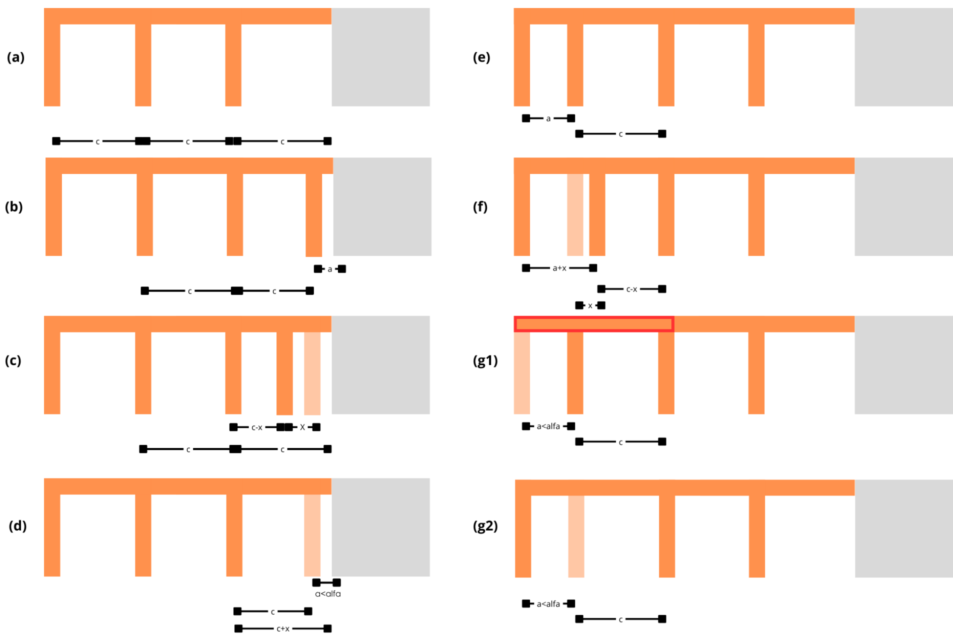

Figure 5.5: Deviating grid size scenarios near facades and structural cores

For columns and beams positioned near the facade, a minimum offset distance is specified. If this minimum offset is not present, the column and beam row is removed, resulting in an increased span. To prevent these spans from becoming too large, a maximum allowable span is given. If this maximum span would be exceeded, the column and beams are not removed; instead, they are moved to the midpoint between the facade and the nearest row of columns or beams adjacent to the facade.

For facades, the minimum offset distance is determined by a factor multiplied by the span, set by default to 60%. The maximum allowable distance is based on a limit for deflection increase, set by default to 10%.

For the core, maximizing vertical load transfer is desired to help counteract tensile stresses. Columns and beams near the core are not only unnecessary material but can also negatively impact the core's performance. However, the methodology for removing a beam and column row near the core is less developed than for those near the facade. A minimum distance has been set for removing beam and column rows, with a default value of 2.1 m, but no additional measures are in place to address excessively large spans near the core. Adjusting the location of beam and column rows is not possible because the core does not extend across the full width of the building.

The code currently removes only those beam and column rows parallel to the core wall, as they are considered the primary elements obstructing load transfer due to the floors' one-way spanning nature. However, modeling issues, as further discussed in 6.2.1, lead to two-way spanning for floors bordering the core. Initial functionality for removing columns and beams near the core has been implemented, though further development is required to make it fully functional.

In figure 5.7 a flowchart is shown of the Geometry and Grid Definition part of the tool with a more detailed flowchart of the Grid adapatation near facade and core in figure 5.6.

Element Cross Section Size Determination

In this chapter all the element sizing aspects are described in detail. The formulas used are given in appendix C and D. The created scripts and python codes are included in appendix A and all assumed loads, safety factors and material properties in appendix G.

The developed Structure Generator Tool focuses on the main load-bearing structure. Which in this thesis is defined as the columns, beams, joints, floors and core. While the foundation is also considered, its inclusion is treated with lower priority due to the high level of uncertainty associated with its material quantities. Including such uncertain values for the foundation could compromise the overall accuracy of the results, especially given the more precise data available for the superstructure. Therefore, emphasis is placed on the superstructure to maintain the integrity of the tool's output, while the substructure is handled separately and provided in a dedicated output folder and graph.

In addition to structural considerations, these structural elements are also subject to non-structural demands. These non-structural demands can be the determining factor in the final sizing of the elements. Therefore, considering only structural demands provides an incomplete representation of the design process.

Figure 5.8 presents an inventory of the variables that influence building design and structural design. In figure 5.9 the structural design is subdivided into the structural element categories. Variables are color-coded, with blue representing non-structural variables and red representing structural variables.

The non-structural variables evaluated for their influence are listed below:

- Stair and elevator requirements
- Daylight
- Acoustics
- Installations

High-rise buildings are subject to strict regulations regarding vertical transportation, possibly necessitating larger dimensions of the concrete core than structurally required. Consequently, stair and elevator requirements are integrated into the Structure Generator Tool. These requirements decide the minimum dimension for the core, serving as a starting point for structural verification's.

Daylight considerations were initially incorporated within the variable range of the floor plan width to ensure the generation of valid designs with sufficient daylight entry into the building. However, at the request of DWA, these considerations were removed. Acoustic properties, specifically airborne sound insulation, are accounted for in the design of the floors. While CLT floors offer many benefits, they have a significant drawback in terms of sound insulation. In practice, this often necessitates the addition of a concrete layer to increase mass and improve sound insulation. There are other options for enhancing insulation, and the tool provides the flexibility to include or exclude this measure. Although this might seem outside the tool's primary focus, it directly relates to this structural choice. Including the option is important for clarifying a potential downside of using this system, helping to prevent a misleading or "greenwashed" outcome.

Installations are assumed to fit between the beams and within the core without requiring openings in the floors or beams, thereby simplifying their integration into the design.

Several structural verification,sizing-, and design methods can be applied during the early stages of a building design. Some of these methods are directly integrated into the Structural Design Configuration part and Developing part of the Final Element Development of the Structure Generator Tool. The structural design is then used as input for Karamba3D, where the design is further analyzed and verified.

In addition to the methods that influence the design, there are other checks that assess the created design without directly altering it. These assessments provide insights into areas where the design may need refinement in the next phase, guiding further optimization and adjustments.

In table 5.3 an overview of these verifications is given. All considered methods are described in the following paragraphs.

Developing	Assessing
• Analytical Methods for Structural Element Sizing: Buckling,axial stress and ODE derived deflection verification • Differential vertical shortening • Dynamic behavior floors • Connection design • Foundation design	• Local sizing with Karamba cross section optimizer • Tensile forces foundation • Detailed core modeling • Creep

Table 5.3: Structural design developing and assessing verifications

Based on prior experience and early results from the Structure Generator Tool, one or more analytical methods are selected for each structural element category to address the governing factors. For columns, the primary considerations are axial force and buckling, using Euler's buckling formula.For beams, the bending behavior is analyzed using the ordinary differential equation (ODE) for bending, with boundary conditions tailored to hinged supports. In reality, timber connections are semi-rigid, which would result in reduced deflection. However, the exact amount of rotational resistance is unknown beforehand, so a minimal resistance is assumed to stay conservative.

These methods are applied to the most heavily loaded elements, with more precise dimensioning required at later stages using specified loads.

Due to the different material properties of concrete and timber differential vertical shortening (DVS) has to be examined. DVS is the difference in shortening of vertical elements under axial loading [63]. The total vertical shortening in concrete is the sum of elastic strain, creep strain, and shrinkage strain. For timber, the calculation is similar, with the additional consideration of potential swelling-induced strain. However, it is assumed that shrinkage and swelling effects are negligible; therefore, only elastic and creep strains are considered.

Due to the significantly lower stiffness of timber than concrete, the timber elements will display more axial deformation than the concrete elements. Due to the magnitude of these settlement differences, they not only lead to the failure of meeting serviceability criteria but also introduce additional stresses in the core and floors.

Without considering at least the initial strain, the construction does not meet the necessary standards. Therefore, initial strain is incorporated as the last verification step in the dimensioning of the timber columns in the Structural Element Cross Section Size Determination part of the Structure Generator Tool. Creep strain, however, is inspected separately in the assessment part of the Final Element Development and Future Enhancement assessment section.

Early calculations revealed that the floors contribute significantly to the total embodied carbon content of the structure. Consequently, the calculated floor thickness plays a critical role and requires a more thorough verification from multiple perspectives. Beside the static verification performed with the deflection verification with the ODE for bending. The dynamic behavior of the floors is taken into account as well by determining a minimum thickness based on a minimal eigenfrequency the CLT floor should have. The final floor thickness is chosen as the larger of the two values, covering multiple aspects of performance.

Karamba3D Analysis

The model is created out of in the output Structural Design Configuration part of the Structure Generator Tool. In Figure 5.11, the mechanical scheme of the Karamba3D model is shown. All joints within the structure are modeled as hinged, including the supports. The floor is divided into several segments, designed as one-way spanning and connected to the rest of the structure with hinged joints. To ensure no direct floor transfer to the columns in the model, since this wont occur in real situation. Floor has rectangular cut outs around the columns. The core is modeled as a continuous shell element.

Rigid hinged support points modeled. Under the core a high density of points is modeled to mimic a line support, which is not possible to use in karamba. The foundation itself is not included in the structural model.

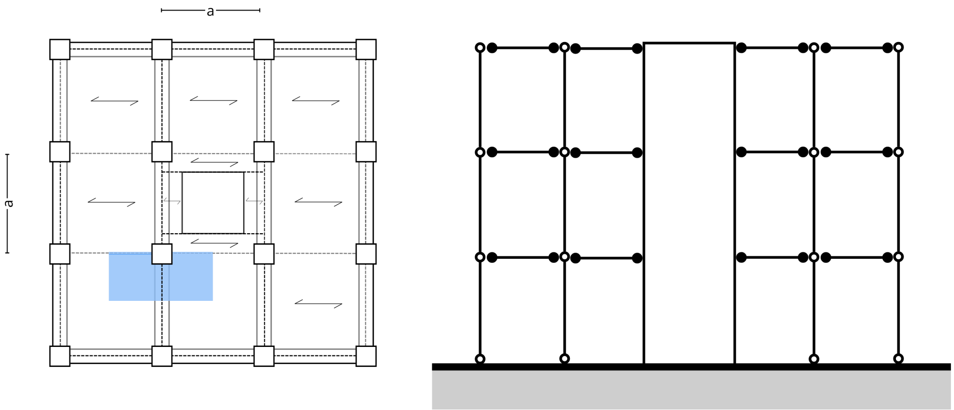

Figure 5.11: Mechanical scheme structure

Final Element Development and Future Enhancements assessment

Initially, the influence of small connection elements may seem minor. However, early calculations revealed that they are one of the higher contributing structural element categories, due to their large quantity and the high embodied carbon factor of steel. The joints are generated by extracting the point load at beam-to-column connections in Karamba3D. An automated script then performs unity checks, adjusting each joint as needed to ensure it meets all requirements.

Due to the semi-rigid nature of these joints, small moments and horizontal forces would likely occur in reality. However, in the Karamba3D model, connections are modeled as fully hinged, so moment and horizontal loads are not included in the Python script. Modeling the joints as hinged, while they may experience some moment load in practice, adds an extra layer of safety to the structural design.

Joints in timber structures tend to be weaker than the members that they connect and require extra attention. Three types of joints are distinguished;

- Rigid glued joints
- Carpentry joints
- Metal fasteners joints

The structure considered in this tool is a timber column-beam structure with a concrete core. The connections that are present are, in order of occurring quantity;

- Column-beam connection
- Beam-Column-Beam
- Beam-Column-Beam-Beam
- Beam-core connection
- Column-foundation connection
- Floor-floor connection
- Floor-beam connection

The goal of this step is not to automate connection design but rather to provide a reasonable estimate of the embodied carbon content of the connections. Therefore, column-to-beam connections will be developed relatively far, as these connections occur in high quantities. For the beam-to-core connections, the same amount of steel is assumed as in the column-to-beam connections. Floor-to-floor and floor-to-beam connections are not included in the Structure Generator Tool, as their impact on the overall embodied carbon is expected to be limited.

In the Column to beam connections high forces may occur, necessitating high-performance joints. Slotted-in steel plates with dowel-type fasteners enable load distribution of the fasteners across multiple shear planes, resulting in high joint strength. Additionally, their compactness and the fact that they are concealed by timber ensure they meet load-bearing, fire safety, and aesthetic requirements, making them the preferred choice in truss-type structures [8]. This type of connection has been selected for the column-beam joints, with bolts chosen as fasteners to facilitate better demountability. It is assumed that all holes are pre-drilled.

The workflow proceeds as follows: Fix all variables except for n, upon which everything depends. Increase n until all checks are satisfied or the maximum value of n is reached. If n reaches its maximum and the checks are still not satisfied, increase one of the initially fixed variable and repeat the procedure with n. Repeat this until the checks are satisfied or the initially fixed variable has also reached its maximum value. If the initially fixed variable also reaches its maximum, repeat the process with the other variables until all checks are satisfied.

Figure 5.12shows a graphic representation of this workflow.

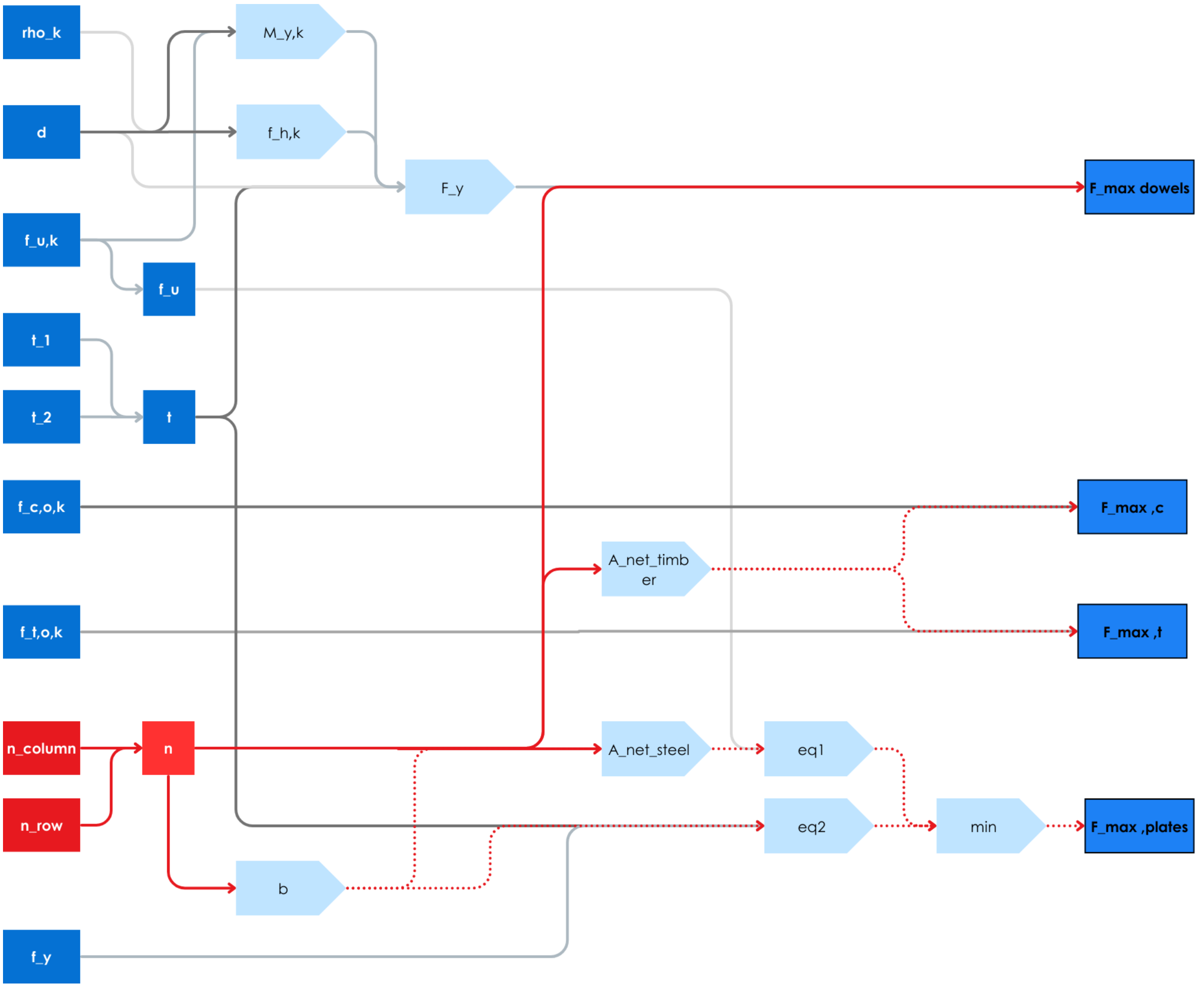

Figure 5.12: Flowchart parametrization column to beam connection generation

To counteract creep, timber elements are designed with additional length, accounting for the anticipated deformation they would undergo under long-term loads compared to concrete elements at the same height. A well thought out construction planning, ensures that by the time all axial deformation has occurred, no significant differential vertical shortening remains. The load on each column is calculated using the Karamba model and is aligned with the creep behavior of the concrete core.

The mass of the foundation in high-rise structures is often a significant portion of the total weight of the structure. One of the advantages of using timber is its relatively low weight, which results in considerably lighter loads on the foundation compared to traditional building materials, allowing for a lighter foundation [52].

A bored pile foundation with cast-in-situ concrete piles and beams is used. The foundation design is determined by taking the force under each ground-floor column and the total force under the core from the Karamba3D model, excluding wind load. Based on the pile bearing capacity derived from a cone penetration test(CPT) done in LLoydkwartier in Rotterdam, the required number of piles per column and under the core walls is calculated. Foundation piles are combined with one-way spanning foundation beams. The height of foundation beams is manually adjustable, with a default value set to 0.8 m. The width is calculated as the pile diameter plus an additional 2 * 50 mm. For edge beams, the width is increased by a factor of 1.5. The reinforcement is assumed to be 150 kg per m^3 of concrete in the foundation. Due to the tool's non-site-specific nature, numerous assumptions and simplifications are necessary, so foundation details are not fully addressed.

It is emphasized that the primary focus of this thesis is on the superstructure. The foundation mass generated by the tool is mainly intended for comparative analysis across design variants, rather than as precise values for the foundation's final design.

As timber buildings increase in height, additional mass is often required in the foundation to prevent tensile forces and ensure sufficient stability. Consequently, a heavy foundation can become a significant drawback for timber structures. In the Karamba3D model with wind load, support reactions are analyzed to determine the tensile forces in the foundation. Due to the rigidity of the support, even a small upward deflection of the core can quickly result in large tensile forces. Assessing the occurrence of tensile forces is valuable, as it highlights the critical interaction between the superstructure and substructure. However, the absolute values are not considered fully accurate; as with the foundation design, this analysis is mainly intended for comparative evaluation across design variants.

All columns and beams have been sized based on the most heavily loaded column and beam, resulting in the oversizing of most timber elements. Initial results have shown, however, that the impact of columns and beams on overall performance is minimal, and the effect of optimization is even smaller. This optimization process requires significant computing power, so while it is available, it is not included in the standard workflow of the Structure Generator Tool.

Early results showed that the concrete core significantly impacts the building's embodied carbon. As a result, this component is modeled in greater detail. Concrete core calculation procedures are well-established, making it possible to create a parametric workflow for these assessments. Using a Python script, the tool verifies whether the core meets unity checks for shear and torsion, based on forces extracted from the Karamba3D model. While the structural dimensions are not adjusted after this verification, the results are included in an assessment to inform further design phases.

Excluded but Considered Verifications

The traditional building materials, concrete and steel, possess a significantly higher mass and stiffness than timber. Timber structures, especially timber high rise, is therefor more susceptible to vibrations. For a timber high rise design it is important to do an analysis of the dynamic behavior to prevent these vibrations from occurring.

To improve the dynamic behavior of a structure the height can be lowered, the stiffness of the structure can be increased and mass can be added to the structure, often in the form of a layer of concrete on the floors[30].

The slenderness ratio is a useful tool in determining governing calculations for core structures. Ratios below 1:8 are typically governed by bending moments, while ratios between 1:8 and 1:20 are more likely governed by deformations. Core structure with ratios above 1:20 are the most susceptible to dynamic behavior. These ratios will not that often be reached within the fixed ranges set in the Embodied Carbon Determination Framework. The dynamic behavior of the building as a whole is therefor excluded from the Structure Generator Tool. Slenderness ratios will be taken into account in the assessment part of the Structure Generator Tool so it can be used for later design phases, but no assessment of the dynamic behavior is included.

The cross-section sizes of all timber elements are determined through one or more verifications that address the most common governing properties. It is expected that these timber elements will meet the majority of other verification requirements as well. All structural elements are currently verified with Karamba3D, though this software is not optimal for timber elements. For more detailed analysis, Beaver could be used, as it provides a more comprehensive verification for timber. However, timber elements (excluding floors) contribute relatively little to the overall embodied carbon. The floors already have more detailed calculations. Even if current calculations for timber elements were off by as much as double, which is highly unlikely, the overall impact on embodied carbon would be around 5%. Implementing Beaver would also require substantial time and computing power. Nonetheless, for future improvements, integrating Beaver into the Structure Generator Tool could be valuable, as it would allow for the verification not only of beams, columns, and floors but also of joints and a more accurate structural design, but for now it is not included.

Fire safety measures can be done in numerous ways

- Sprinklers
- Plate cladding
- Spray on cladding
- Extra material

The addition of sprinklers and cladding's to the Embodied Carbon is expected to be minimal and falls outside the scope of the tool since these are not strictly structural materials and do not have a strong influence on the embodied carbon content as a direct result from a structural choice.

A relevant aspect of fire safety that could be included, especially in timber structures, is the method of adding material for fire resistance. In the event of a fire, this added material is designed to burn away, ensuring that there is still sufficient material to carry the loads and prevent the building from collapsing. The charred layer of timber protects the remaining timber, maintaining structural integrity.

Previous experiences with this method have shown that minimal to no additional material is needed. This is because, when calculating the required dimensions for fire situations, it is allowable to work with a reduced load. Once serviceability demands are met in the original design, meeting ultimate limit state (ULS) demands with a reduced load during a fire situation has proven to be relatively easily attainable.

Given these considerations, it is not anticipated that fire safety provisions will have a notable impact on the Embodied Carbon of the building. Therefore, this aspect is not included in the Structure Generator Tool.

5.2.4. Level of development

The level of development, LOD, is a reference tool for clear communication between BIM model users about the state of development of their models. The LOD levels go from LOD 100 to LOD 500, where the higher the level the further the elements geometry has been worked out [32]. The different levels are shown in table 5.4 and are taken directly out of the level op development specification report. The LOD is used to describe the level of detail to which the models are worked out. The generator creates structures with a LOD of 300.

Level	Definition
LOD 100	The Model Element may be graphically represented in the Model with a symbol or other generic representation, but does not satisfy the requirements for LOD 200. Information related to the Model Element (e.g., cost per square foot, tonnage of HVAC, etc.) can be derived from other Model Elements.
LOD 200	The Model Element is generically and graphically represented within the Model with approximate quantity, size, shape, location, and orientation.
LOD 300	The Model Element, as designed, is graphically represented within the Model such that its quantity, size, shape, location, and orientation can be measured.
LOD 400	The Model Element is graphically represented within the Model with detail sufficient for fabrication, assembly, and installation.
LOD 500	The Model Element is a graphic representation of an existing or as-constructed condition developed through a combination of observation, field verification, or interpolation. The level of accuracy shall be noted or attached to the Model Element.

Table 5.4: LOD levels [32]

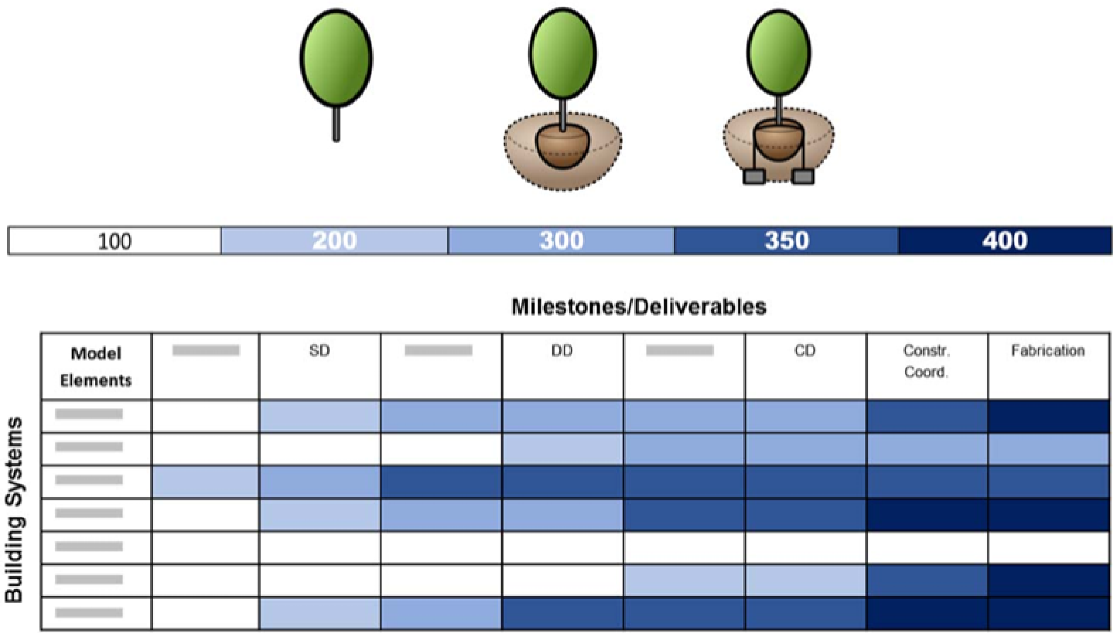

Figure 5.13: Level of development[32]

5.3. Iterator and Data Evaluation Tool

All data is exported in a format compatible with Design Explorer, enabling clear comparison between design variants. This approach expands accessibility, allowing more people to use the tool without requiring specialized software or Grasshopper expertise. Additionally, results can be easily shared through a simple link, enhancing usability. DWA is also developing its own version of Design Explorer, therefor this tool aligns with DWA's future developments.

In Figure 5.14, an example of the framework's output in DesignExplorer is presented. The columns in the interface are categorized by color: black represents input variables, while blue denotes output results. Each column contains a list of options corresponding to specific variable values. The plotted lines display design variants, with each line representing a unique combination of input variables and resulting outputs. This structured layout enables users to evaluate and compare design variants efficiently, offering clear insights into how variations in input variables influence the resulting outputs.

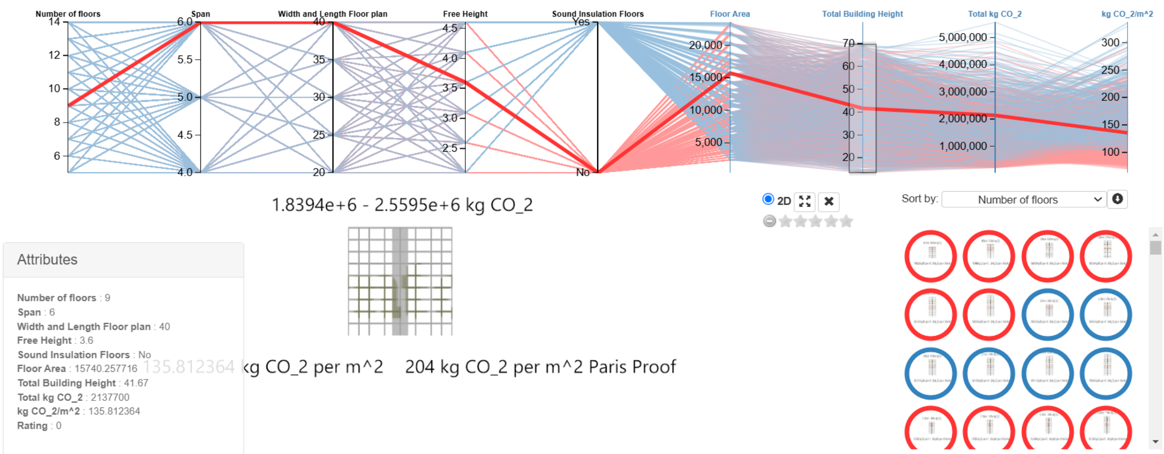

Figure 5.14: Example DesignExplorer Variant Selected

5.3.1. Sensitivity analysis

In the early stages of design, assumptions and estimations are necessary. This leads to a unavoidable level of uncertainty in the end results. A key principle of the framework is to acknowledge uncertainty and to address it appropriately. To support this, the Iterator and Data Evaluation tool includes a function that allows for adjustments to the calculated dimensions of the structural elements.

Changes in the dimensions of a structural element lead to changes of mass of the structural elements which naturally impact the final Embodied Carbon Content of a building. These adjustments also alter the redistribution of contributions across different structural element categories, potentially influencing design decisions. The Sensitivity Analysis function can be used in a twofold manner; 1) To address potential shifts in carbon distributions and incorporate these considerations into the weighing of design choices 2) At later design stages, to refine the calculated dimensions and provide a more accurate assessment of Embodied Carbon Content as the design becomes more fixed throughout the process.

5.4. Script overview

In figures 5.15 and 5.16 a overview is shown of the translation of the described design into a grasshopper script. This script will be used in the simulation phase to evaluate the framework design. In appendix A a enlarged version of this figure is included as well as documentation of selected parts of the script, python code that has been written and additional flowcharts.

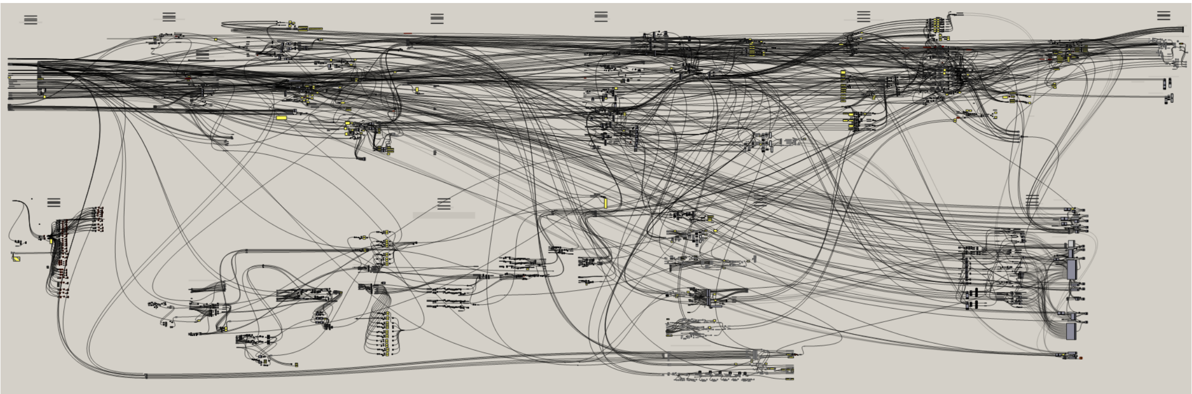

Figure 5.15: Script Overview

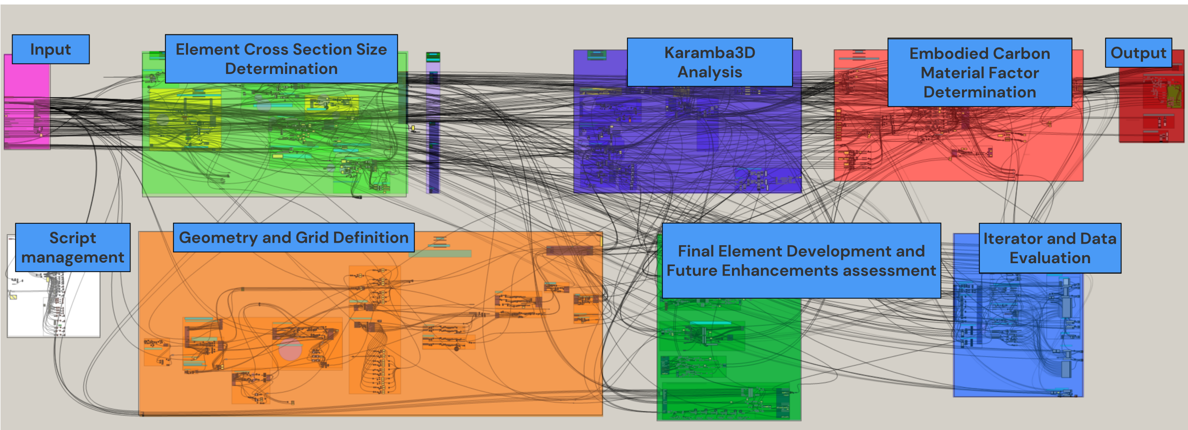

Figure 5.16: Script Overview Grouped

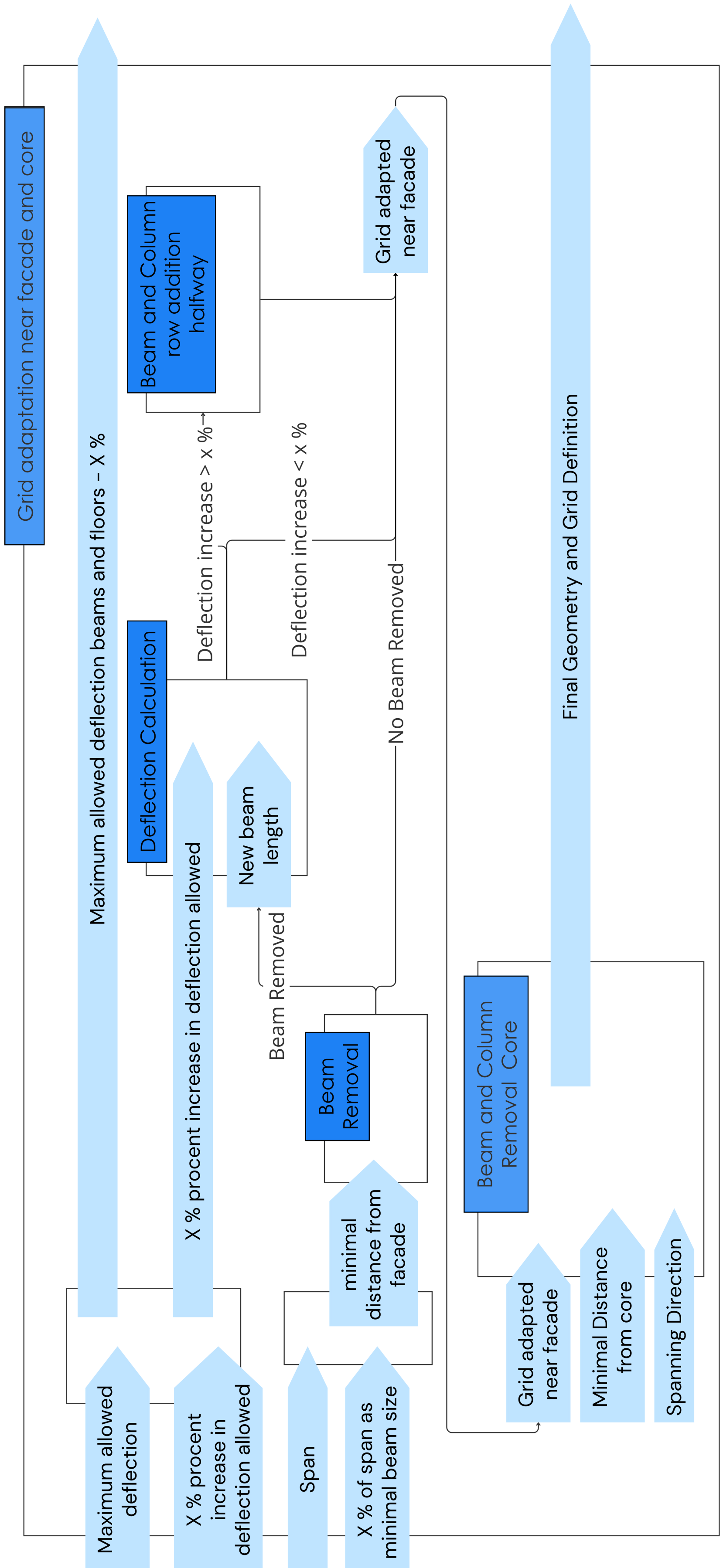

Figure 5.6: Detailed Flowchart Grid Adaptation near Facade and Core

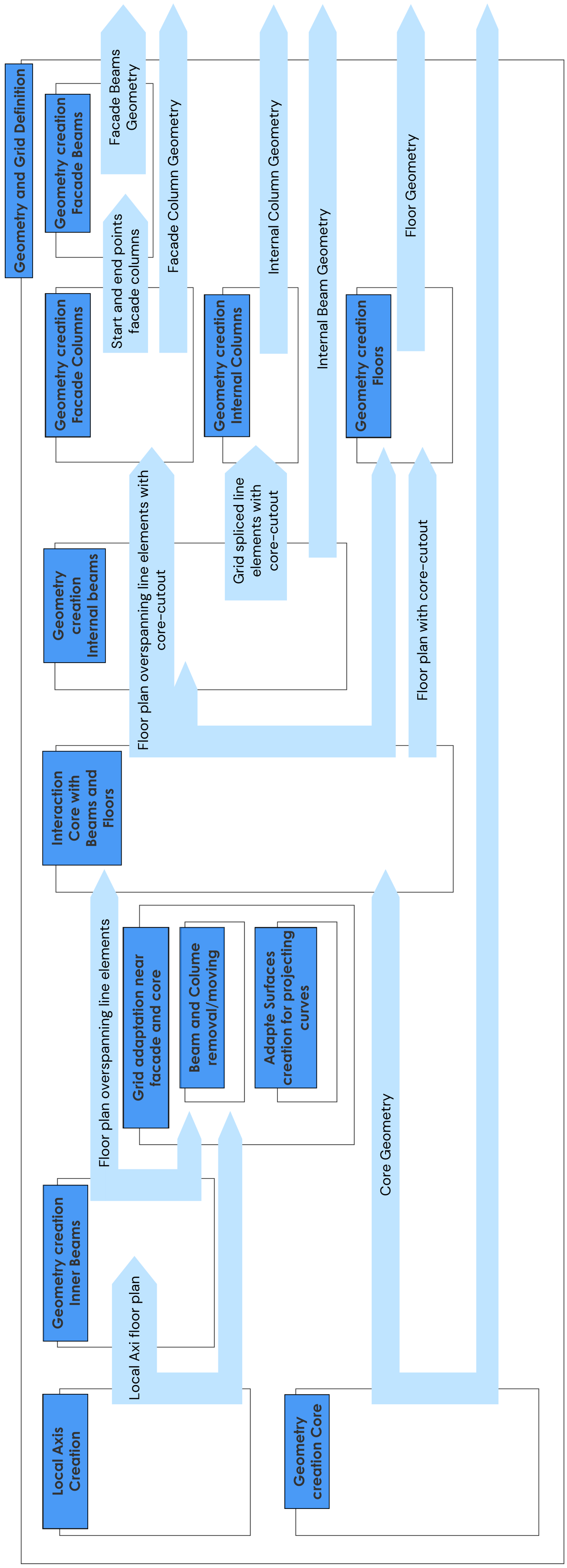

Figure 5.7: Geometry and Grid Definition Flowchart

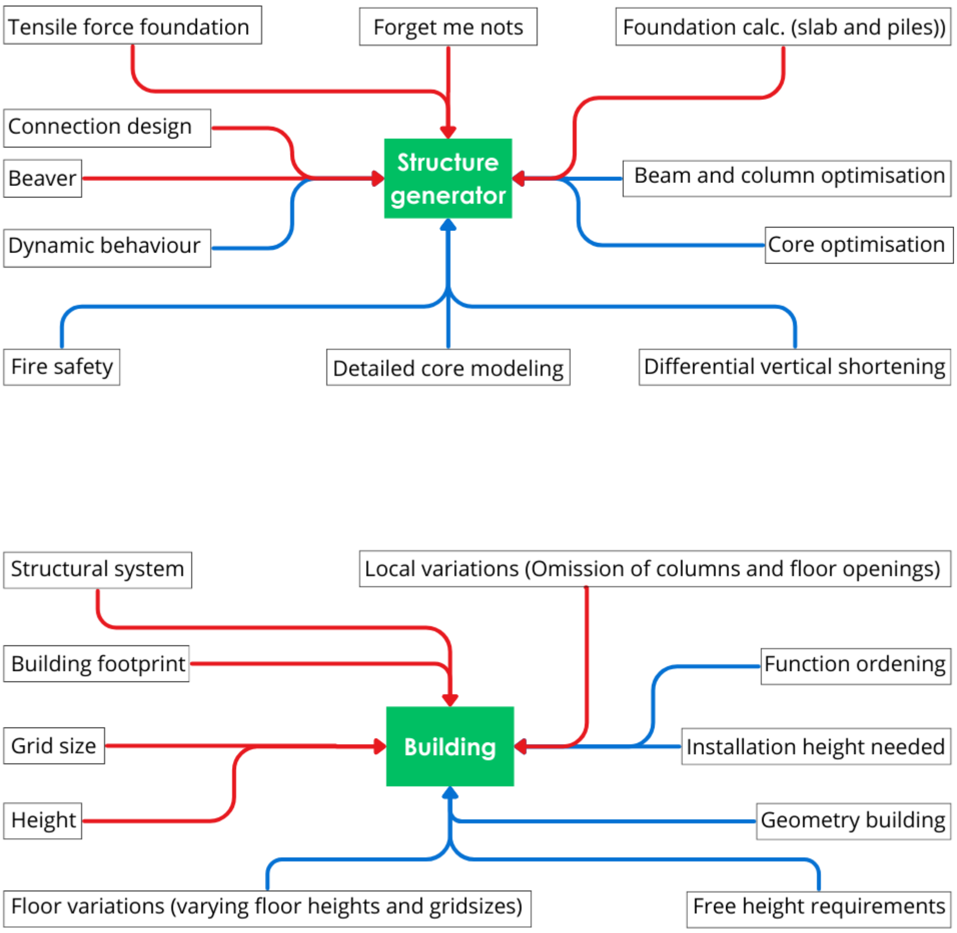

Figure 5.8: Input Structure generator and Building

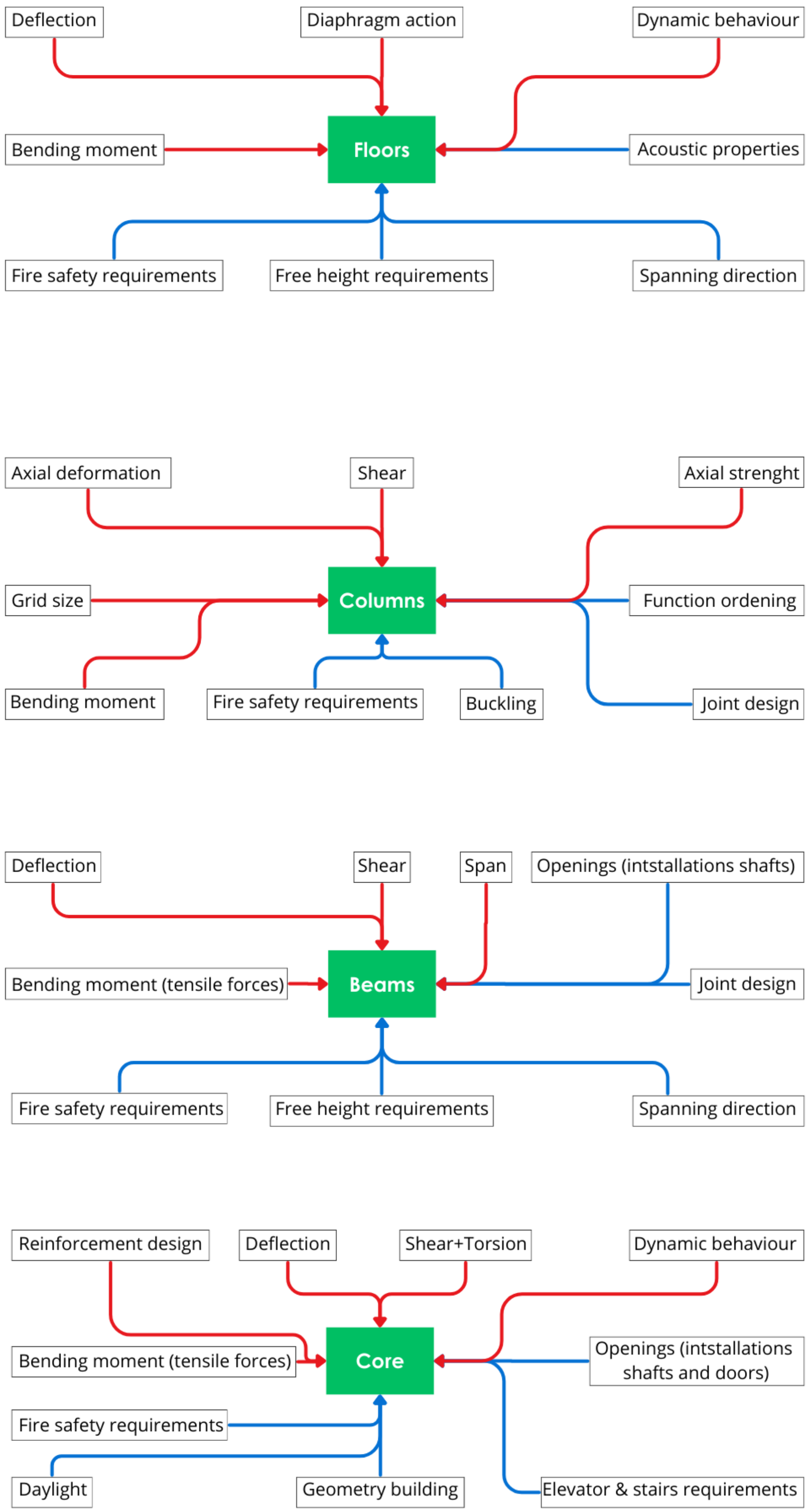

Figure 5.9: Input structural element categories

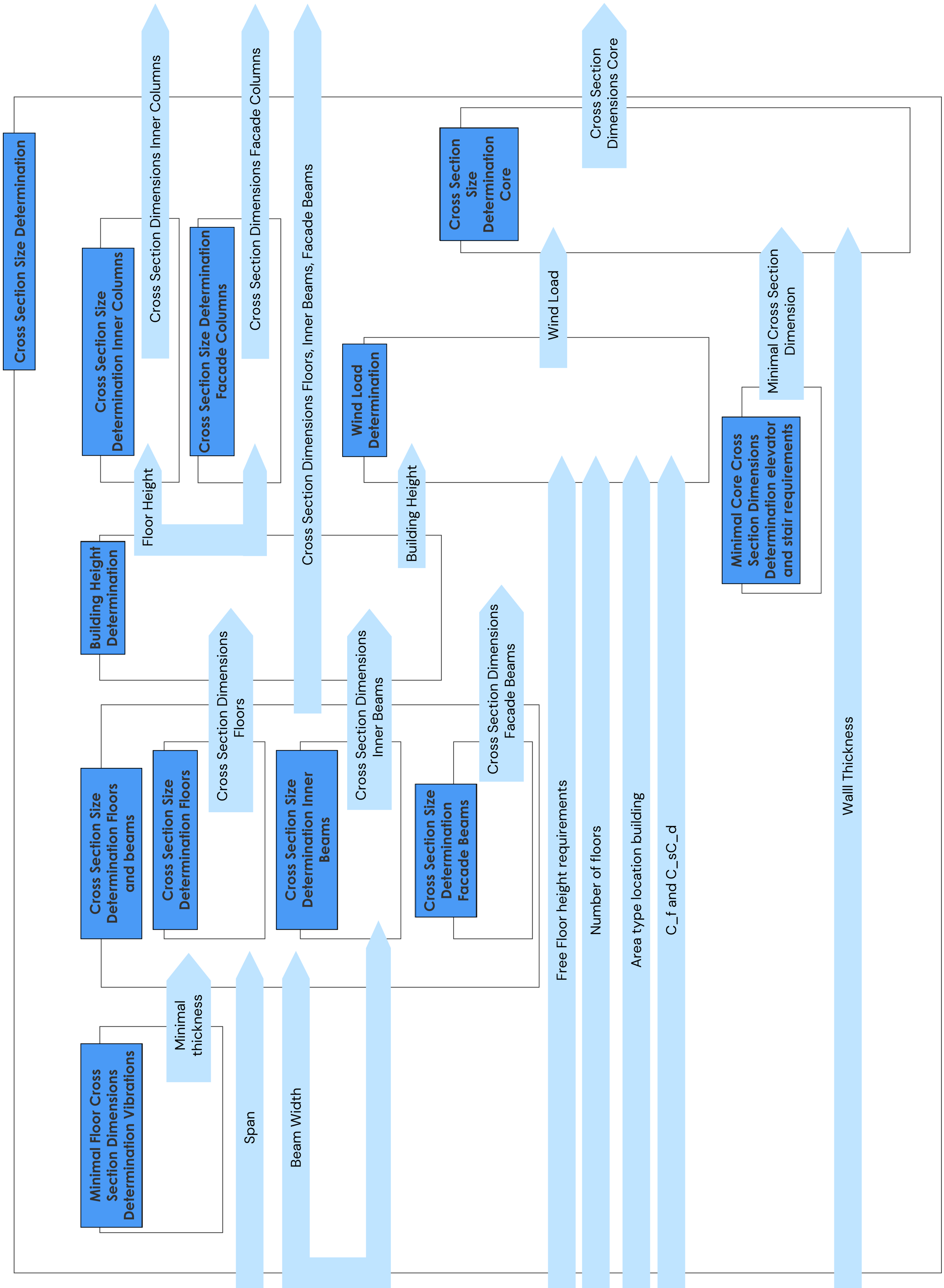

Figure 5.10: Cross Section Size Determination Flowchart

Part IV: Simulation

6 Verification

In the simulation phase the created framework is verified and validated. Verification assesses the extent to which the framework's output is accurate, reliable, and correct, while identifying any limitations or considerations that should be taken into account when interpreting the results. The validation , given the results from the verification, evaluates the usefulness of the framework's output. It explores how the results can contribute to the design process and in what ways the framework can be effectively used. In this chapter, the verification process will be conducted, while the validation will be addressed in Chapter 7.

6.1. Embodied Carbon Material Factor Determination Tool

To verify the tool the calculated results are compared with Karamba3D outputs. The Karamba3D Element Query component is used to extract the masses of structural elements from the Karamba3D model. These masses are compared with those calculated by the Embodied Carbon Material Factor Determination Tool. For consistency, the comparison excludes the mass of the ground floor, joints, and any sound insulation layers since these are not included in the Karamba3D model. They are, however included in the verification of the final value.

The final value, expressed in kg $C0_2/m^2$, is evaluated to ensure it falls within a reasonable expected range based on typical building practices. According to Figure 3.3, total building emissions generally range between 205 and 333 kg CO_2/m^2. For a Paris-proof office building with a 2025 target, 204 CO_2/m^2. Assuming that the structure contributes approximately 65% of the total embodied carbon, the expected range for structural emissions alone falls between 133 and 217 kg CO_2/m^2. The 65% contribution of the structure to the total Embodied Carbon value is a rough estimate. A deviation of around 15% from this value is also considered acceptable. Creating a range from 103 to 264 CO_2/m^2 and a Paris Proof structure between 102 to 163 CO_2/m^2.

6.2. Verification Structure Generator Tool

The output of the Structure Generator Tool is verified in a 5 step manner. First it is verified if the tool functions as it was intended with the modeling; 1)Coding Verification 2)Karamba3D Model Verification.

The next step involves verifying the soundness of the methodologies applied; 3)Methodology Verification 4) Comparability Variants Verification 5)Granularity Verification.

1)The code is evaluated to ensure that applied methods operate as intended. Small verification checks are embedded within the Grasshopper script, highlighted by pink groups. These checks include basic hand calculations, identification of duplicated elements and determinations if results fall within an expected range. Once the iterator has run, the outcomes of these checks are compiled into a CSV file which can be used to verify that no bugs have occurred.

2)The Karamba3D model is verified in a two step manner; 1)By analyzing support reactions, deflection curves, and moment lines to ensure it aligns with the same assumptions, mechanical schemes, and loads as the Structural Design Configuration part of the Structure Generator Tool 2)By performing several calculations of basic cases within Karamba3D and comparing them with the formulas used in the Structural Design Configuration Section to evaluate the differences between the methods on a fundamental level. The influence of differences in assumptions and boundary conditions between the Karamba3D model and the calculations performed in Structural Design Configuration section are examined here as well.

3)To validate the structural element dimensions determined in the Element Cross Section Size Determination section of the Structure Generator Tool, the deflections and/or utilization rates are compared with those calculated by Karamba3D. Each structural elements cross section size is based on either a maximum deflection (SLS) or an Ultimate Limit State (ULS) check, whichever is believed to be governing for that specific element. The justification for selecting deflection or utilization as the governing criterion is verified by comparing which is closer to its respective limit in Karamba3D. If the chosen criterion is indeed closer to its limit, it is considered the governing one. It is than checked if the structure is valid according to Karamba3D, meaning a utilisation <100% or deflection < limit value. Given that the aim of this tool is to generate structurally reasonable outputs in terms of mass, and considering that Karamba3D is a preliminary analysis software, structural elements with utilization rates and deflection unity checks between 50% and 150% are noted down separately and considered acceptable.

4)For a fair comparison, all variants should be dimensioned so that their respective structural elements have similar unity check values. A comparison between variants with a U.C. of 0.1 and a U.C. of 0.9 would be misleading. According to the checks performed in the Element Cross Section Size Determination section of the Structure Generator Tool, this uniformity is achieved. In this step, it is assessed whether this uniformity is also present in the Karamba3D results where other factors are also considered and, if not, the extent of those deviations are analyzed. Additionally, it is evaluated whether Karamba3D systematically produces higher or lower values by default.

In the comparison of design variants, not only differences in unity checks/utilization need to be considered. In the Geometry and Grid Definition part of the Structure Generator Tool, grids are generated for a given footprint, however, not all grids are equally efficient. Similar to unity checks, comparing a very efficient grid with a very inefficient one gives skewed results. The variation in efficiency can originate from the fact that certain grid sizes align better with specific floor plan dimensions. However, grid generation is not determined solely by span and the width and length of the floor plan. Structural Grid Optimization Variables, such as the minimum required distance from the facade and core, as well as the maximum allowable deflection increase that may occur with extended beam lengths when removing a column or beam row before placing a central row, also influence the grid's configuration. The optimal values for these Structural Grid Optimization Variables may vary depending on the specific span and floor plan dimensions. As a result, certain spans and floor plan dimensions may get less optimal grids than others. Therefore grid efficiency variation based on variation in these Grid Optimization Variables is also verified to determine if further research and development is needed on this aspect.Grid efficiency is measured by m^3 of timber per m^2 of floor plan.

5)The methods employed in the Element Cross Section Size Determination section of the Structure Generator Tool differ in terms of complexity and depth. Early results indicated that certain structural element categories(Beams and Columns, Floors, Core, Joints) needed to be explored in greater detail than others, based on their contribution to the building's total embodied carbon. Table 6.14 presents the decision matrix used to determine the necessary level of detail in the calculations as a function of each category's contribution. It is analyzed if within the variable range the applied level of detail in the calculations is justifiable for each structural element category.

6.2.1. Karamba3D Structural model verification

The Karamba3D Model is created according to the mechanical schemes shown in figure 5.11 discussed in 5.2.3. A more detailed description of the verification steps is given below. The analyses confirmed that all the condition described below were met, with the floors being the only exception. If a floor boarders a facade beam or core wall it, disregarding their spanning correction, makes a hinged connection to that element. Creating in this area not a single, but two way spanning floor. If a floor slab that does not boarder the facade or core is present this is not a problem since the maximum deflection is taken out of the model and a accurate value will be given. But with smaller footprints where these are not present this may lead to a too positive image of the floor deflection in Karamba3D.

Floors

The floors in the model are designed to be connected solely to the beams. To ensure that the floors are fully decoupled from the columns, the shear force at the ends of the beams, where they connect to the columns, should closely match the results of equation 6.1. This calculation determine the shear force at the end of the beams. This would indicate that all floor loads are being transferred through the beams. The floor slab is modeled as a single spanning slab. Deflected results should therefor be multiple mono-clastic curved surfaces.

$$Shearforce = \frac{1}{2} \cdot Span^2 \cdot Floorload \tag{6.1}$$

Joints

The Deflection curves of the columns if they are connected by hinges should all be single curvature and coming into the joints under an angle. If coming in straight this means that there is a (partially) fixed joint there. The beams should also come into the joints under an angle. The deflection curve however will, if modeled correctly, not be a single curvature. Due to the decoupling of the floors from the columns the floor is slightly pulled backwards. The first part of the beams has therefore no floor, at the point of attachment of the floor a change of curvature is expected. For both the beams and the columns the moments at the end points should be zero.

To ensure that the core is carrying the full horizontal wind load the total horizontal force is calculated and the shear force at the foot of the core. If these are equal this means that the full wind load is carried by the core and there are no fixed joints present in the model.

Beams

The moment lines of beams are slightly distorted. To let beams and floors work together in Karamba3D, the beam has to be split into multiple smaller beams. A hinged joint is only placed at the end of the last and beginning of the first of these spliced beams. The rest of the beam parts are fully rigid connected to mimic a solid beam. The amount of distortion in the moment line is used to verify the validity of this method.

Loads

The total horizontal wind load applied to the facade is calculated and compared with the total horizontal reaction forces from the structural model. Similarly, the total applied floor load is determined using hand calculations and compared with the support forces in the model that excludes self-weight and wind load. The structure's self-weight is verified through the mass calculations in the Embodied Carbon Material Factor Determination Tool.

Material behavior modeling

Timber exhibits orthotropic behavior, meaning its material properties vary depending on the direction. In Karamba3D, however, only shell elements can be modeled as orthotropic [2], but no specific Cross-Laminated Timber (CLT) option is available. Consequently, floors are modeled as a single homogeneous glulam slab with orthotropic properties, while beams and columns are assigned properties based on the primary direction.

For shell elements, utilization is calculated by dividing the applied load on each face by the tensile or compressive strength of that face. In the case of timber, the Tsai-Wu strength criterion is used, while for the isotropic material concrete (assumed to be uncracked), the Von Mises criterion is applied.

In Karamba3D, the core is modeled as uncracked; however, in reality, it is likely to experience cracking due to tensile forces, leading to greater deflections than predicted. For timber elements, while the approach accounts for some orthotropic behavior in shell elements, modeling them as glulam rather than cross-laminated timber (CLT) overestimates deflections compared to actual performance. Approximating beams and columns as isotropic only in the grain direction provides a practical yet simplified solution. Overall the Karamba3D output is considered viable but should be applied with caution in precise assessments.

Modeling Differences and basic cases output evaluation

In this section point two of the Karamba3D model verification is performed. Assessing the difference between the Karamba3D output and results from the calculations on which the Structural Design Configuration section is based for basic cases.

This is done for the core, beams and floors. For each structural element category it is first determined what the difference in output is between the basic Karamba3D model and the calculations from the Structural Design Configuration section given the same boundary condition in both the Karamba3D model as the calculations. Next, the influence of differences in boundary conditions and assumptions between the two approaches is assessed, addressing each factor and combination of factors individually.

Starting with the core. The core has on average a deflection that is 50% lower than the calculated deflection given the same boundary conditions and assumptions used as with the formula on which the Structural Design Configuration section is based.

The ratio difference based on building height, chosen span, and building floor plan dimensions are shown in figures 6.1, 6.2 and 6.3 in that order.

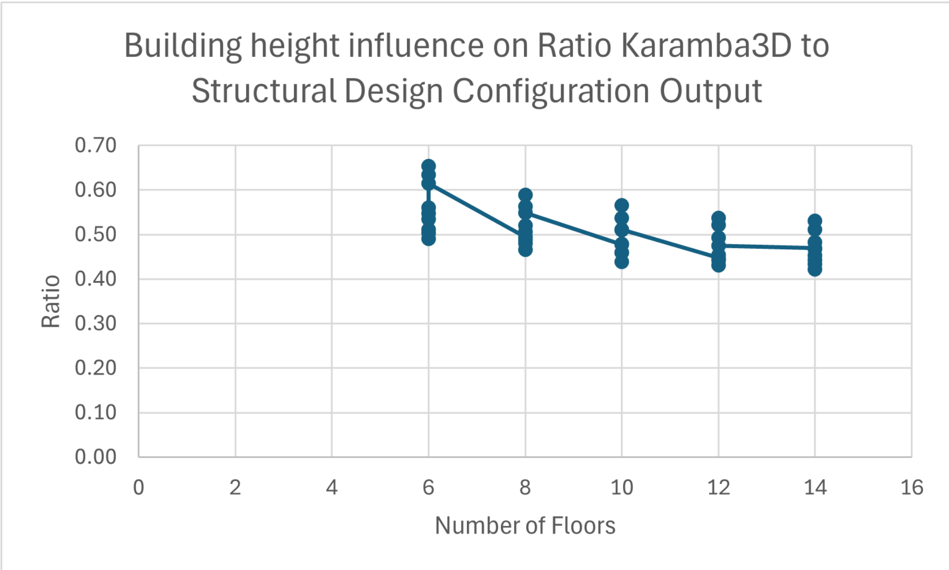

Figure 6.1: Building height influence on Ratio Karamba3D to Structural Design Configuration Output

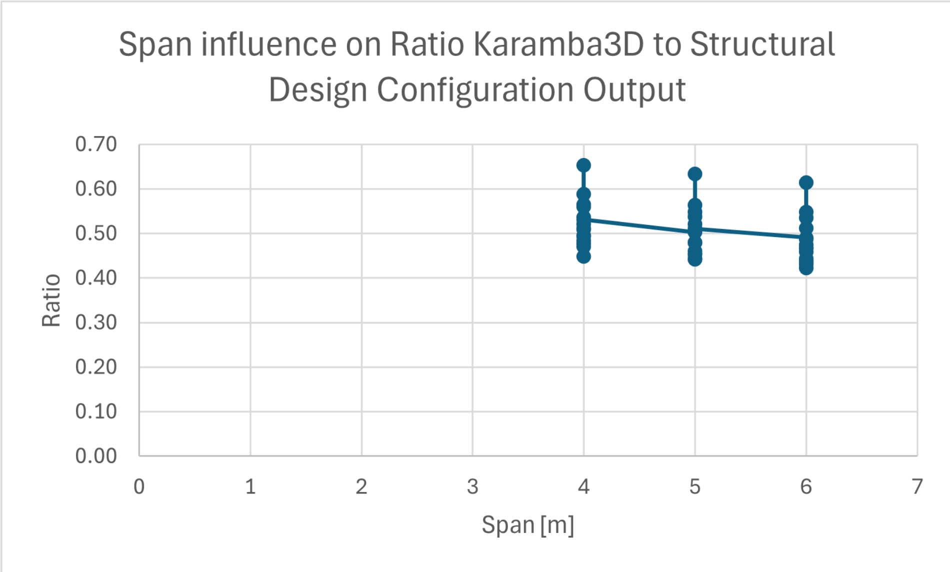

Figure 6.2: Span influence on Ratio Karamba3D to Structural Design Configuration Output

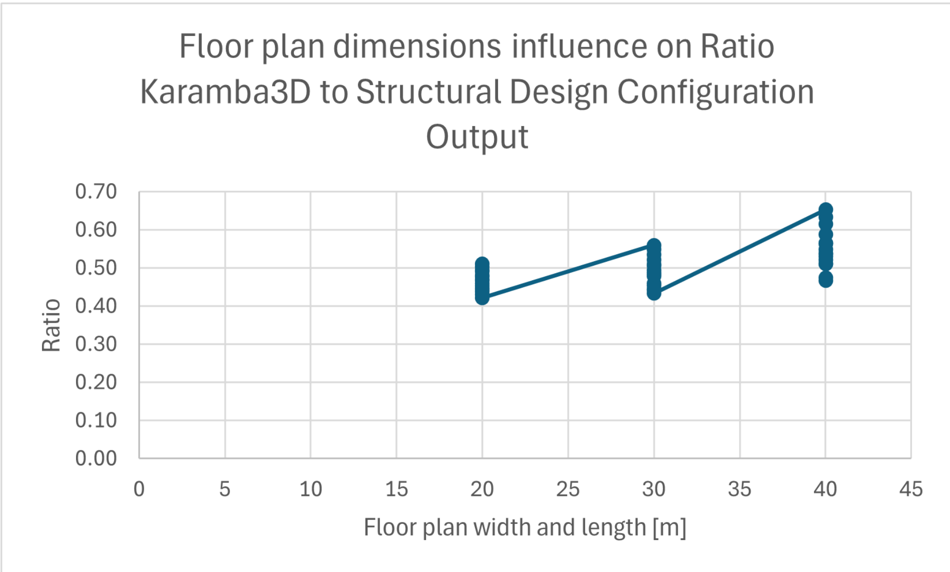

Figure 6.3: Floor plan dimensions influence on Ratio Karamba3D to Structural Design Configuration Output

There are three modeling differences between the Karamba3D model and the Element Cross Section Size Determination part of the structure generator tool. The differences can be categorized into three parts; 1)Material Level 2)Model Level 3)Scope.

At the material level, the calculations performed in the Element Cross Section Size Determination part of the Structure Generator Tool incorporate a modified elastic modulus, accounting for the fact that the core will crack under tensile forces, which leads to increased flexibility. This heightened flexibility results in an larger cross section requirement for the core. However, within Karamba3D, it is not possible to modify only specific material properties.

On the model level a difference is that in the calculation the core is modeled as a clamped cantilevering beam. While in the model it is a 3-dimensional brep with tensile forces on one side and compression forces on the other side. The second form is expected to be slightly more efficient. Leading to a lower deflection of the model.

The model in Karamba3D considers both horizontal and vertical loads, whereas the calculations in the Element Cross Section Size Determination section of the Structure Generator Tool accounts only for horizontal forces, resulting in a difference in scope.

These differences are investigated to asses the influence of them on the end results and to determine to what extend the outcome from the verification calculations has to be adjusted. This is done through varying all the different combinations of the modeling differences through a reduced variable range. The variables are varied as is described in 6.2, resulting in 45 iterations per situation. Situation 1 is a Element Cross Section Size Determination section calculated with a modified elastic modulus and Karamba3D model with a Brep and both horizontal and vertical loads. All different situation are show in table 6.1

Iteration	Fictive E-modulus	Regular E-modulus	Clamped	Brep	Horizontal	Horizontal and Vertical
1	x			x		x
2	x		x		x	
3	x			x	x	
4	x		x			x
5		x	x			x
6		x		x	x	
7		x		x	x	
8		x	x			x

Table 6.1: Core modeling differences investigation variants

Variable	Minimum Value	Maximum Value	Step size
Number of levels	6	14	2
Width and length of the footprint	20	40	10
Span	4	6	1

Table 6.2: Variables and ranges used for Core modeling verification

The generated data reveals a difference of a few millimeters when comparing results using the same elastic modulus for both a clamped and a 3D brep model of the core, with or without vertical loads. When the same E modulus used in Karamba3D is applied in the Element Cross Section Size Determination section of the Structure Generator Tool, a significant impact on the results is observed. With this consistent E modulus, Karamba3D deflections were increased with 30%. The biggest difference, appears in utilization values: with the same E modulus, the core's utilization increase with an average of 66%.

For the beams, the deflection output from Karamba3D is analyzed. A single beam is modeled with a one-meter-wide floor strip, and the span is varied. For each span, the required cross-sectional sizes are determined, and the resulting deflection is measured. In the Karamba3D model used in the Structure Generator Tool, the beam and floor are coupled, whereas in the Structural Design Configuration section, they are treated as uncoupled elements. The results from the analyses are plotted in graph 6.5 and 6.6. The model set-up is shown in figure 6.4, the accompanying script can be found in appendix A.

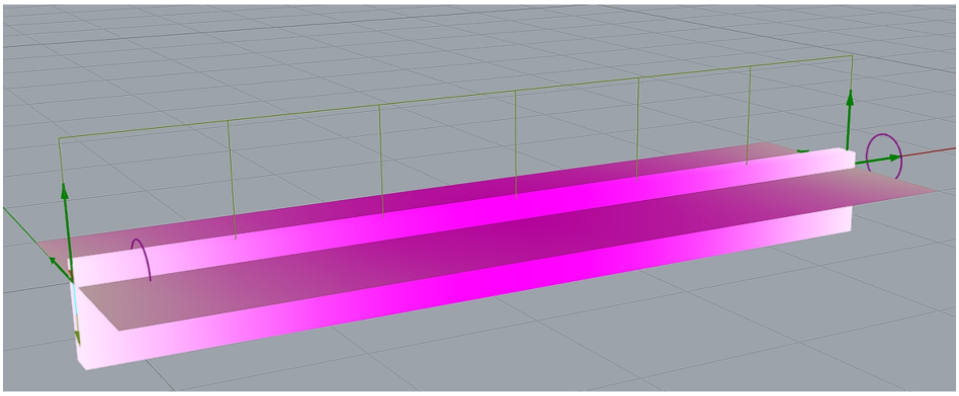

Figure 6.4: Model Set-up Beam Deflection Output Verification

The deflection of the Karamba3D output is on average 66% of the deflections calculated in the Structural Design Configuration section of the Tool, provided that all assumptions are consistent between the two methods

In the Karamba3D model however the beam and floors are modeled as connected. This causes a higher stiffness overall and a lower deflection. Due to this increased stiffness the stresses in the beam also enlarge. With a fully decoupled beam SLS criteria is governing in 100% of the cases. With a coupled beam and floors system SLS criteria is governing in 20% of the cases. With a coupled system the Karamba3D results ratio to the output from the Structural Design Configuration is reduced with 30% and drops to a ratio of 46%

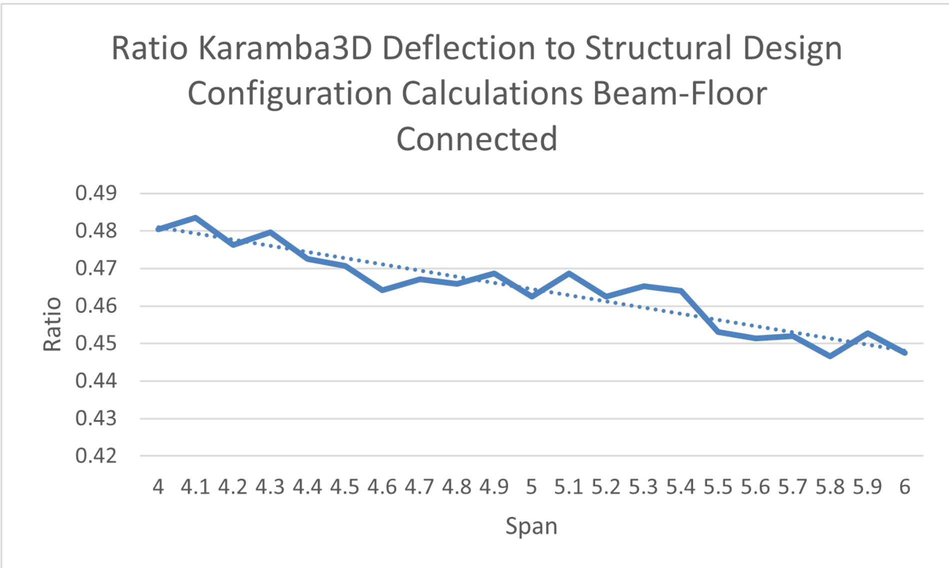

Figure 6.5: Graph Ratio Karamba3D Deflection to Structural Design Configuration Calculations Beam-Floor Connected as a Function of the Span

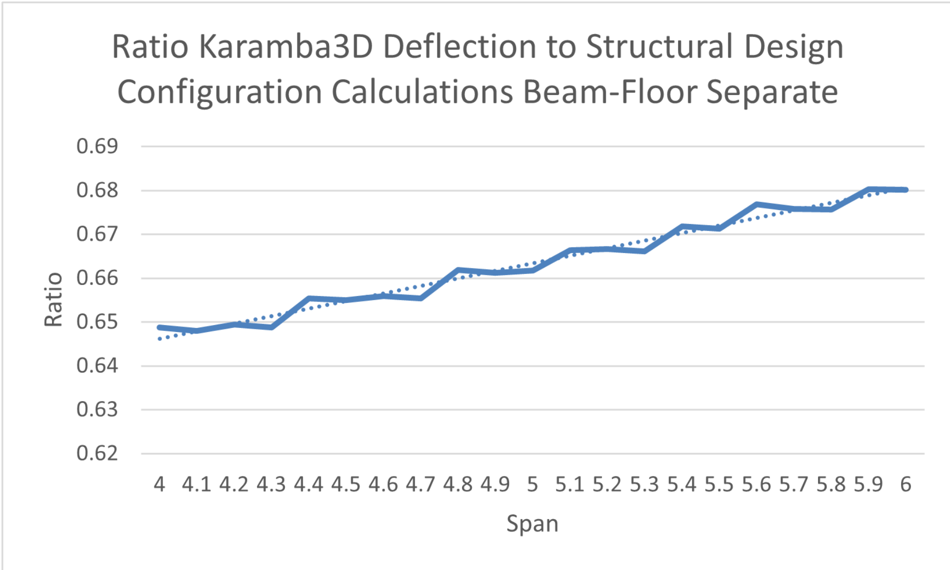

Figure 6.6: Graph Ratio Karamba3D Deflection to Structural Design Configuration Calculations Beam-Floor Separate as a Function of the Span

For the output verification of the floors a similar method as with the beams has been applied. The model set-up is shown in figure 6.7. Out of these results an average ratio of 137% was concluded. Meaning that according to Karamba3D the deflections are higher than those of the Structural Design Configuration. No clear correlation was observed between the change in span and this ratio.

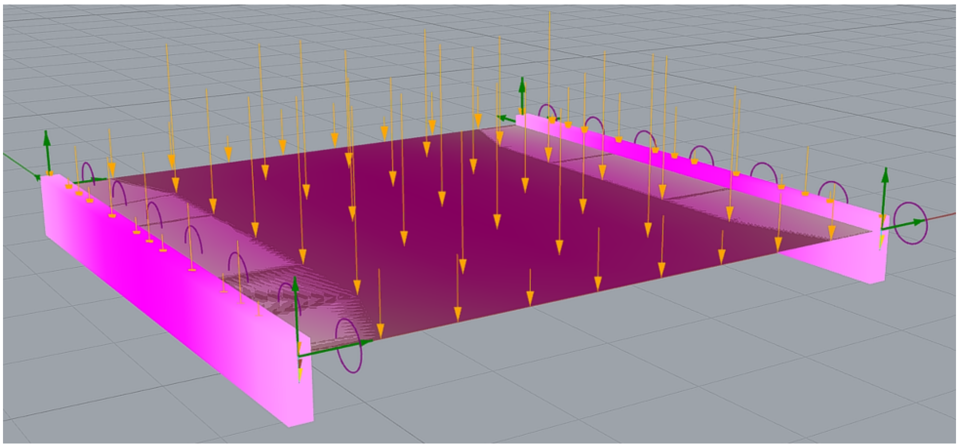

Figure 6.7: Model Set-up Floor Deflection Output Verification

6.2.2. Analysis of Methodology Validity and Structural Design Consistency

The iterations have been performed with the variable ranges shown in table 6.3 resulting in 324 iterations. The same variable range has been used to produce the results of the framework presented in chapter 7.

Variable	Minimum Value	Maximum Value	Step size
Number of levels	6	14	1
Width and length of the footprint	25	35	5
Span	4	6	1
Free Floor Height	2.6	4.1	0.5

Table 6.3: Variables and ranges used for Structural element verification

Methodology Verification

Structural Element	%-Governing Check Used	%-Karamba3D verified	%-50% <U.C.Karamba3D< 150%
Inner beams	4.6%	100%	22.4%
Facade Beams	0.9%	99.1%	0%
Inner Columns	100%	99.1%	30.1%
Facade Columns	98.2%	98.8%	20.6%
Floors	99.4%	78.6%	87.1%
Core	0.9%	99.1	21.5%

Table 6.4: Methodology Verification Structural Design Configuration Local Beam Displacement

Structural Element	%-Governing Check Used	%-Karamba3D verified	%-50% <U.C.Karamba3D< 150%
Inner beams	100%	98.2%	57.0%
Facade Beams	99.1%	98.2%	0%

Table 6.5: Methodology Verification Structural Design Configuration Global Beam Displacement

Structural Element	Average SLS UC	Average ULS UC
Inner beams local	0.28	0.42
Facade Beams local	0.10	0.22
Inner beams global	0.63	0.42
Facade Beams global	0.40	0.22
Inner Columns	0.45	0.16
Facade Columns	0.44	0.22
Floors	0.98	0.44
Core	0.09	0.42
Joint Beams	-	0.87
Joint Columns	-	0.80

Table 6.6: Average Unity Checks Per Structural Element Category

The joint design verification was conducted by manually comparing three different variants and calculating the average values. Individual results are shown in F.1.1. This verification is based on a small test group; therefore, further verification should be conducted with a larger set of variants in the future. Additionally, assumptions such as the use of a point load and the influence of a symmetric dowel design have not yet been investigated. The influence of a asymmetric steel plate depending on the loading direction is included in the verification. In excel this asymmetrical plate shape is included in the Tool it is not. The results are shown in tables F.1 til F.6.

Variable	1st Variant	2nd Variant	3rd Variant
Number of levels	6	10	14
Width and length of the footprint	25	30	35
Span	4	5	6
Free Floor Height	2.6	3.1	4.1

Table 6.7: Variables Used For Variants For Joint Verification

	UC Dowels	UC Compression Timber	UC Tension Timber	UC Plates
Excel results	0.11	0.11	0.78	0.012
Tool results	0.11	0.11	0.78	0.02

Table 6.8: Methodology Verification Joints average values Beams

	UC Dowels	UC Compression Timber	UC Tension Timber	UC Plates
Excel results	0.38	0.02	0.02	0.01
Tool results	0.38	0.02	0.02	0.03

Table 6.9: Methodology Verification Joints average values Columns

	Beam Part	Column Part	Connecting part	Total
Excel results	79.06 kg	14.28 kg	34.44 kg	127.78 kg
Tool results	129.82 kg	29.66 kg	58.77 kg	218.25
Percentage				59%

Table 6.10: Average Mass Joint Parts

Out of the comparison with the excel calculations no difference between the unity check for the dowels, compression of the timber or tension of the timber occur. A difference is noted in the mass and unity check for the steel plates. The unity check increase slightly for the steel plate and the average mass reduction for asymmetric plates is 41.5%. The average results are shown in 6.10. For the individual variants results see appendixF.1 until F.6.

Comparability Structural Design Configuration and Karamba3D

Structural Element	Average deviation SLS UC	Average deviation ULS UC
Inner beams	0.15	0.09
Facade Beams	0.05	0.04
Inner Columns	0.07	0.06
Facade Columns	0.05	0.08
Floors	0.37	0.22
Core	0.00	0.1

Table 6.11

Span	Width and Length			Average	Deviation
	25m	30m	35m		
4m	0.078 +/- 0.024	0.057 +/- 0.015	0.065 +/- 0.021	0.066	0.021
5m	0.076 +/- 0.019	0.057 +/-0.013	0.070 +/-0.020	0.068	0.019
6m	0.118 +/- 0.037	0.085 +/- 0.023	0.070 +/- 0.016	0.090	0.030
Average	0.091	0.066	0.067	0.075	-
Deviation	0.030	0.020	0.019	-	0.024

Table 6.12: Grid efficiency as a function of the floor plan dimensions and applied spanning distance.

Granularity Verification

Structural Element	Average %
Beams and Columns	14.3 %
Floors	34.6%
Core	37.2%
Joints	13.9%

Table 6.13: Total Average Contributions Embodied Carbon Content per Structural Element Category

Class	Granularity sizing methods	Contribution to total embodied carbon
1	Rules of thumb	0-1%
2	ODE for bending	1-5%

Class	Granularity sizing methods	Contribution to total embodied carbon
3	ODE for bending + additional relevant hand calculations	5-10%
4	ODE for bending + simplified Eurocode formulas	10-30%
5	ODE for bending + significant amount of Eurocode formulas	>30%

Table 6.14: Required Granularity Sizing Methods Classification based on Embodied Carbon Contribution

6.2.3. Discussion Verification Analysis Results

Methodology Columns, Beams and Floors

Table 6.4 presents the verification output of the methodology. Columns and beams generated by the Structural Design Configuration Tool are between 98% and 100% of the time structurally sufficient according to Karamba3D. However, the percentage of cases where the selected check was used for dimensioning is notably low, as is the percentage of elements within the 50% to 150% Karamba3D unity check range. This result, combined with the overall validity of the structures according to Karamba3D, suggests that the columns and beams are generally overdimensioned. Which is confirmed by the local results in table6.6. The low percentage of governing checks used implies that deflection is not the suitable criteria for dimensioning.

The methodology applied assumed, however that not only the local deflection of the beam but the total displacement of the beam should be accounted for. Meaning the nodal displacements at the beam ends plus the deflection of the beams. To obtain this criteria the columns were given a larger cross section size until a specified axial strain criteria had been met. The total displacement verification is depicted in the 'global' results of the beams. Table 6.5 presents the results when global beam displacement is considered, including both the beam's deflection and the nodal displacement contributed by the columns deflection. With this approach, deflection governs in 100% of cases, with beams meeting Karamba3D criteria in 98% of the time. With this methodology in mind the created beams and columns both have deflections as governing criteria in close to all cases and are with unity checks varying between 0.4 and 0.63, although to big, reasonably dimensioned.

This dimensioning methodology does not accurately reflect real-life practice. In practical applications, columns are designed to exceed the floor height to account for anticipated axial strain. With strategic construction planning, all columns are eventually compressed to their intended floor height. To assess the impact of this incorrect methodology on the total embodied carbon content, it is necessary to evaluate the increase in timber due to larger column dimensions and the additional material required to elongate the columns and to subtract these from one another.

The error in column dimensioning methodology results in a 5% increase in embodied carbon content for designs where columns dominate, such as those with small spans, wide and long floor plans, and tall buildings. For opposite designs, the increase is approximately 3%. Appendix A.1.4 provides the script used to calculate the additional timber required to elongate the columns. The script concluded that the extra material required is negligible.

Therefore, the unjustly added embodied carbon content varies between 3% and 5%, which has a minimal impact on the total embodied carbon content of the structure. However, for specific design comparisons where columns play a more significant role, this issue may warrant closer attention.

The dimensions of the beams were determined under the assumption that beams and columns are uncoupled. However, in the Karamba3D model, these elements are modeled as coupled. As discussed in Section 6.2.1, transitioning from a coupled to a decoupled system would make deflection the governing criterion, increasing the SLS Unity Check by an average of 0.3. This results in a unity check of approximately 0.6 for the inner beams and 0.4 for the façade beams,values that are similar to those derived using the incorrect global methodology. Section 6.2.1 also highlights that deflection values calculated in the Structural Design Configuration section are 34% higher than those produced by Karamba3D. Considering all factors, the beam design methodology results in conservative cross-sectional dimensions. While these beams are overdimensioned, they are less so than indicated by the verification table 6.6, due to the coupled modeling approach in Karamba3D, which does not reflect real-life conditions.

As discussed in Section 6.2.1, Karamba3D tends to predict more favorable behavior for floors than what may be observed in reality. The current unity check is already near its maximum value and therefor it is concluded that the floors are slightly underdimensioned. In 6.2.1 it was determined that the Karamba3D deflection is for basic cases on average 137% of the deflection calculated in the Structural Design Configuration section of the Structure Generator Tool. In most cases the static deflection is however not the governing SLS criteria, but the dynamic vibrations from the floor. Therefor this is in most cases of less relevance. Reducing the allowable floor deflection criteria in the Structural Design Configuration section would result in a more robust dimensioning system. To address the potential inaccuracies in the floor analysis, the floor dimensions have been cross-verified with design tables provided by Stora Enso for their CLT floors. These tables confirm that the floor thicknesses determined by the Cross Section Size Determination part of the Structure Generator Tool align with Stora Enso's recommendations for the specified loads [18]. Based on this, the designed floors are deemed reasonable, but still slightly underdimensioned.

Methodology Core

The results in tables 6.4 and 6.6 show significant differences between the results from the Karamba3D model and the expected results calculated in the Element Cross Section Size Determination part of the Structure Generator Tool. The results from the modeling difference verifications reveal a negligible difference of only a few millimeters for all the combinations where the same E modulus was used in both the Karamba3D model as in the Element Cross Section Size Determination part of the Structure Generator Tool, but the loads and geometry modeling were different. The differences in modeling the core like a 3D brep or a clamped beam, with or without vertical load has no significant influences.

If there is a difference in E modulus the results vary significantly. Karamba3D calculates with a significantly higher elastic modulus, resulting in much lower deflections. If the E modulus in the Element Cross Section Size Determination section of the Structure Generator Tool is set to its uncracked value, the same value as the core in Karamba3D, the generated core become significantly smaller and will, on average, be a slightly under dimensioned element, with ULS checks as governing. That ULS checks are governing instead of SLS checks could possibly be due to the low height range for the tool or that due to the low weight of timber tensile stresses play a more significant role. The created core evaluation in Karamba3D, appears to slightly exceed utilization limits if the same modulus of elasticity is assumed for both the Element Cross Section Size Determination section of the Structure Generator Tool and Karamba3D. However, the core is modeled using the minimum E modulus, which likely underestimates its actual stiffness. It is reasonable to assume the real E modulus is higher. Additionally, the Karamba3D analysis does not account for reinforcement, which would improve the tensile stress capacity of the core, indicating that the load-bearing potential in reality may be greater than the analysis suggests and the core is not under-dimensioned.

Methodology Joints

The verification of the joint showed for three of the four unity checks,as expected equal results. Proving the connection generator applies the Eurocode correctly. For the one unity check being influenced by the spacing of the dowels a small difference was noted. This small increase in the unity check for the steel plates bears no further consequence since it is still far below its maximum value. The mass is however quite influenced, on average the excel shows a reduction of 40% in mass compared to the mass from the tool. Programming the joints as symmetrical with a maximum spacing, rather than asymmetrical with more precise spacing, was initially considered a minor simplification. However, the results indicate that even slight deviations in the assumptions can have a significant impact on the final outcomes. This finding suggests that, given the numerous assumptions made in the joint design, the accuracy and reliability of the final calculated values has a high uncertainty.

Comparability

The total average deviation in grid efficiency is 0.024, meaning the average grid efficiency translates to a variance of $0.263 \cdot 2500 \cdot 0.024 = 15.78 kgCO_2/m^2$. In Table 6.12, the grid efficiency across different footprint and span combinations is shown. The variation in grid efficiency per combination of footprint and span is now due to variating floor heights and number of levels, both of which influence column dimensions and, therefore, grid efficiency. This deviation should also account for the influence of the Structural Grid Optimization Variables. It is likely that the optimal settings for these variables vary with different spans and floor plan dimensions. Creating for some floor plan dimensions a less optimal grid than possible. Creating a possible skewed comparison. These variations are currently not accounted for.

For inner beams, a relatively larger deviation is observed in the SLS check. This deviation is likely due to variations in span caused by the moving or removing of column and beam rows near the facade or core. In some cases, this results in more conservative deflection limits, while in others, the values are closer to the threshold. The floor shows significant variation in unity check results across different variants, potentially this is due to the floor modeling issues discussed in Section 6.2.1. Meaning that in some case a two-way spanning floor is compared with a one-way spanning floor. Notably, the core has a very small deviation. This is advantageous, as the core significantly contributes to the building's embodied carbon content.

Granularity

The Embodied Carbon from the Core and the floors form on average 72% of the total Embodied Carbon content. With floors being the dominant factor at low and wide buildings and cores at small and tall buildings.

The core contributes on average 34.6% of the total Embodied Carbon content of the structure. Detailed calculations of the core are however primarily included in the Final Element Development and Future Enhancements assessment section of the Structure Generator Tool. Additional calculations should be incorporated into the Element Cross Section Size Determination part, although the cores generated are almost always valid,the current dimensioning methods are most of the time not governing.

Beams and columns have a greater impact than initially anticipated, with current checks appearing to govern their design, though verification of the created structure by Karamba3D due to its timber simplifications could be improved.

For the floors, the Karamba3D modeling approach for CLT floors is simplified even more and, as discussed in Section 6.2.1, not entirely accurate. While CLT floors are determined by static, dynamic, and manufacturer-specified design tables, the Structure Generator Tool falls short in its verification, particularly given the significant contribution of the floors to the total Embodied Carbon content of the structure.

Joints also contribute a notable amount to the structural behavior, and the level of calculation detail reflects their influence. However, with the reduction in joint mass discussed in Section 6.2.3, the percentage contribution of joints is expected to decrease.

6.3. Conclusion

The Karamba3D model functions acceptably within the framework but requires several interpretation steps and output transformations to ensure usability. To better align with the framework's needs, the floors and beams should be modeled as uncoupled to more accurately reflect real-world behavior. Additionally, the concrete core would benefit from the use of a fictive E-modulus to simulate the effects of cracked concrete. While Karamba3D provides useful insights, more specialized software is necessary for detailed and accurate analysis of timber behavior.

In the current design approach, beams and columns are generally over-dimensioned. The unity checks for the beams are deemed acceptable for this stage of the design, while the columns are more significantly over-dimensioned. However, their influence on the total embodied carbon content, varying between 3–5%, is minimal and their design is also considered acceptable at this stage. The combined effect of the over-dimensioning of beams and columns is estimated to increase the total embodied carbon content by around 5%, depending on the specific variables.

While the interpretation of the core results from Karamba3D with compensation for the elastic modulus difference suggest a under-dimensioned core, due to the exclusion of reinforcement in the verification process and the assumption of a minimal E modulus it is considered slightly over-dimensioned. Floors are modeled optimistically in Karamba3D, resulting in unity check values that are likely higher in practice, leading to under-dimensioned floors. However, a secondary evaluation using design tables from the producer suggests that the floor dimensions are correct, indicating that the floors are acceptable but slightly under-dimensioned.

While the joints produced by the tool are structurally valid, their calculated masses are overestimated. Including an asymmetric joint design in the coding is advised due to its significant impact on accuracy. Current estimates suggest that joint mass output could be reduced by approximately 40%, though further iterations are required to validate this estimate.

Overall, the under-dimensioning and over-dimensioning of structural elements reasonably balance each other out, resulting in a reasonably valid estimate of the structure for Embodied Carbon assessment at this stage of the design process. Given the significant differences in the embodied carbon content contributions of the beams, columns, floors, and core, the slightly inaccurate distribution of Embodied Carbon content is not anticipated to have a major impact on the comparison of design variants. Currently the joints currently represent the biggest source of uncertainty in the assessment of the superstructure.

The tool produces structural variants that are comparable to one another according to Karamba3D, though there is still room for improvement. Additional research is needed to establish an uncertainty range that accounts for variations in unity checks and optimal grid configurations.

Beams and columns have a larger impact than anticipated, but following the over-dimensioning of the columns and beams this is explained. The floor modeling requires more precise verification, Karamba3D's simplifications for timber limits accuracy. Finally, although joints currently add considerably to the total Embodied Carbon Content of the structure, the potential mass reduction due to asymmetric plate inclusion in the code suggests that the allocated level of detail in the joint calculations is excessive based on contribution amount ,but the influence of one 'minor detail' established that this level of detail is in fact required or even not yet adequate.

7 Validation

In Chapter 6, the accuracy of the framework's output is evaluated. This chapter focuses on assessing the framework's validity. How useful the output from the framework is assuming satisfied results from the verification chapter. This is done by presenting an overview of the ways the framework can be used and outputs it is able to generate.

An analysis is conducted on the influence of the selected material factor database on Embodied Carbon content, and the framework's integration into the design process is demonstrated through a fictive design case. This demonstration highlights the framework's capability to analyze the impact of specific changes in design and Embodied Carbon determination choices within the complex web of variables and interdependencies.

A questionnaire designed for further user experience evaluation is included in Appendix E.

7.1. Input and Output options framework

In tables 7.2 and 7.3, all adaptable variables within the framework are given. Table 7.1 presents potential insights and applications for the framework.

An example of the output is shown in figure 7.1. Variations in the number of floors, span, and width are considered, with an ICE average value excluding biogenic carbon storage, and displaying the total embodied carbon as output. Based on the variable ranges specified in Table 7.4. Possible ways this output could be used is to determine the emission of a specific variant as shown in 7.2, by selecting variants with the lowest emission given design boundary conditions or all variables set to a fixed value except one to analyze the influence of solely that variable.

Variable	Minimum Value	Maximum Value	Step size
Number of levels	6	14	1
Width and length of the plot size	20	40	5
Span	3	7	1

Table 7.4: Variables and ranges Validation Example

Possible Insights and Applications in Framework
Downside using CLT Floor - Sound Insulation
Influence of Facade System Choice on Embodied Carbon Content of the Structure
Superstructure vs. Substructure
Concrete Strength Class Influence
Concrete Wall Thickness Influence
Reinforcement Core
Softwood Strength Class Influence
Beam Width Influence
CLT Strength Class Influence
Steel Plate Thickness Joint
Reinforcement Inclusion in Concrete Material Factor vs. Separate Reinforcement factor
Specific EPD Selection Influence
Database Selection Influence
Biogenic Carbon Storage Influence

Table 7.1: Possible Insights and Application Framework

Structure Generator Tool Variables
Design Variables
Number of floors
Span
Width
Floor Height
Sound Insulation Inclusion
Facade Engineer Variables
Weight of Chosen Facade System
Maximum Deflection Facade System
Structural Engineer Variables
Concrete Strength Class
Softwood Strength Class
CLT Strength Class
Floor Loading
Wind Load
Conus Resistance (Bearing Capacity Soil)
Required Pile Depth
Elevator and Stairwell Requirements
Width of Timber Beams
Thickness of Core Walls
Amount of Reinforcement per m^3 Concrete Core
Amount of Reinforcement per m^3 Concrete Foundation
Joint Variables (e.g., Number of Plates, Dowel Diameter, Plate Thickness)
Minimal Distance Column Row from Facade
Minimal Distance Column Row from Core

Table 7.2: Structure Generator Tool Variables

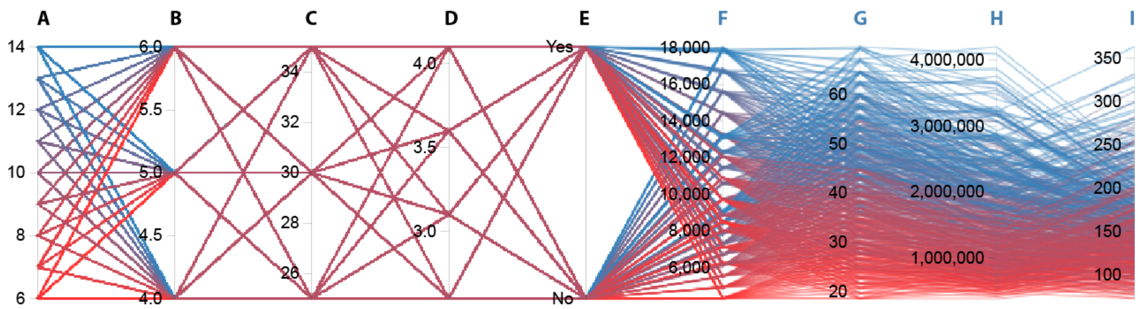

Figure 7.1: Example DesignExplorer Output. A: Number of floors, B: Span, C: Width and Length Floor plan, D: Free Height,E: Sound Insulation Floors,F: Floor Area, G: Total Building Height, H: Total kg CO_2, I: kg CO_2/m^2

Embodied Carbon Material Factor Determination Tool Variables
Average ICE value, Incl. Biogenic Carbon Storage
Average ICE value, Excl. Biogenic Carbon Storage
Range ICE value sd 1, Incl. Biogenic Carbon Storage
Range ICE value sd 1, Excl. Biogenic Carbon Storage
Range ICE value sd 2, Incl. Biogenic Carbon Storage
Range ICE value sd 2, Excl. Biogenic Carbon Storage
Average NMD value, Incl. Biogenic Carbon Storage (Not all NMD data taken into account)
Average NMD value, Excl. Biogenic Carbon Storage (Not all NMD data taken into account)
Specific EPD out of NMD value, Incl. Biogenic Carbon Storage (Not all NMD data taken into account)
Specific EPD out of NMD value, Excl. Biogenic Carbon Storage (Not all NMD data taken into account)

Table 7.3: Embodied Carbon Material Factor Determination Tool Variables

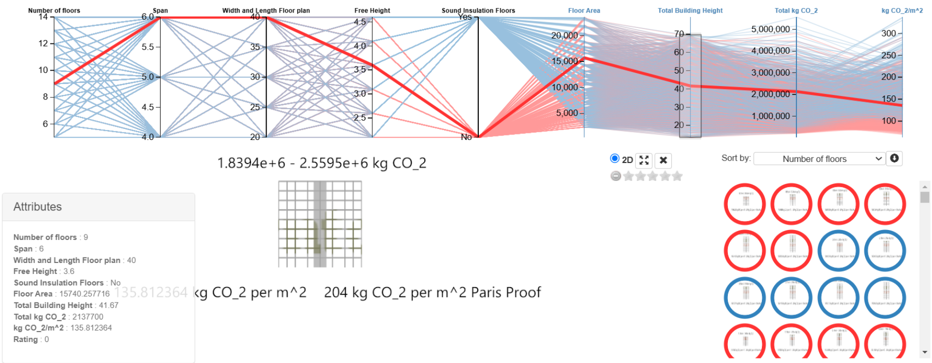

Figure 7.2: Example DesignExplorer Variant Selected

7.2. Database Influence

Two databases for the Embodied Carbon content of structural materials have been integrated in this framework; 1)The ICE V3.0 database 2)The NMD. As discussed in section 5.1.3 not all data entries from the NMD could be integrated. Table 7.5 shows to which amount the NMD has been integrated in the framework.

Structural Element Category	Amount of data entries in NMD	Integrated in Framework
Columns and Beams	14	21%
Floors	3	100%
Core	3	67%
Joints	1	100%

Table 7.5: NMD integration in framework

In Figure 7.3, the Embodied Carbon Content of all variants is evaluated using the NMD (blue) and ICE V3.0 (red) databases. Figure 7.4 focuses on variants with 10 floors, revealing several emerging trends. These trends are further clarified in Figure 7.5, where a single variant comparison shows a difference of $131,000$ kg CO_2, approximately 14% of the total Embodied Carbon Content.

In contrast, Figure 5.2 demonstrates a case with only a $3,900$ kg CO_2 difference, representing around 0.2% of the total Embodied Carbon Content. Despite the smaller variation in total Embodied Carbon Content shown in Figure 5.2, both figures highlight significant differences in the distribution of Embodied Carbon across Structural Element Categories between the NMD and ICE variants.

Table 7.6 summarizes the average Embodied Carbon content per structural category and the ratio of NMD emissions to ICE emissions. For columns and beams, only a limited subset of the NMD data could be integrated into the framework, as shown in Table 7.5. This dataset is too small to draw definitive conclusions for these structural elements.

For CLT floors and the concrete core, the NMD reports more favorable values compared to ICE, whereas steel is significantly less favorable. On average, the total Embodied Carbon Content is 7% lower when calculated using the NMD compared to the ICE V3.0 database.

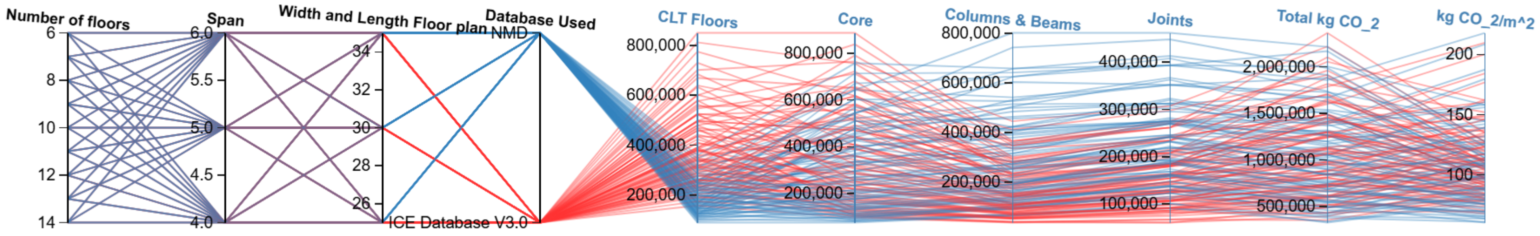

Figure 7.3: DesignExplorer Database influence all variants

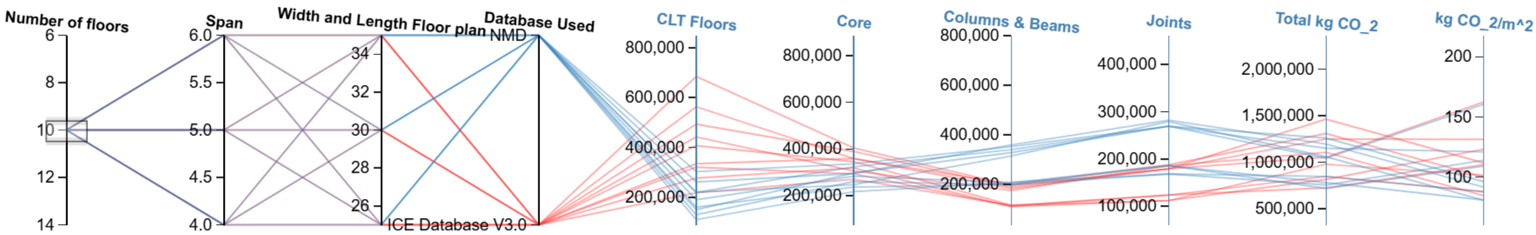

Figure 7.4: DesignExplorer Database influence 10 floors variants

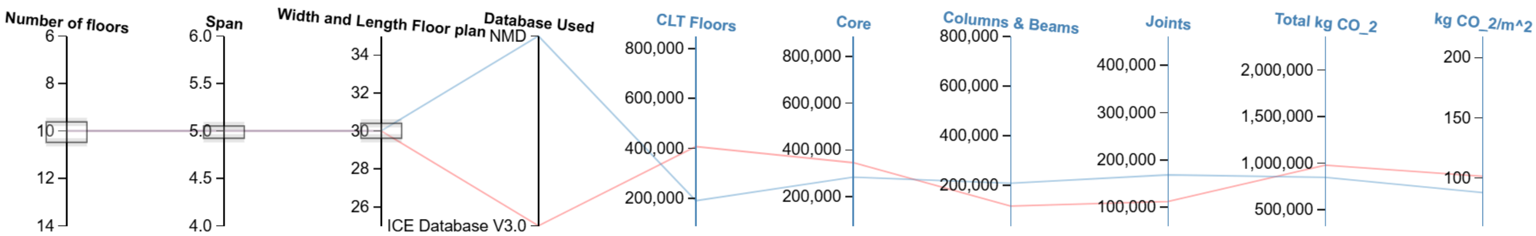

Figure 7.5: DesignExplorer Database influence single variant

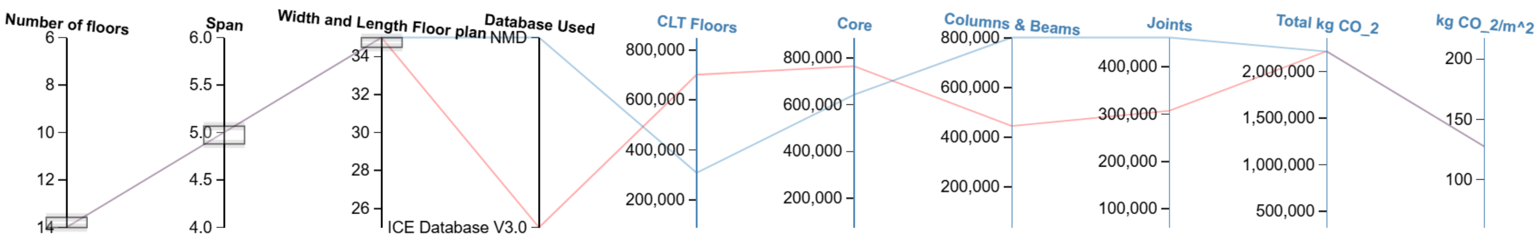

Figure 7.6: DesignExplorer Database influence Structural Element Categorie distribution versus end value

Database	Floors	Core	Columns and Beams	Joints	Total kg CO_2	kg CO_2/m^2
NMD	190554	307144	298135	232999	1028829	105
ICE	409137	372956	166723	155963	1104783	113
Ratio	47%	82%	179%	149%	93%	93%

Table 7.6: NMD ICE database comparison

7.3. Design Case

To assess the functionality of the developed framework in the design process a design case has been created. In figure 7.7 an overview is given. This case study demonstrates how architects or designers might use the framework to enhance interdisciplinary workflows and make more informed early-stage design decisions regarding Embodied Carbon impacts. Importantly, this case study showcases that the framework does not have to be used as a strict tool to dictate the most sustainable design choice, rather it serves to quantify the impact of different design preferences. By providing accessible data, the framework supports designers in adjusting design aspects of their building and to make clear which design aspects should be dictated by the tool versus where more design freedom is possible.

A single average value from the ICE Database (excluding biogenic carbon storage) is used as the material factor.

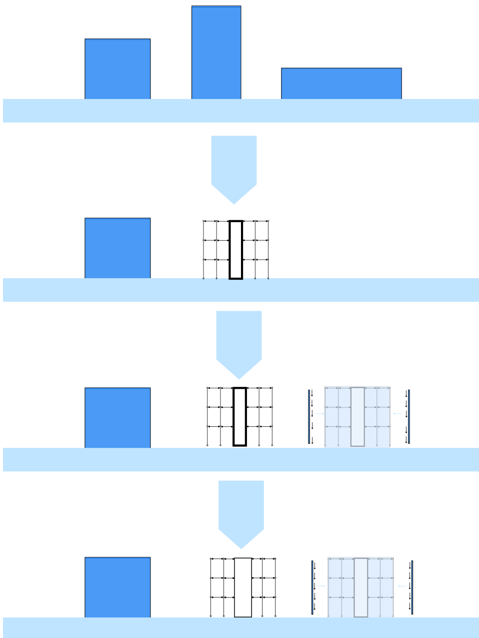

Figure 7.7: Multidisciplinary Validation Embodied Carbon Determination Framework

7.3.1. Step 1: Variations in Span and Floor Height

A number of design variants are investigated by the designer of the building, each with roughly the same floor area. Variations in span, floor height, number of floors and the dimensions of the buildings plot size are assessed. Based on the goals and wishes of the building designer the framework can be used to find the design variant with the lowest embodied carbon content or provide a quantification of the influence of a certain wish the designer has.

Results Step 1

The floor print of the building is a maximum of 35x35, the needed floor area is around 10,000 m^2 and the maximum height is 60 m. Some logical things that were clear before hand are shown by the frameworks output, bigger building equals a higher embodied carbon content.

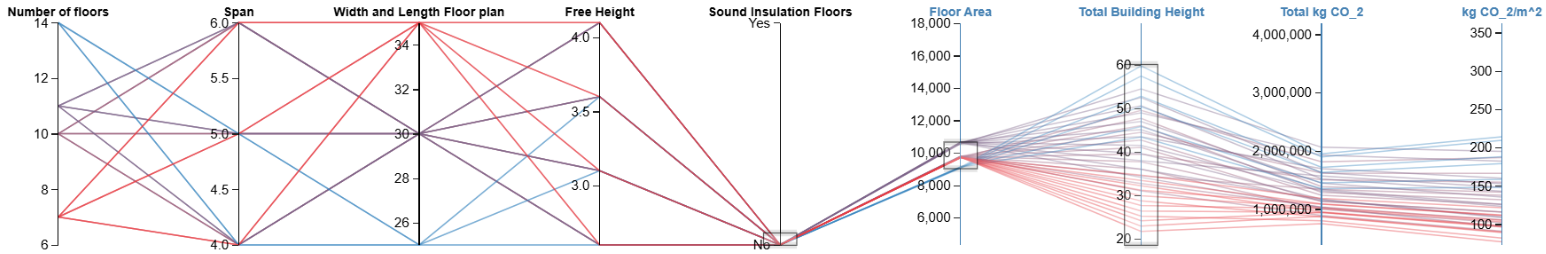

Figure 7.8: DesignExplorer Design Boundary Conditions Selection. A: Number of floors, B: Span, C: Width and Length Floor plan, D: Free Height,E: Sound Insulation Floors,F: Floor Area, G: Total Building Height, H: Total kg CO_2, I: kg CO_2/m^2

If we look at equal area buildings we can also see that lower buildings with a bigger plot size, figure 7.9, have a lower Embodied Carbon content than buildings with the same volume but higher and with a smaller plot size, figure 7.10, per m^2. The client initially wanted a building with at least 14 levels but has decided to reduce it to a minimum of 11 levels, resulting in a reduction of approximately 65 kg CO_2/m^2.

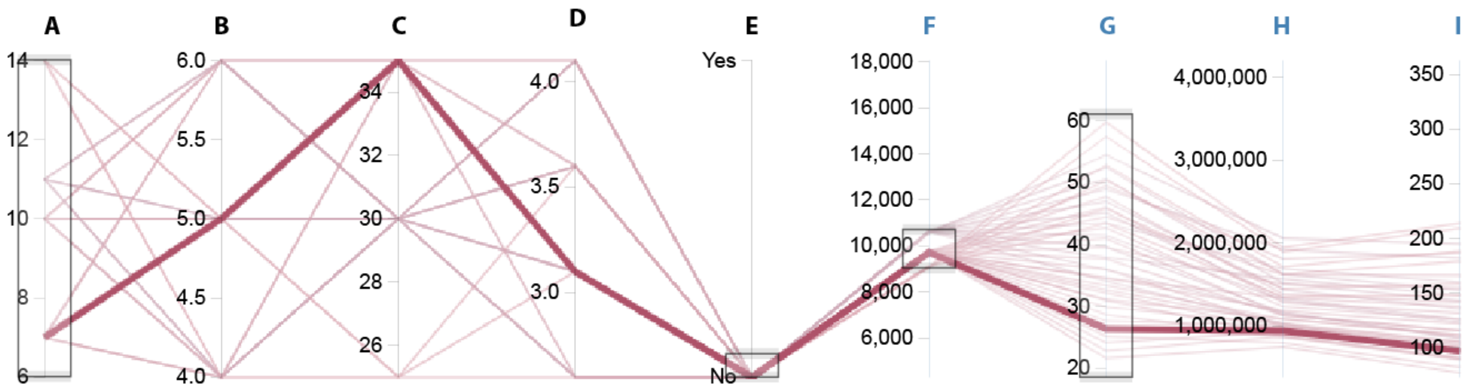

Figure 7.9: DesignExplorer Low building with a big plot size variant. A: Number of floors, B: Span, C: Width and Length Floor plan, D: Free Height,E: Sound Insulation Floors,F: Floor Area, G: Total Building Height, H: Total kg CO_2, I: kg CO_2/m^2

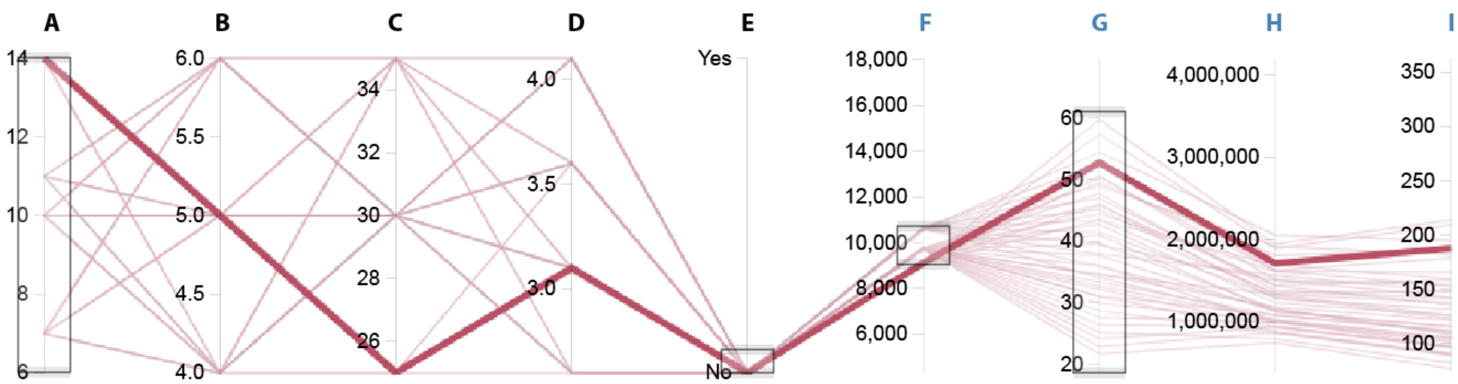

Figure 7.10: DesignExplorer High building with a small plot size variant. A: Number of floors, B: Span, C: Width and Length Floor plan, D: Free Height,E: Sound Insulation Floors,F: Floor Area, G: Total Building Height, H: Total kg CO_2, I: kg CO_2/m^2

As a general principle, the greater the floor height, the more material is needed, leading to a higher embodied carbon content. The designer considers a minimum clear floor height of 4 m essential, so it's useful to examine the combined influence of floor height with other design choices on Embodied Carbon. Buildings with equal volumes but larger plot sizes, as opposed to higher structures, typically have lower embodied carbon content. Figures 7.11 and 7.12 illustrate that increasing the floor height has a much larger impact on taller buildings. An 11-level building experiences an embodied carbon increase of approximately 44 kg CO_2/m^2, whereas a 7-level building increases by only around 22 kg CO_2/m^2 by changing the floor height from 2.6 m to 4.1 m. Ultimately, the number of floors was lowered to 10 levels.

The designer preferred a big span as well, initially opting for a 6 m span. However, comparing span options reveals that a 4 m span saves approximately 55 kg CO_2/m^2 compared to a 6 m span.

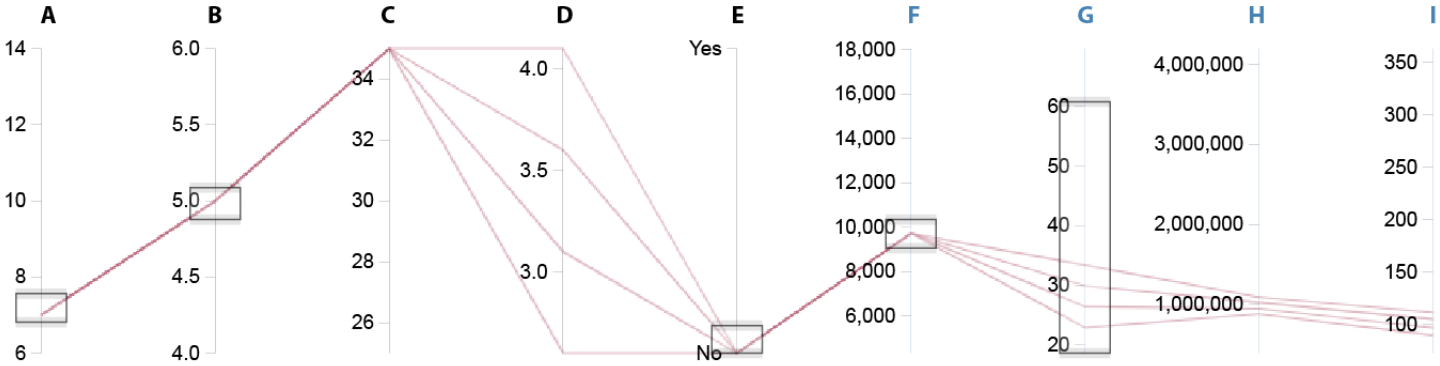

Figure 7.11: DesignExplorer Floor height influence on a low building. A: Number of floors, B: Span, C: Width and Length Floor plan, D: Free Height,E: Sound Insulation Floors,F: Floor Area, G: Total Building Height, H: Total kg CO_2, I: kg CO_2/m^2

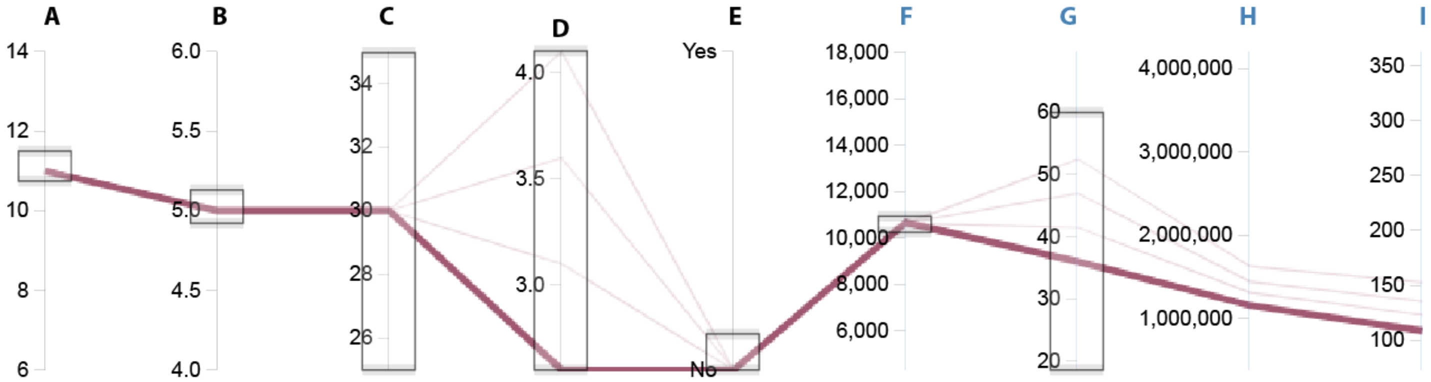

Figure 7.12: DesignExplorer Floor height influence on a high building. A: Number of floors, B: Span, C: Width and Length Floor plan, D: Free Height,E: Sound Insulation Floors,F: Floor Area, G: Total Building Height, H: Total kg CO_2, I: kg CO_2/m^2

With all variants sound insulation has not been selected. CLT floors generally have poor sound insulation due to their lightweight nature. One way to improve sound insulation is by adding mass through a concrete layer. If this method is selected there is a reduction of influence of the span. A span of 5 m now even has a 4 kg lower CO_2/m^2 value than that with a span of 4 m. This is shown in figure 7.14 with the red line representing the variant with a 4 m span and purple with a 5 m span. In figure 7.15 a more detailed output of the results is shown. The results show that as the span increases, the Embodied Carbon content of the beams and floors rise. Meanwhile, the number of columns and joints decreases, which lowers the Embodied Carbon content. Without a concrete insulation layer this results in a net increase of Embodied Carbon the larger the span becomes. The reason this variation in span becomes less significant if a concrete sound insulation layer is applied, is that due to increased floor thickness to support longer spans, less additional mass is needed to meet sound insulation requirements. The concrete sound insulation Embodied Carbon Content is therefor smaller for a bigger span than a smaller span, resulting in some cases in a smaller increase and in some even to a decrease. For a span of 5 m the emission is reduced compared to a span of 4 m, but at a span of 6 m, the embodied carbon of the beams and CLT floor surpasses the savings from reduced insulation again. Since this method of sounds insulation will most likely be applied according to the designer, a span of 5 m is selected.

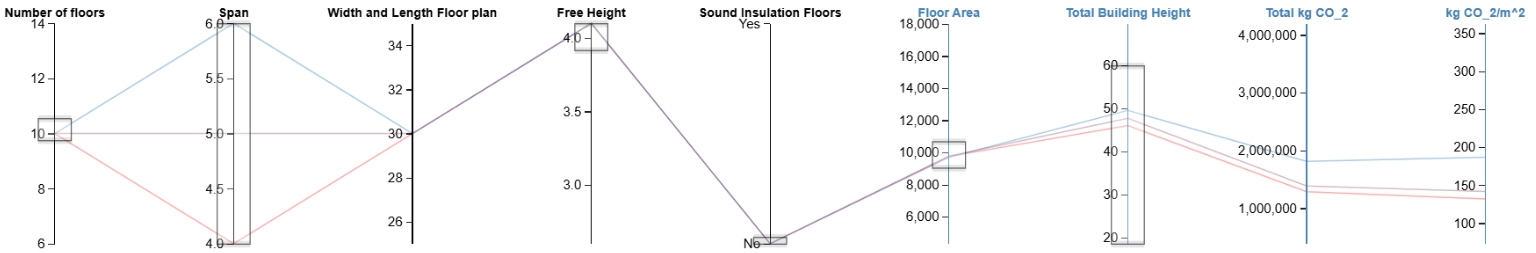

Figure 7.13: DesignExplorer Span Size Evaluation. (left to right) Number of floors - Span- Width and length floorplan - Core Height - Sound inuslation - Floor Area - Building Height - Total kg CO_2 - kg CO_2/m^2

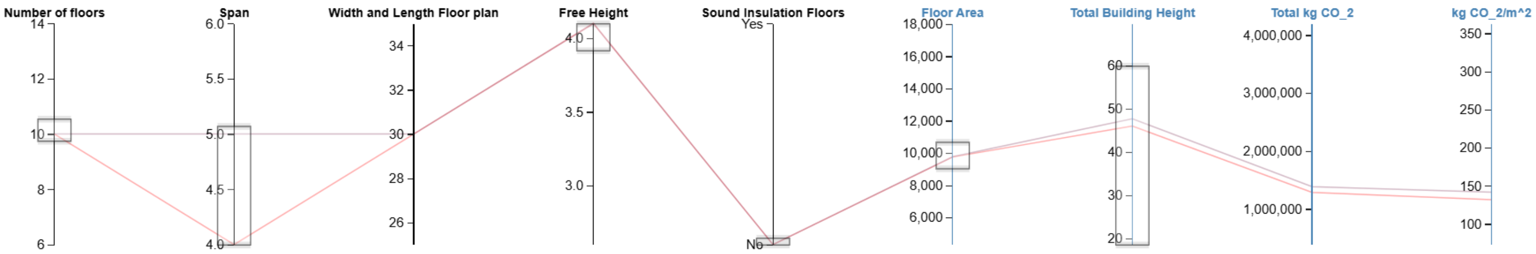

Figure 7.14: DesignExplorer Span Size Evaluation with Sound Insulation. (left to right) Number of floors - Span- Width and length floorplan - Core Height - Sound inuslation - Floor Area - Building Height - Total kg CO_2 - kg CO_2/m^2

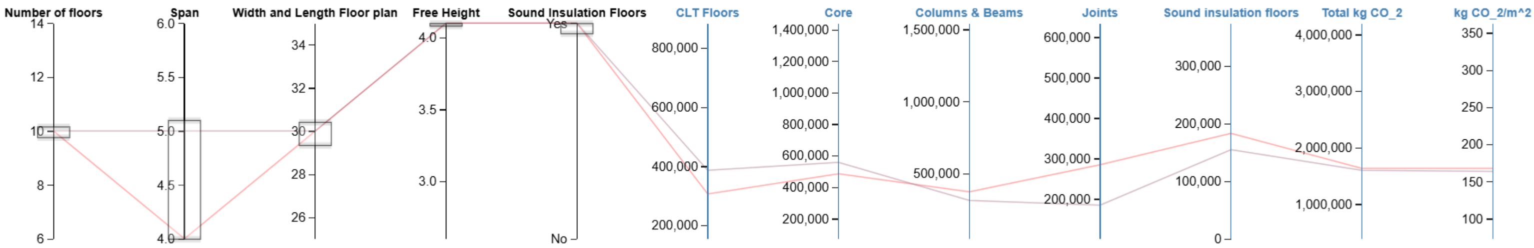

Figure 7.15: DesignExplorer Span Size Evaluation with Sound Insulation Detailed output. (left to right) Number of floors - Span - Width and Length Floor plan - Free Height - Sound Insulation Floors - CLT Floors - Core - Columns and Beams - Joints - Sound insulation floors - Total kg CO_2 - kg CO_2/m^2

7.3.2. Step 2: Interaction with Facade Designer

Based on the goals and wishes of the building designer a initial design has come out of step 1. The next step is the facade design. Although the facade itself is not part of the framework, its impact on the structure is included. Assuming the facade uses prefabricated elements attached to facade beams, each element imposes a load on the beams and requires specific allowances for deflection and rotation. Based on this, facade beams may need adjustments in height. If facade beams become taller than interior beams, it also necessitates taller columns and core adjustments to maintain the desired floor height. All factors that influence the Embodied Carbon content of the building.

Results Step 2

Figure 7.16 shows all different Facade variants. In figures 7.17 and 7.18 these variants are either solely variated by facade deadweight and maximum allowed deflection. Out of these figures it is concluded that the influence of maximum deflection is higher than that of the facade deadweight. In this scenario six variants are possible for the facade. All different combinations and the total kg's CO_2/m^2 derived from figure 7.16 are shown in table 7.7 and analyzed in tables 7.8 and 7.9. The largest increase in Embodied Carbon occurs when the facade beam has a maximum deflection of 10 mm. Switching between 17 mm or 50 mm maximum allowed deflections has minimal impact. Meeting the 10 mm deflection requirement means the facade beam must be taller than the inner beams, which in turn requires an increase in floor height to maintain the desired free height. This adjustment results in longer, larger columns and a higher, potentially larger core.

While Variant 4 is the most sustainable option, the designer prefers Variant 2 aesthetically and finds that the additional 0.81 kg CO_2/m^2 is acceptable for the visual appeal. Overall, the structural impact of the facade is relatively minor in this case. In practical applications, a heavier facade element will likely contribute more to embodied carbon than a lighter one. Thus, from a sustainability perspective, prioritizing the facade's embodied carbon on itself over its structural impact is advisable.

Variant number	Deadweight Facade	Allowed Deflection Facade Beam	total kg CO_2/m^2
1	4	50	147.15
2	4	17	147.61
3	4	10	150.97
4	0.5	50	146.80
5	0.5	17	147.27
6	0.5	10	148.98

Table 7.7: Facade Variants

Deflection	Deadweight increase	Difference in kg CO_2/m^2 with variating Facade Deadweight
10	0.5-4	+2.01
17	0.5-4	+0.34
50	0.5-4	+0.35

Table 7.8: Comparison Facade Variants Deadweight influence

Facade Deadweight	Deflection increase	Difference in kg CO_2/m^2 with variation in Deflection
4	10 - 17	-3.36
4	17-50	-0.50
0.5	10-17	-1.71
0.5	17-50	-0.47

Table 7.9: Comparison Facade Variants Maximum Allowed Displacement influence

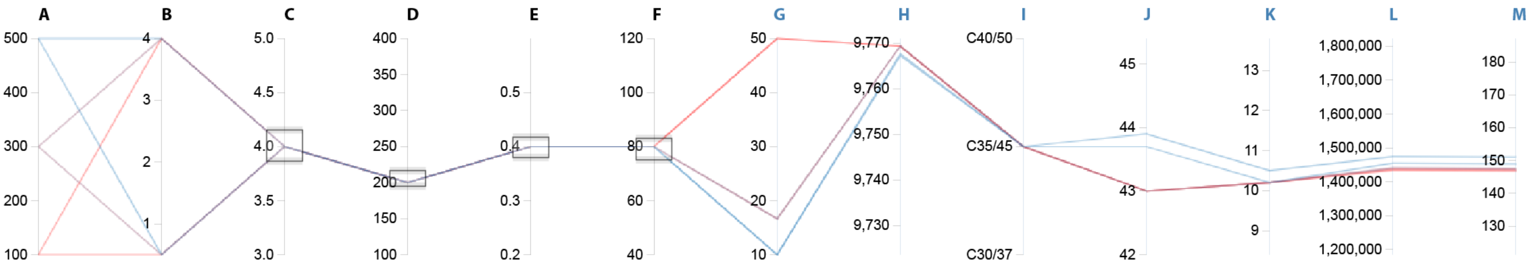

Figure 7.16: DesignExplorer All Facade Variants. A: Displacement Factors Facade Beams, B: Facade Deadweight [kN/m], C: List item Concrete, D: Beam Width, E: Thickness Core Walls, F: Reinforcement per m^3 concrete, G: Allowed Displacement Facade Beams, H: Floor Area, I: Concrete Strength Class, J: Building Height, K: Core Cross Section Height [m], L: Total kg CO_2, M: kg CO_2/m^2

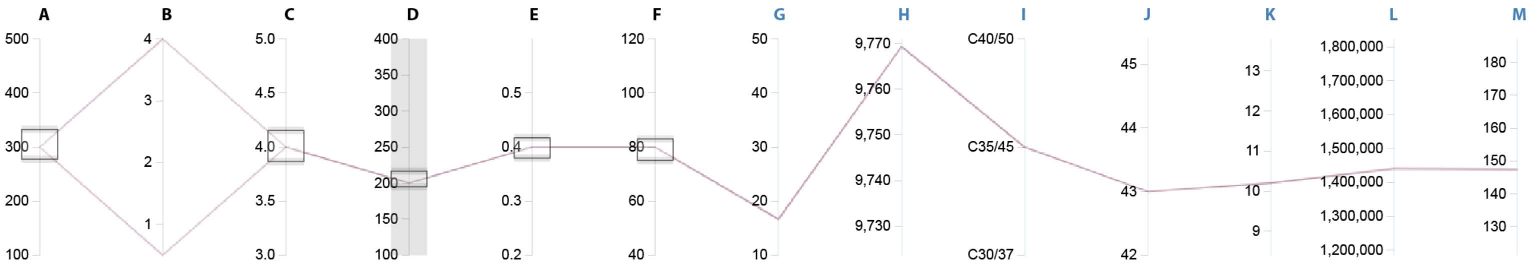

Figure 7.17: DesignExplorer Influence Facade Deadweight A: Displacement Factors Facade Beams, B: Facade Deadweight [kN/m], C: List item Concrete, D: Beam Width, E: Thickness Core Walls, F: Reinforcement per m^3 concrete, G: Allowed Displacement Facade Beams, H: Floor Area, I: Concrete Strength Class, J: Building Height, K: Core Cross Section Height [m], L: Total kg CO_2, M: kg CO_2/m^2

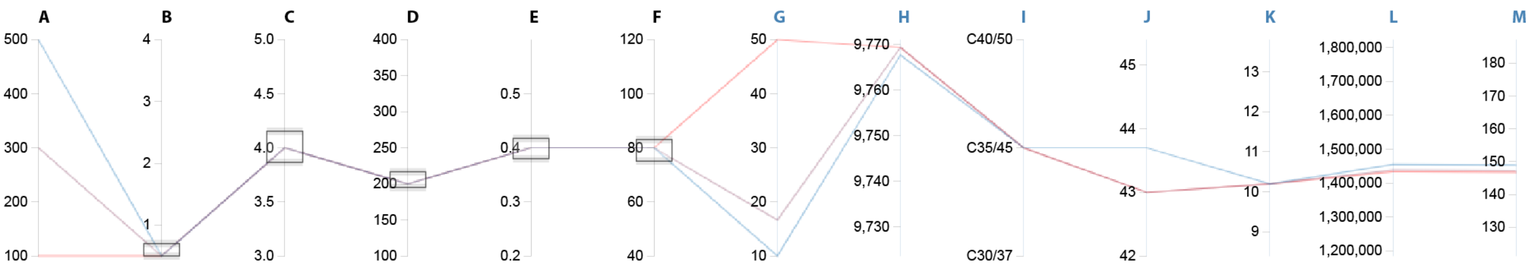

Figure 7.18: DesignExplorer Influence Allowed Displacement Facade A: Displacement Factors Facade Beams, B: Facade Deadweight [kN/m], C: List item Concrete, D: Beam Width, E: Thickness Core Walls, F: Reinforcement per m^3 concrete, G: Allowed Displacement Facade Beams, H: Floor Area, I: Concrete Strength Class, J: Building Height, K: Core Cross Section Height [m], L: Total kg CO_2, M: kg CO_2/m^2

7.3.3. Step 3: Collaboration with Structural Engineer

Following the initial structural design established in Step 1, further structural design variants are explored in greater detail. One such variable is the concrete strength class. Higher strength classes produce higher emissions per kilogram, but requires less material. Adjusting the strength class impacts the dimensions of structural elements, which in turn influences the floor plan layout.

Results Step 3

Now that the facade system has been selected figure 7.19 shows the remaining structural variables that could still be altered.

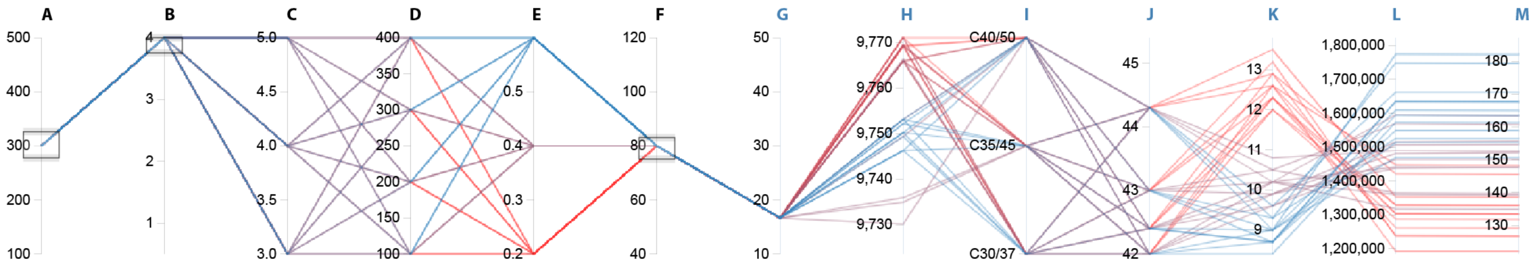

Figure 7.19: DesignExplorer Structural Options A: Displacement Factors Facade Beams, B: Facade Deadweight [kN/m], C: List item Concrete, D: Beam Width, E: Thickness Core Walls, F: Reinforcement per m^3 concrete, G: Allowed Displacement Facade Beams, H: Floor Area, I: Concrete Strength Class, J: Building Height, K: Core Cross Section Height [m], L: Total kg CO_2, M: kg CO_2/m^2

Figure 7.20 illustrates how the core size increases as the concrete strength class decreases. Table 7.10 presents the Embodied Carbon material factor for each strength class. Although a lower strength class requires a larger core, the reduction in Embodied Carbon per material factor outweighs the increase in core size, resulting in a more sustainable option even when the reduced usable floor area is considered. However, practical considerations such as cost and available floor area also come into play. From a structural perspective there are also aspect not taken into consideration, changing the concrete strength class affects the amount of reinforcement required, which could alter these results.

Strength Class	Material Factor
C20/25	0.112
C25/30	0.119
C28/35	0.126
C32/40	0.138
C35/45	0.149
C40/50	0.159

Table 7.10: Embodied Carbon Material Factor per Concrete Strength Class

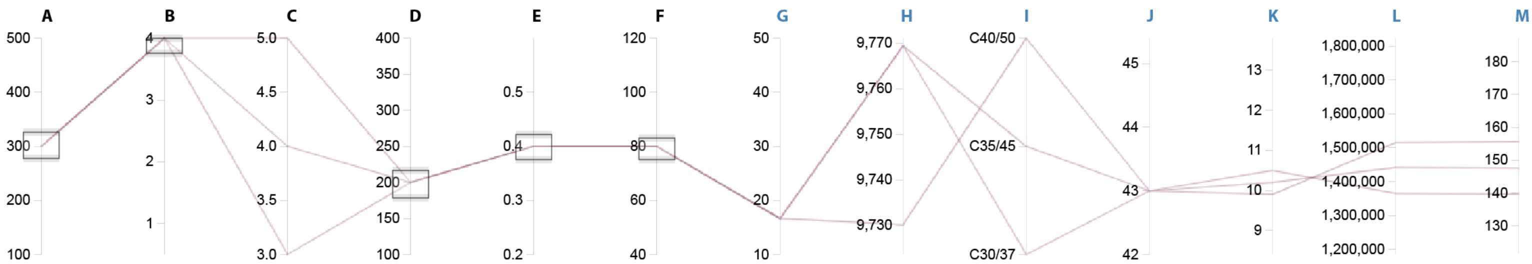

Figure 7.20: DesignExplorer Influence Concrete Strength Class A: Displacement Factors Facade Beams, B: Facade Deadweight [kN/m], C: List item Concrete, D: Beam Width, E: Thickness Core Walls, F: Reinforcement per m^3 concrete, G: Allowed Displacement Facade Beams, H: Floor Area, I: Concrete Strength Class, J: Building Height, K: Core Cross Section Height [m], L: Total kg CO_2, M: kg CO_2/m^2

For the beam width instead of a stepwise examination of results, a different approach is used here by initially selecting the option with the lowest emissions, as shown in Figure 7.21. However, the designer finds the thick beams aesthetically unappealing. Figure 7.22 provides insights into the impact of various beam widths on emissions. The results show that a width of 100 mm has the highest emissions, while 400 mm performs the best. Nevertheless, a 400 mm width is aesthetically undesirable, and although a 100 mm width is preferred aesthetically, its high environmental impact makes it unsuitable. The influence on emissions between widths of 200 and 300 mm is minimal, so a width of 200 mm is selected as the optimal compromise.

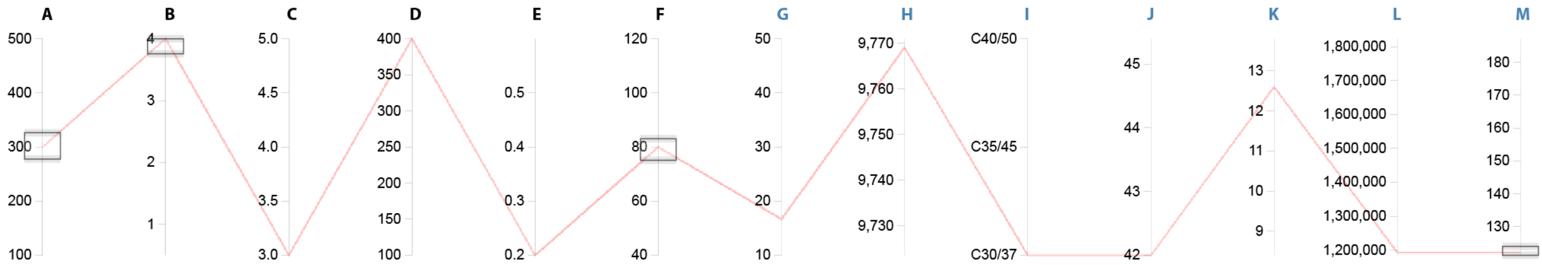

Figure 7.21: DesignExplorer Lowest Embodied Carbon Content Structural Options A: Displacement Factors Facade Beams, B: Facade Deadweight [kN/m], C: List item Concrete, D: Beam Width, E: Thickness Core Walls, F: Reinforcement per m^3 concrete, G: Allowed Displacement Facade Beams, H: Floor Area, I: Concrete Strength Class, J: Building Height, K: Core Cross Section Height [m], L: Total kg CO_2, M: kg CO_2/m^2

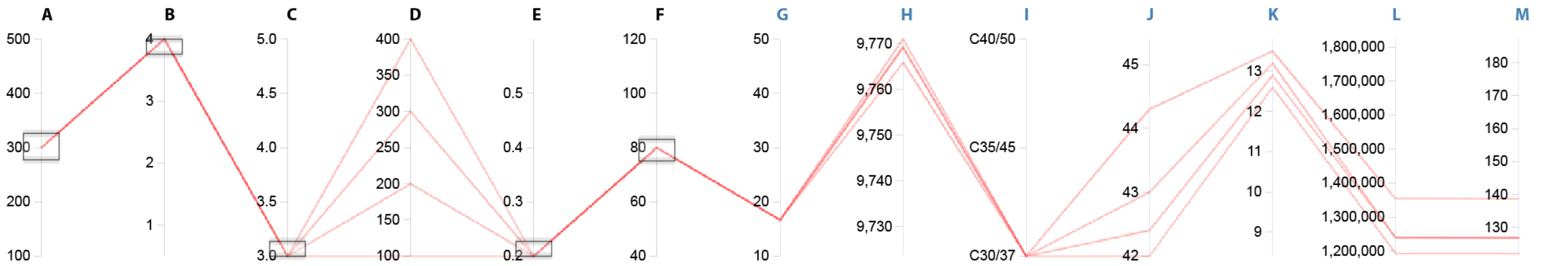

Figure 7.22: DesignExplorer Beam Width Options A: Displacement Factors Facade Beams, B: Facade Deadweight [kN/m], C: List item Concrete, D: Beam Width, E: Thickness Core Walls, F: Reinforcement per m^3 concrete, G: Allowed Displacement Facade Beams, H: Floor Area, I: Concrete Strength Class, J: Building Height, K: Core Cross Section Height [m], L: Total kg CO_2, M: kg CO_2/m^2

7.3.4. Step 4: Output refinement

In the end, an average embodied carbon value is displayed. However, because specific products are not yet chosen, this average represents a range rather than an exact value. This range is calculated by applying a standard deviation of 1 to the average material factor value of each structural element, including close to 70% of potential EPD values.

Results Step 4

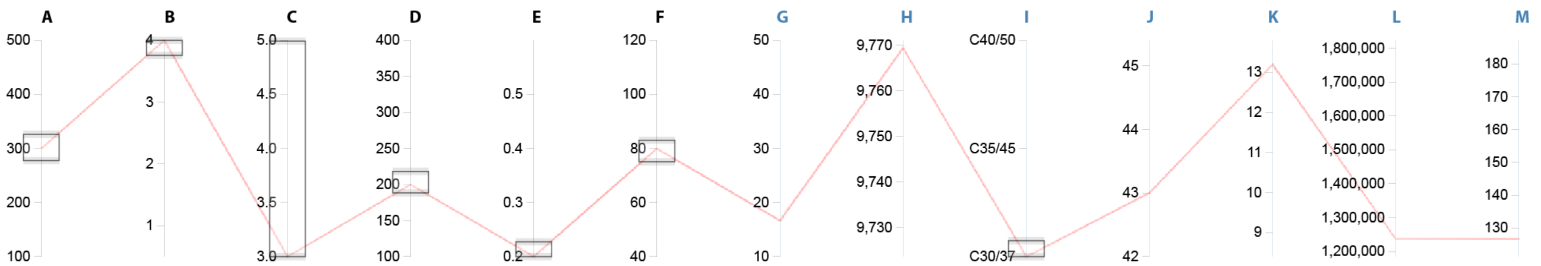

Figure 7.23: DesignExplorer Final Design A: Displacement Factors Facade Beams, B: Facade Deadweight [kN/m], C: List item Concrete, D: Beam Width, E: Thickness Core Walls, F: Reinforcement per m^3 concrete, G: Allowed Displacement Facade Beams, H: Floor Area, I: Concrete Strength Class, J: Building Height, K: Core Cross Section Height [m], L: Total kg CO_2, M: kg CO_2/m^2

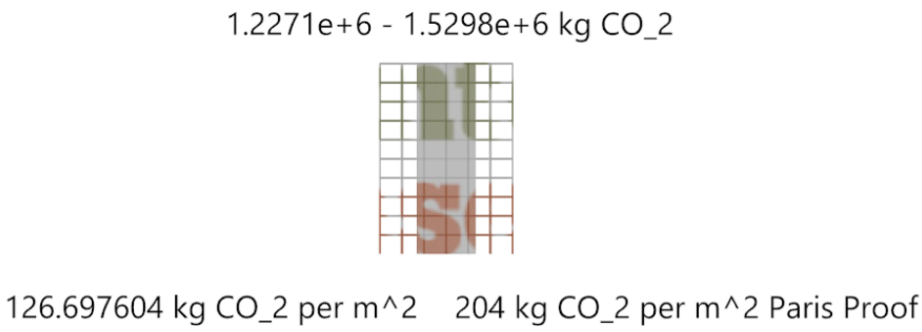

Figure 7.24: DesignExplorer Final Design Range

7.4. Discussion Validation

In this section, the framework's usefulness was validated in two ways. First, it was tested as a research tool to compare and evaluate the influence of different databases. Secondly it was applied to a fictive design case.

For the database evaluation columns and beams were not compared due to the limited dataset available from the NMD. However, their contribution was included in the total embodied carbon percentage. The overall results showed a 93% ratio when comparing NMD data to ICE. The ratio of columns and beams alone was 178%. With more data entries for columns and beams, it is expected that this percentage will converge closer to 100%, reducing the disproportionate influence on the total ratio. Consequently, the total ratio is also expected to decrease. This implies that the 93% embodied carbon content ratio obtained from the NMD compared to ICE is likely an overestimate. A more accurate value would be lower than 93%.

A significant difference in joint results was noted between the two databases. The NMD database contains only a single entry for steel, specifically pre-stressed steel, which has a very high Embodied Carbon content. This leads to a substantially higher contribution from joints when the NMD database is used compared to the ICE database. For this type of building, which uses only a small amount of steel, the inaccuracy in the structural element category of joints has a limited influence on the total Embodied Carbon content. However, for buildings with a larger steel content, this discrepancy would pose a greater issue.

The average contribution of the concrete core was for the NMD 80% of that of the ICE V3.0 database. The NMD integrates reinforcement as a fixed percentage of the mass of concrete used, simplifying the input process but limiting flexibility. In contrast, the ICE V3.0 database allows for separate inputs of concrete and reinforcement steel, providing greater precision and customization in calculating Embodied Carbon Content, but also requiring more insight. The NMD showed that with a assumption of 80 kg reinforcement per m^3 of concrete the average Embodied Carbon contribution from the core with the NMD is 80% compared to that when the ICE database is used. The ICE database uses solely CEMI type of cement while the NMD uses a combination of 25% CEMI and 75% CEMII in most cases. The NMD concrete material factor includes a assumed 10 kg of reinforcement per m^3 of concrete. A eight times as high reinforcement assumption of the framework and the less sustainable cement content assumption of the ICE V3.0 database lead to this 20% higher Embodied Carbon content for the core when the ICE V3.0 database is used compared to the NMD in the framework.

The framework was applied to a fictive design case, showcasing its potential use within the Design Process. In a steering, conversation-like workflow, the design was adjusted, resulting in significant Embodied Carbon reductions. Not all variables were included in a single output, which meant that not all variable combinations were explored and some optimal solutions might have been missed. Including all variables would have required a number of iterations that was not feasible given the current calculation time. Furthermore, such an approach could decrease the framework's readability.

Step 2 of the design case highlighted the framework's ability to determine the extent to which design freedom can be granted without significant impact. In this specific case, the focus was on identifying the point at which the required facade beam height, dictated by increasing maximum deflection demands, started to influence the total building height. This point marked a significant increase in Embodied Carbon. While the additional weight of the facade beams did not substantially affect structural considerations in this scenario, the assumption that the embodied carbon value of heavier facade elements would be comparable to lighter alternatives is not typically observed in practice.

A disconnected material input and unexpected verification results led to changes in the mass of the columns and connections, given them significantly more mass and the columns a higher stiffness than in reality. This impacted the results of the design case of the validation chapter. While the design case remains valid for demonstrating its potential applications, definitive statements regarding correlations between design variables and the precise quantification on the Embodied Carbon content cannot be drawn out of the data presented there.

7.5. Conclusion Validation

The analysis of the NMD and ICE V3.0 databases concluded that the NMD provides significantly lower Embodied Carbon values for CLT and Concrete, while giving a higher value for steel. For this type of structural system, using the NMD instead of the ICE database results in a minimum reduction of 7% in the total Embodied Carbon outcome.

The fictive design case demonstrated that the framework can be effectively integrated into the design process. By determining and quantifying the direct influence of design choices, the framework proved capable of reducing the Embodied Carbon content of a structure without dominating the design process. This enables it to function as a supplementary design tool.

Part V: Evaluation

8

Discussion

In this chapter the decisions made in chapter 4 and 5 and the results from chapter 6 and 7 are assessed and interpreted. A assessment of the validity and usefulness of the framework is given, a limitation overview and a section discussing the added value and possible users of the framework developed in this master thesis.

8.1. Validity and usefulness framework

The framework showed the ability to give quick feedback and insights in a dynamic, rapidly changing design environment. It was used to; 1)Create smooth communication between disciplines by integrating relevant variables from multiple disciplines into one environment. 2)Quantify the influence of design changes. 3)Facilitate a easy design space exploration. 4)Produce results fast.

In Chapter 6, it was concluded that the framework generates reasonable structures and provides valid Embodied Carbon predictions. All combinations of the design variables, along with the default values for the structural variables, have been verified for structural integrity. However, not all combinations of the design variables with non-default structural variables have undergone verification. Although the framework prevents unreasonable combinations, certain outputs may not result in fully valid structures and could require adjustment to the cross section dimensions. This limitation should be considered when analyzing the results.

A particularly strong feature of the framework is the range-based output of the Material Factor Determination tool, which addresses a key limitation of other tools that attempt to provide exact values. By leveraging an average paired with a standard deviation, this tool delivers a more realistic representation of embodied carbon's variability at this design stage. However, this range-based approach is not incorporated into the Structure Generator Tool's outputs while uncertainties are present there as well.

The uncertainties associated with the Structure Generator Tool output differ from those of the Embodied Carbon material factors. While uncertainties in material factors can be addressed with a reasonable range, structural design uncertainties often cannot be quantified in a similarly reliable way. Despite some inherent uncertainties in the design stage, the framework's predictions of the structural design are grounded in logical assumptions. While accounting for uncertainty is essential, excessive inclusion of uncertainty factors can produce a range so broad that it becomes impractical, undermining its usefulness and making it difficult to draw meaningful conclusions. The output of the framework is therefor not deemed less valid by not taking uncertainties of the structure generator output into account.

Inherent to this phase of the design it is important to acknowledge that the contributions of each structural element category may evolve as the design progresses, influenced by refinements in assumptions, dimensioning, or other design adaptations. When making design decisions based on these outputs, it is needed to distinguish between conclusions that are robust and those that may be more susceptible to change and at later design stages when the design becomes more fixed, to refine the used calculated dimensions and provide a more accurate assessment of Embodied Carbon Content. To support this, the framework incorporates a sensitivity analysis feature for the calculated dimensions of the structural elements. This functionality enables a systematic evaluation of the reliability of conclusions for design choices and helps identify areas where significant deviations may still occur. By allowing for the personalization of outputs, the framework can be effectively utilized throughout the entire design process, incorporating potential shifts in the distribution of Embodied Carbon across structural elements into the weighing of design decisions.

As illustrated in the overview of the total script in Figure 5.15 by a abundance of wires connecting different components, determining the embodied carbon content of structural elements and their interrelations is a highly complex process. The developed framework successfully integrates all these relationships into a unified environment, providing fast and clear outputs. This integration untangles processes that would be incomprehensible if performed manually, or at the very least, significantly more time consuming, rendering them impractical for use during the early design stages.

8.2. Limitations

In this section a selection of the most important limitations on specific parts of the framework are discussed.

8.2.1. Software and scripting

The background Grasshopper script lacks a clear organizational structure, making it difficult to interpret for someone who was not involved in its creation. This decreased readability of the script can be partly attributed to the evolving nature of the project, as adjustments to the relationships between various components during development made it difficult to maintain a consistently structured script. While the primary focus was on adapting to changing requirements and functionalities, dedicating more time to organizing and documenting the script during its development would have been beneficial. A more structured and well-documented approach would have ensured that the script remained accessible and understandable, enabling future research and better verifiability of the framework.

Karamba3D was used to verify the results of the Structural Design Configuration component within the Structure Generator Tool. Its full integration with Grasshopper and relatively low computation time were key reasons for its inclusion in the framework. However, Karamba3D has certain limitations. It cannot incorporate a fictive E-modulus to account for cracking, nor can it model non-orthotropic material behavior in columns and beams. These limitations necessitate greater user insight and are a limiting factor for easy analysis of this type of structural system.

8.2.2. NMD integration

The range output of the Embodied Carbon Material Factor Determination tool is most developed for the ICE V3.0 database. For floors and steel sections, all relevant data points from the NMD have been integrated. For the core, a valid representation,comprising 70% of the data points, allows for drawing reasonable conclusions. However, for timber beams and columns, the NMD is underrepresented, with only 20% of the relevant data points integrated due to restrictions in data extraction from the NMD. While this partial inclusion of column- and beam-related EPDs is useful for specific cases, it limits the ability to derive accurate averages and ranges for this structural category. Additionally, minor inaccuracies may still be present in the core data from the NMD.

8.2.3. Foundation

In Chapter 6, it was concluded that the primary failure criteria for the core in most cases is the occurrence of tensile stresses, suggesting that tensile stresses in the foundation are likely to pose a challenge as well. In the Final Element Development and Future Enhancements Assessment section of the Structure Generator Tool, one of the assessments involves analyzing the tensile forces in the foundation using Karamba3D. However, the foundation in the Karamba3D model is simplified as rigid, which led to unrealistically high tensile forces being reported when only small displacements of the core occurred.

The foundation was modeled as a separately evaluable building section due to the higher level of uncertainty associated with its design and a focus of the scope on the superstructure. This decision resulted in a significant difference in the granularity of analysis between the superstructure and substructure. Consequently, including the substructure's mass in the calculations would have diminished the superstructure's results. However, this split approach has limitations, particularly in accounting for the interactions between the superstructure and substructure.

For example, Variant 1 might have a superstructure with a 1,000 kg lower CO_2 emission compared to Variant 2. However, if Variant 1's foundation requires 2,000 kg more CO_2 than Variant 2 due to increased loads or tensile stresses, the current workflow would incorrectly identify Variant 1 as the more sustainable option.

The interactions between the superstructure and foundation are largely determined by the magnitude and direction of the loads transmitted to the foundation. Increased loads result in a heavier foundation, and if tensile forces are present, additional mass is required to counteract these forces, further increasing the foundation's weight. While the superstructure design process partially accounts for this by striving to minimize mass to reduce Embodied Carbon in general, the relationship between material weight and Embodied Carbon is not always linear. Therefor although the framework can give some, although coarse, insights in the foundation. Its integration in the framework is limited.

8.3. Joint Design Granularity

The framework focuses on defining relationships between various design aspects and facilitating automated collaboration and generation of all structural elements. Due to the overall complexity, some designs, though valid, are kept relatively simplified. This is inherent for the design stage and not problematic on itself. All structural elements have been worked out to a level of detail befitting their contribution to the end result. The conclusion of the verification chapter stated that the connection are possibly underdeveloped. Due to the influence of small adjustment to their overall impact. Reasonable connections are parametrically created and while these uphold to Eurocode demands and initial efforts have been made to assign different joint types to appropriate locations, there is significant potential for improvement in accuracy. This is especially relevant given the high material factor of steel and the substantial quantity of joints, both of which contribute significantly to the Embodied Carbon. The framework has already demonstrated that connections have a notable influence on Embodied Carbon. Minor adjustments to the dimensioning method for connection elements have shown significant variations in the Embodied Carbon output, underscoring that the level of detail in joint design is a more critical limiting factor compared to other structural element categories.

8.3.1. Biogenic Carbon Storage Workflow inclusion

The structural system applied in this framework is a timber-concrete hybrid, featuring a concrete core and ground floor, steel connections, timber columns, beams and floors. Due to the high proportion of timber, including biogenic carbon storage significantly reduces the structure's embodied carbon content, often resulting in a net-negative carbon footprint. Which comes down to a value of zero.

Due to the negative material factor of timber elements less material-efficient variants ,timber wise, appear more sustainable, as the biogenic carbon storage rewards higher material usage, which can be argued overstates the sustainability benefits of timber. When biogenic carbon storage is excluded, the framework more effectively supports sustainable design by encouraging material minimization. However, in this case, it may favor variants with lower overall Embodied Carbon content but a higher proportion of emissions from concrete, as illustrated in figure 8.1. This approach may than understate timber's sustainability benefits.

The framework provides detailed output via the DesignExplorer setup, showing contributions from different structural elements and enabling precise identification of emissions from concrete and timber enabling the more sustainable material minimization method with biogenic carbon storage excluded whilst giving insights into its distribution preventing the ratio drawback from figure 8.1. Yet, this output method complicates variant comparison. Biogenic carbon storage is therefor not fully efficiently represented in the design workflow of the framework.

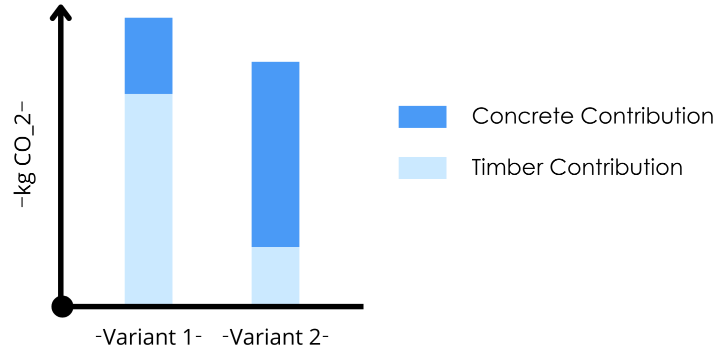

Figure 8.1: Material Ratio Carbon Emissions

8.4. Importance and application

This thesis contributes to integrating Embodied Carbon considerations into early design stages, addressing a major problem in the building industry. This thesis serves as a proof of concept, demonstrating how such a framework can be made, what its limitations are and how it can enhance sustainability in the design processes.

The validation case study illustrates potential applications for architects, designers, and structural engineers. By enabling rapid feedback and collaborative exploration, the framework supports a multidisciplinary collaboration.

The framework can serve as a foundation for conducting research. As illustrated by the database influence investigation of section 7.2. By further developing and expanding the range of materials and design choices the framework has the potential to become a powerful tool for reducing Embodied Carbon in structural design.

9 Conclusion

The aim of this master thesis was to develop a scientifically validated and transparent framework that enables both designers without structural expertise and structural engineers to gain insights into the Embodied Carbon content of a structure during the early design stages. To provide clarity and a quantification on how design choices impact the Embodied Carbon content of the structure, facilitating the integration of Embodied Carbon considerations into the early design process and promoting the creation of more sustainable buildings.

The main research question of this master thesis is;

How can a parametric framework be developed that integrates Embodied Carbon assessment effectively in the early design stages?

To answer this main question four subquestions were created.

What is Embodied Carbon, and how can its levels be accurately measured and evaluated in the context of building design?

This question was addressed in Sections 3.1 through 3.1.7 of the analysis phase. Embodied Carbon refers to the total amount of CO_2 emitted during life cycle modules A1–A5, which contains the product stage (A1–A3) and the construction stage (A4–A5). Given that the majority of Embodied Carbon emissions occur during the product stage, this thesis focuses solely on modules A1–A3. Databases exist that provide environmental impact data for building materials, for UK and the Netherlands respectively the ICE database and NMD. The data entries can be categorized as either generic or product-specific. To obtain product-specific data, a product must undergo a life cycle assessment (LCA) in accordance with NEN-EN 15804+A2, resulting in an Environmental Product Declaration (EPD). Since EPDs are specific to individual products, grouping them by material and presenting their emissions as a range provides a useful estimate for the potential emissions of building elements when detailed design information is not yet available. Criteria like the MPG score and Paris Proof Carbon Budget provide benchmarks to assessing a design. Of these two criteria the Paris Proof Carbon Budget more accurately reflects current societal needs with stricter criteria, the MPG score is considered too easily attainable at the moment to drive meaningful sustainability improvements.

What core functions must the framework include to effectively support Embodied Carbon assessment in early design stages?
This question was answered during sections 3.1.8 , 3.2 and chapter 3.4.4.

To effectively support Embodied Carbon assessment in the early design stages, the framework must facilitate a multidisciplinary workflow that is accessible to all disciplines without requiring extensive specialist,but allowing its application, knowledge. It should provide results quickly and efficiently and present them in a clear visualization not requiring expert software. Stimulating the comparing of variants and with easy sharing among different parties evolved in the building design. The framework must translate basic design characteristics into a structural system and subsequently into Embodied Carbon values while ensuring transparency regarding the assumptions and methods used.

This transparency allows users to make adaptations and refinements that better align the tool with specific design cases or future developments and to be clear in the limitation in the accuracy of the output. Additionally, it should incorporate multiple verification points within the output to ensure that errors in inputs or bugs are identified and addressed. By combining this verification process with transparency in assumptions and methodologies, the framework can effectively reduce the "black box" effect, creating a higher user confidence and promoting clarity in the underlying processes.

Given the inherent uncertainties and complexities of early-stage design, the framework should not aim to deliver precise values but rather acknowledge these uncertainties by providing a range of values. This approach aligns with the flexible and dynamic nature of the design process at this stage, offering more realistic and practical support.

Which Tools need to be integrated into a single framework and how could they be individually build up and relate to one another in a manner that satisfies the requirement to effectively support Embodied Carbon assessment in early design stages?
This question is answered in chapters 4, 5 and 6.

The framework needs three tools; 1)Structure Generator Tool 2)Embodied Carbon Material Factor Determination Tool 3)Iterator and Data Evaluation Tool.

The Structure Generator Tool to translate the design variables into a valid structure and subsequently into a list of material masses. Filling in the possible knowledge gap making the framework usable without structural knowledge whilst allowing further detailed knowledge application in possible variable adjustments.

The Embodied Carbon Material Factor Determination Tool, which translates the mass output from the Structure Generator Tool into kg's CO_2. Including several functions like range creations, selecting of database or specific EPD's. And facilitating the easy switching between including or excluding biogenic carbon storage.

Third, the Iterator and Data Evaluation Tool. Iterating different combinations of inputs and combining them with different combinations of outputs to make the data comprehensible and to analyze certain properties. Exporting them to a DesignExplorer suitable format in which variants are easily compared and results easily shared. Creating a format that is more accessible than the grasshopper script environment.

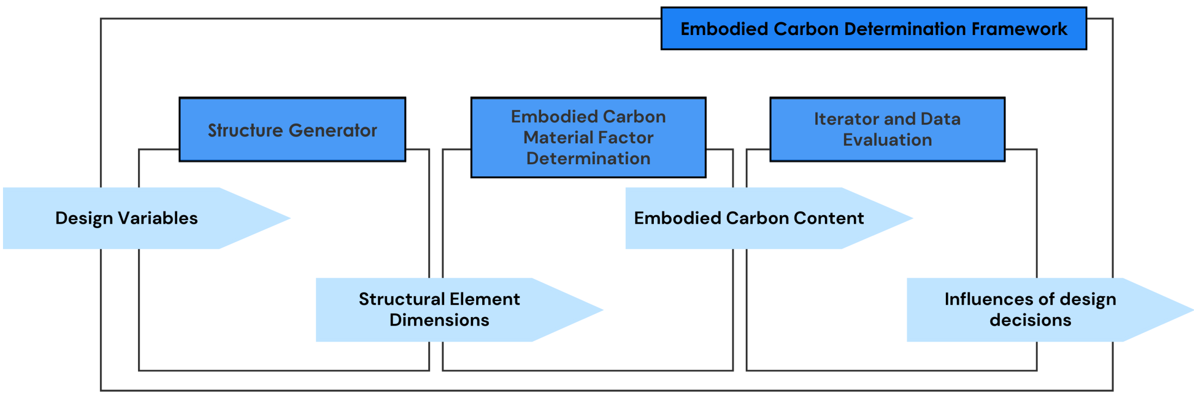

Figure 9.1: Diagram Concept Embodied Carbon Determination Framework

For a more detailed individual build up of the tools, flowcharts along with several grasshopper script and python codes are added in appendix A.

How effectively does the framework integrate embodied carbon assessment into the early design stages, and to what extent can it aid in reducing a building's embodied carbon content?
This question is answered in Chapters 6 and 7.

As demonstrated in Chapter 7, the framework effectively supports the design process by providing quick feedback and insights, enabling designers to quantify the impact of their choices. The tool's ease of use, accessibility and multiple discipline based variable inclusion with default values and automatically generated element supports an effective interdisciplinary workflow which can be used without requiring specialist knowledge, but allowing its application. This allows for a efficient explorations of the design space and the creation of more sustainable designs.

The framework acknowledges uncertainties based in the EPD selection by using a range-based approach, which is more realistic at this design stage compared to exact value predictions. The sensitivity analysis feature helps users understand the reliability of conclusions, distinguishing between robust findings and those more susceptible to changes during later design phases. At the same time it allows the modification of element dimensions allowing a more accurate assessment of Embodied Carbon Content as the design becomes more fixed throughout the process.

While the created structure by the Structure Generator Tool could still be improved and refinements can be made, particularly the connection design considering the superstructure and a more developed substructure design making its integrations in the main output possible. Overall, the output of the structure generator tool results in a reasonably valid estimate of the structure for Embodied Carbon assessment at this stage of the design process and the created variants can be compared to one another and used for analyses of design choices.

The analysis of the NMD and ICE V3.0 databases concluded that, for this type of structural system, using the NMD instead of the ICE database results in a lower Embodied Carbon content. Therefore, when the ICE database is used, the framework is will produce slightly conservative results for the Dutch building industry.

Overall, it is concluded that the developed framework establishes a strong foundation for enhancing Embodied Carbon assessments. Serving as a proof of concept, the framework demonstrates how Embodied Carbon can be effectively integrated into the early design stage and significantly lower the Embodied Carbon content of a design.

Some key-findings are listed below.

Key-findings

- The NMD will give for the type of structural system created in this framework on average a lower Embodied Carbon value than the ICE V3.0 Database.
- The NMD gives very low emissions for CLT compared to the ICE V3.0
- Structural steel is highly underrepresented in the NMD and using it leads to a overestimation of the Embodied Carbon content of the design.
- Assuming a 80 kg steel per m^3 concrete reinforcement ratio. The NMD methodology for reinforcement inclusion in its emission factors and its cement type assumptions lead to a 20% lower Embodied Carbon content than with the ICE V3.0 database.
- Deflection is for most structural elements a governing dimensioning method.
- Designs with a small plot size and big building height have the core as the biggest contributor to Embodied Carbon content. Whilst designs with an equal volume, but a bigger plot size and lower building height have the floors as biggest contributor to the Embodied Carbon content.
- On average throughout the variable range of this framework the floors contribute the most to the Embodied Carbon content of the building followed by the core, beams and columns and joints.
- When applying a concrete sound insulation layer variants with bigger spans can have a lower embodied carbon content than buildings with smaller spans.

To answer the main research question ; *How can a parametric framework be developed that integrates Embodied Carbon assessment effectively in the early design stages?*

A parametric framework that integrates Embodied Carbon assessment effectively in the early design stages can be developed by combining three tools into a transparent, flexible, and multidisciplinary workflow. This framework must address the uncertainties in early design stage design and ensure accessibility for both non-specialist designers and structural engineers and have a clear data generating, visualization and sharing function.

The three tools it must contain are; 1)A Structure Generator Tool to translate basic design variables into a structural system, generating material quantities and addressing the knowledge gap for users without structural expertise. 2)An Embodied Carbon Material Factor Determination Tool to convert material quantities into Embodied Carbon values, allowing for the inclusion of biogenic carbon storage, EPD selection, and material factor ranges. 3)An Iterator and Data Evaluation Tool to automate the exploration of design variations, compare outputs, and provide accessible visualization and sharing of results.

10 Recommendations

Based on the topics discussed in the discussion and conclusion several recommendations are made for the further development of the framework.

10.1. NMD integration

To further enhance the framework's applicability to the Dutch building industry, it is recommended to integrate additional data points from the NMD, particularly for timber materials used in beams and columns. This would allow to better predict the outcome of final MPG calculations and improve the comparability of the NMD with other database. Allowing for a critical review and further development of the database in the future.

10.2. Joint Design

It is recommended to prioritize the refinement of joint design within the superstructure created by the framework, focusing on increasing accuracy in the placement and dimensioning of connection elements. Enhancing the detail level of joint modeling would help minimize uncertainties and better reflect their true impact on Embodied Carbon. Additionally, incorporating more advanced parametric tools for analyzing joints is advised.

10.3. Foundation Integration

The foundation was left mostly outside the scope of this thesis. The results from the coarse way it has been integrated in the framework show that its contribution is however significant. The biggest improvements in accuracy are to be made by including a more developed foundation design. More development in this area is advised. Including the design of the foundation as well as the relation between superstructure and substructure design.

10.4. Using the Framework as a research model

The framework makes simulating Embodied Carbon development throughout the building design process possible. By isolating and evaluating specific variables and outputs, the framework simplifies what is otherwise a highly complex process. It is advised to make use of this capability and use the framework for exploring correlations and conducting background research to support the creation of more sustainable designs.

To enhance the reliability and applicability of the conclusions derived using this framework, it is recommended to perform a sensitivity analysis for the structural dimensions and masses of each structural element category. This analysis helps clarify the specific ratios between structural element category Embodied Carbon emissions for which the conclusions are valid, ensuring that findings are well-substantiated and applicable to a broader range of scenarios.

References

[1] NEN-EN 15804+A2. *NEN-EN 15804+A2*. A2. NEN, Nov. 2019. URL: www.nen.nl.

[2] *3.5.1: Material Properties | Karamba3D v3*. URL: https://manual.karamba3d.com/3-in-depth-component-reference/3.4-material/3.4.1-material-properties.

[3] Saheed O Ajayi et al. "Life cycle environmental performance of material specification: a BIM-enhanced comparative assessment". In: *International Journal of Sustainable Building Technology and Urban Development* 6.1 (2015), pp. 14–24.

[4] Ali Akbarnezhad and Jianzhuang Xiao. "Estimation and minimization of embodied carbon of buildings: A review". In: *Buildings* 7.1 (2017), p. 5.

[5] Zaid Alwan and Paul Jones. "The importance of embodied energy in carbon footprint assessment". In: *Structural survey* 32.1 (2014), pp. 49–60.

[6] *Artikel 2.108. Capaciteit van een vluchtroute*. URL: https://rijksoverheid.bouwbesluit.com/Inhoud/docs/wet/bb2012/hfd2/afd2-12/par2-12-1/art2-108#:~:text=90%20personen%20per%20meter%20vrije%20breedte%20van%20een%20doorgang%2C%20indien,d.&text=e.,breedte%20van%20een%20andere%20doorgang..

[7] Saso Basic et al. "A design integrated parametric tool for real-time Life Cycle Assessment–Bombyx project". In: *IOP conference series: earth and environmental science*. Vol. 323. 1. IOP Publishing. 2019, p. 012112.

[8] Hans Joachim Blaß and Carmen Sandhaas. *Timber engineering-principles for design*. KIT Scientific Publishing, 2017.

[9] Judith Blau. *The Paris Agreement: climate change, solidarity, and human rights*. Springer, 2017.

[10] Cristiane Bueno and Márcio Minto Fabricio. "Comparative analysis between a complete LCA study and results from a BIM-LCA plug-in". In: *Automation in construction* 90 (2018), pp. 188–200.

[11] Roberto Caranta Caranta and Martin Trybus. "The Law of Green and Social Procurement in Europe ()." In: (2010). URL: http://www.cepc.gob.es/publicaciones/revistas/revistaselectronicas?IDR=1&IDN=1265&IDA=35659.

[12] Thomas Connolly et al. "Feasibility study of mass-timber cores for the UBC tall wood building". In: *Buildings* 8.8 (2018), p. 98.

[13] American Chemistry Council and American Chemistry Council. "Whole Building Life Cycle Assessment Tools - American Chemistry Council". In: (June 2023). URL: https://www.americanchemistry.com/better-policy-regulation/plastics/resources/whole-building-life-cycle-assessment-tools.

[14] *DGBC Rekenprotocol Paris Proof Embodied Carbon*. URL: https://www.dgbc.nl/publicaties/de-berekening-achter-paris-proof-materiaalgebonden-emissies-49.

[15] A Dimoudi and C Tompa. "Energy and environmental indicators related to construction of office buildings". In: *Resources, Conservation and Recycling* 53.1-2 (2008), pp. 86–95.

[16] Grace KC Ding. "Life cycle assessment (LCA) of sustainable building materials: an overview". In: *Eco-efficient construction and building materials* (2014), pp. 38–62.

[17] Department for Energy Security and Net Zero. *Greenhouse gas reporting: conversion factors 2021*. Jan. 2022. URL: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021.

[18] Stora Enso. *CLT*. Tech. rep. URL: storaenso.com/woodproducts/clt.

[19] Demi Fang et al. "Reducing embodied carbon in structural systems: A review of early-stage design strategies". In: *Journal of Building Engineering* 76 (2023), p. 107054. ISSN: 2352-7102. DOI: https://doi.org/10.1016/j.jobe.2023.107054. URL: https://www.sciencedirect.com/science/article/pii/S2352710223012330.

[20] Maria Felicita. *Timber High-Rise Buildings: Parametric study of the influence of preliminary design parameters on the wind-induced dynamic response of timber high-rise buildings*. 2021. URL: http://resolver.tudelft.nl/uuid:332ec3a4-7cd7-48be-97ea-cbaa2104ab4c.

[21] O P Gibbons and J J Orr. *How to Calculate Embodied Carbon (Second Edition) - The Institution of Structural Engineers*. Mar. 2022. URL: https://www.istructe.org/resources/guidance/how-to-calculate-embodied-carbon/.

[22] Tarja Häkkinen et al. “Reducing embodied carbon during the design process of buildings”. In: *Journal of Building Engineering* 4 (2015), pp. 1–13.

[23] Geoffrey Hammond et al. “Embodied carbon”. In: *The inventory of carbon and energy (ICE). Version (2.0)* (2011).

[24] Terry Harmelink. *Construction of SAWA Rotterdam has started - Mei architects and planners*. Nov. 2022. URL: https://mei-arch.eu/en/construction-of-sawa-rotterdam-has-started/#:~:text=Construction%20of%20SAWA%20%E2%80%93%20the%20first,residential%20building%20on%20Rotterdam's%20Lloydpier..

[25] Ivan T. Herrmann and Andreas Moltesen. “Does it matter which Life Cycle Assessment (LCA) tool you choose? – a comparative assessment of SimaPro and GaBi”. In: *Journal of Cleaner Production* 86 (2015), pp. 163–169. ISSN: 0959-6526. DOI: https://doi.org/10.1016/j.jclepro.2014.08.004. URL: https://www.sciencedirect.com/science/article/pii/S0959652614008269.

[26] Jelmer Hoogzaad. *Embodied carbon regulation in the Euopean construction sector*. Tech. rep. Dec. 2023. URL: https://shiftingparadigms.nl/projects/eu_embodiedc/.

[27] Lizhen Huang et al. “Carbon emission of global construction sector”. In: *Renewable and Sustainable Energy Reviews* 81 (2018), pp. 1906–1916.

[28] Bahriye Ilhan and Hakan Yaman. “Green building assessment tool (GBAT) for integrated BIM-based design decisions”. In: *Automation in Construction* 70 (2016), pp. 26–37.

[29] AJM Jorissen and AJM Leijten. “Tall timber buildings in the netherlands”. In: *Structural engineering international* 18.2 (2008), pp. 133–136.

[30] Victor Karlberg. *Dynamic analysis of high-rise timber buildings: A factorial experiment*. 2017.

[31] Jens Klitgaard, Poul Henning Kirkegaard, and Michael Mullins. “On the integration of digital design and analysis tools”. In: *WIT Transactions on The Built Environment* 90 (2006).

[32] *Level of Development (LOD) Specification – BIM Forum*. Tech. rep. 2023. URL: https://www.bimforum.org/lod.

[33] *Mass timber Embodied Carbon Factors - The Institution of Structural Engineers*. July 2022. URL: https://www.istructe.org/resources/blog/mass-timber-embodied-carbon-factors/#:~:text=The%20currently%20adopted%20factors%20are,for%20CLT%20and%20glulam%20respectively..

[34] Stichting Nationale Milieudatabase. *Bepalingsmethode Milieuprestatie Bouwwerken*. 2020.

[35] *MilieuPrestatie Gebouwen - MPG*. URL: https://www.rvo.nl/onderwerpen/wetten-en-regels-gebouwen/milieuprestatie-gebouwen-mpg.

[36] Jennifer Monahan and James C Powell. “An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework”. In: *Energy and buildings* 43.1 (2011), pp. 179–188.

[37] Freya Morris, Stephen Allen, and Will Hawkins. “On the embodied carbon of structural timber versus steel, and the influence of LCA methodology”. In: *Building and Environment* 206 (2021), p. 108285.

[38] Kristoffer Negendahl. “Building performance simulation in the early design stage: An introduction to integrated dynamic models”. In: *Automation in construction* 54 (2015), pp. 39–53.

[39] *NEN Connect - ISO 14025*. URL: https://connect.nen.nl/Family/Detail/54315?compId=10037&collectionId=0.

[40] RVO Netherlands Enterprise Agency. *Tendering rules*. URL: https://business.gov.nl/regulation/tendering-rules/#art:basic-rules-for-tendering.

[41] *Netherlands Wood Imports by country region 2021 | WITS Data*. URL: https://wits.worldbank.org/CountryProfile/en/Country/NLD/Year/2021/TradeFlow/Import/Partner/all/Product/44-49_Wood.

[42] Nederlandse norm et al. *Environmental labels and declarations - Type I environmental labelling - Principles and procedures*. EN ISO 14024. CEN, Apr. 2018. URL: https://connect.nen.nl/Family/Detail/45464?compId=10037&collectionId=0.

[43] Nederlands Normalisatie-instituut. *Environmental labels and declarations - Self-declared environmental claims (Type II environmental labelling) (ISO 14021:2016)*. Apr. 2016.

[44] Nederlands Normalisatie-instituut, International Organization for Standardization (ISO), and European Committee for Standardization (CEN). *Environmental labels and declarations - Type III environmental declarations - Principles and procedures*. CEN, May 2010.

[45] Anita Ogrin and Tomaž Hozjan. "Timber-Concrete Composite Structural Elements". In: *Engineered Wood Products for Construction*. Ed. by Meng Gong. Rijeka: IntechOpen, 2021. Chap. 14. DOI: 10.5772/intechopen.99624. URL: https://doi.org/10.5772/intechopen.99624.

[46] Oscar Ortiz, Francesc Castells, and Guido Sonnemann. "Sustainability in the construction industry: A review of recent developments based on LCA". In: *Construction and building materials* 23.1 (2009), pp. 28–39.

[47] Elisabetta Palumbo et al. "How to obtain accurate environmental impacts at early design stages in BIM when using environmental product declaration. A method to support decision-making". In: *Sustainability* 12.17 (2020), p. 6927.

[48] Martin Uhre Pedersen. "Dowel type timber connections". In: *Report BYG. DTU R-039, Technical University of Denmark (DTU)* (2002).

[49] Bruno Peuportier, Stéphane Thiers, and Alain Guiavarch. "Eco-design of buildings using thermal simulation and life cycle assessment". In: *Journal of Cleaner Production* 39 (2013), pp. 73–78.

[50] Erik A Poirier et al. "Design and construction of a 53-meter-tall timber building at the university of British Columbia". In: (2016).

[51] Francesco Pomponi and Alice Moncaster. "Scrutinising embodied carbon in buildings: The next performance gap made manifest". In: *Renewable and Sustainable Energy Reviews* 81 (2018), pp. 2431–2442.

[52] Michael H Ramage et al. "The wood from the trees: The use of timber in construction". In: *Renewable and Sustainable Energy Reviews* 68 (2017), pp. 333–359.

[53] Bryant Ramirez. "Mass Timber Design of a Multi-Story Building". In: (2023).

[54] Saaruja Rathy. "A Case Study on High-Rise Timber Building under Wind Load: Numerical Analysis on Global Serviceability Response of the Different Stabilizing Systems for Mass Timber Buildings". MA thesis. Norwegian University of Life Sciences, 2023.

[55] DG Openbaar Bestuur Democr Rechtsstaat et al. *Voorhang ontwerpbesluit tot wijziging van het Bbl t.b.v. het verder aanscherpen van de grenswaarde voor de milieuprestatie van woonfuncties en kantoorfuncties en het regelen van de grenswaarden voor de milieuprestatie voor andere gebruiksfuncties*. Tech. rep. 2024, pp. 1–4.

[56] Daniel Safarik, Jacob Elbrecht, and William Miranda. "State of tall timber 2022". In: *CTBUH Journal* 2022.I (2022), pp. 22–31.

[57] EC Slooten. "Feasibility study of a wood-concrete hybrid super tall building and optimization of its wind-induced behaviour". In: *Delft University of Technology* (2018).

[58] Ryan E Smith et al. "Mass timber: evaluating construction performance". In: *Architectural Engineering and Design Management* 14.1-2 (2018), pp. 127–138.

[59] M. Spitsbaard et al. *Paris Proof Embodied Carbon Background report*. Tech. rep. 2021. URL: https://www.dgbc.nl/upload/files/Circulariteit/BuildingLife/Background%20report%20paris%20proof%20embodied%20carbon_EN.pdf.

[60] John A Stark. "Parametric Study and Early-Stage Structural Design for Tall Timber Buildings". PhD thesis. Massachusetts Institute of Technology, 2023.

[61] Christian Struck et al. "An investigation of the option space in conceptual building design for advanced building simulation". In: *Advanced Engineering Informatics* 23.4 (2009), pp. 386–395.

[62] Z Toth and J Volt. "Whole-life carbon: challenges and solutions for highly efficient and climate-neutral buildings". In: *Buildings Performance Institute europe (BPIE)* (2021).

[63] Okke Willebrands. *Differential vertical shortening in Timber-Concrete high-rise structures*. 2017. URL: http://resolver.tudelft.nl/uuid:7c3367c2-8700-4704-b913-bf0e957ab5b4.

[64] LETI Embodied Carbon Case Studies Workstream et al. *LETI Embodied carbon case studies*. Tech. rep. 2021.

[65] David Yeoh et al. "State of the art on timber-concrete composite structures: Literature review". In: *Journal of structural engineering* 137.10 (2011), pp. 1085–1095.

[66] Xiaocun Zhang and Fenglai Wang. "Analysis of embodied carbon in the building life cycle considering the temporal perspectives of emissions: A case study in China". In: *Energy and buildings* 155 (2017), pp. 404–413.

[67] Xiaoyue Zhang et al. “Structural Design and Analysis for a Timber-Concrete Hybrid Building”. In: *Frontiers in Materials* 9 (Feb. 2022). DOI: 10.3389/fmats.2022.844398.

Appendix

A

Blueprints Framework

In this

A.1. Grasshopper scripts and python codes

A.1.1. Stairs & Elevator requirements

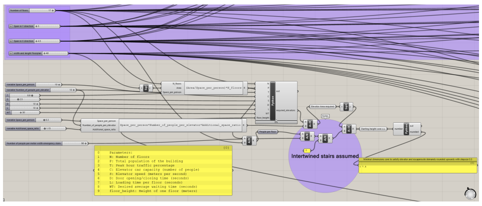

Figure A.1: Script vertical transportation requirements core

```
import math

def calculate_elevators(N, P, T, C, S, D, L, WT, floor_height):
    """
    Calculate the required number of elevators for a building.

    Parameters:
    N (int): Number of floors
    P (int): Total population of the building
    T (float): Peak hour traffic percentage (e.g., 0.10 for 10%)
    C (int): Elevator car capacity (number of people)
    S (float): Elevator speed (meters per second)
    D (float): Door opening/closing time (seconds)
    L (float): Loading time per floor (seconds)
    WT (float): Desired average waiting time (seconds)
    floor_height (float): Height of one floor (meters)

    Returns:
    int: Number of elevators required
    """
    # Calculate Peak Hour Traffic
    PHT = P * T

    # Average travel height (assuming evenly distributed floors)
    H = (N - 1) / 2 * floor_height

    # Calculate Round-Trip Time (RT)
    RT = (2 * H / S) + (D * (H/floor_height)) + (L * (H/floor_height))

    # Calculate Handling Capacity (HC)
    HC = (3600 / RT) * C
```

```

    # Calculate the initial number of elevators required
    E = PHT / HC

    # Always round up to ensure sufficient capacity
    E = math.ceil(E)

    # Adjust the number of elevators based on desired waiting time
    while True:
        average_interval = RT / E
        if average_interval <= WT:
            break
        E += 1

    return int(E)

required_elevators = calculate_elevators(N, P, T, C, S, D, L, WT, floor_height)
print( required_elevators)
# Output the result
```

A.1.2. Windload

```
def get_windload_value(gebied, height, table):
    # Dictionary to map pink values to their corresponding keys in the table
    pink_values = {
        "Area␣I:␣Coastal": "wind_load_Gebied1_Kust",
        "Area␣I:␣Rural": "wind_load_Gebied1_Onbebouwd",
        "Area␣I:␣Urban": "wind_load_Gebied1_Bebouwd",
        "Area␣II:␣Coastal": "wind_load_Gebied2_Kust",
        "Area␣II:␣Rural": "wind_load_Gebied2_Onbebouwd",
        "Area␣II:␣Urban": "wind_load_Gebied2_Bebouwd",
        "Area␣III:␣Rural": "wind_load_Gebied3_Onbebouwd",
        "Area␣III:␣Urban": "wind_load_Gebied3_Bebouwd"
    }

    # Check if the provided gebied exists in the pink_values dictionary
    if gebied in pink_values:
        # Retrieve the corresponding key from the pink_values dictionary
        key = pink_values[gebied]
        # Check if the provided height exists in the table
        if height in table:
            # Retrieve the value corresponding to the key and height
            if key in table[height]:
                return table[height][key]
    return value  # Return None if the provided gebied or height is not found

# Full table
#Imporant note: for the wind values the table only goes until 25 m. For the height 20, 15 and
     10 the same windspeeds have been copied. These are not from the official table and give
     a conservative result.
table = {
    "15": {"wind_load_Gebied1_Kust": 1.88, "wind_load_Gebied1_Onbebouwd": 1.36, "
        wind_load_Gebied1_Bebouwd": 1.16,
           "wind_load_Gebied2_Kust": 1.57, "wind_load_Gebied2_Onbebouwd": 1.14, "
               wind_load_Gebied2_Bebouwd": 0.97,
           "wind_load_Gebied3_Onbebouwd": 0.94, "wind_load_Gebied3_Bebouwd": 0.80},
    "20": {"wind_load_Gebied1_Kust": 1.88, "wind_load_Gebied1_Onbebouwd": 1.36, "
        wind_load_Gebied1_Bebouwd": 1.16,
           "wind_load_Gebied2_Kust": 1.57, "wind_load_Gebied2_Onbebouwd": 1.14, "
               wind_load_Gebied2_Bebouwd": 0.97,
           "wind_load_Gebied3_Onbebouwd": 0.94, "wind_load_Gebied3_Bebouwd": 0.80},
    "25": {"wind_load_Gebied1_Kust": 1.88, "wind_load_Gebied1_Onbebouwd": 1.36, "
        wind_load_Gebied1_Bebouwd": 1.16,
           "wind_load_Gebied2_Kust": 1.57, "wind_load_Gebied2_Onbebouwd": 1.14, "
               wind_load_Gebied2_Bebouwd": 0.97,
           "wind_load_Gebied3_Onbebouwd": 0.94, "wind_load_Gebied3_Bebouwd": 0.80},
    "30": {"wind_load_Gebied1_Kust": 1.94, "wind_load_Gebied1_Onbebouwd": 1.43, "
        wind_load_Gebied1_Bebouwd": 1.23,
           "wind_load_Gebied2_Kust": 1.63, "wind_load_Gebied2_Onbebouwd": 1.20, "
               wind_load_Gebied2_Bebouwd": 1.03,
           "wind_load_Gebied3_Onbebouwd": 0.99, "wind_load_Gebied3_Bebouwd": 0.85},
```

```
    "35": {"wind_load_Gebied1_Kust": 2.00, "wind_load_Gebied1_Onbebouwd": 1.50, "wind_load_Gebied1_Bebouwd": 1.30,
           "wind_load_Gebied2_Kust": 1.67, "wind_load_Gebied2_Onbebouwd": 1.25, "wind_load_Gebied2_Bebouwd": 1.09,
           "wind_load_Gebied3_Onbebouwd": 1.03, "wind_load_Gebied3_Bebouwd": 0.89},
    "40": {"wind_load_Gebied1_Kust": 2.04, "wind_load_Gebied1_Onbebouwd": 1.55, "wind_load_Gebied1_Bebouwd": 1.35,
           "wind_load_Gebied2_Kust": 1.71, "wind_load_Gebied2_Onbebouwd": 1.30, "wind_load_Gebied2_Bebouwd": 1.13,
           "wind_load_Gebied3_Onbebouwd": 1.07, "wind_load_Gebied3_Bebouwd": 0.93},
    "45": {"wind_load_Gebied1_Kust": 2.09, "wind_load_Gebied1_Onbebouwd": 1.60, "wind_load_Gebied1_Bebouwd": 1.40,
           "wind_load_Gebied2_Kust": 1.75, "wind_load_Gebied2_Onbebouwd": 1.34, "wind_load_Gebied2_Bebouwd": 1.17,
           "wind_load_Gebied3_Onbebouwd": 1.11, "wind_load_Gebied3_Bebouwd": 0.97},
    "50": {"wind_load_Gebied1_Kust": 2.12, "wind_load_Gebied1_Onbebouwd": 1.65, "wind_load_Gebied1_Bebouwd": 1.45,
           "wind_load_Gebied2_Kust": 1.78, "wind_load_Gebied2_Onbebouwd": 1.38, "wind_load_Gebied2_Bebouwd": 1.21,
           "wind_load_Gebied3_Onbebouwd": 1.14, "wind_load_Gebied3_Bebouwd": 1.00},
    "55": {"wind_load_Gebied1_Kust": 2.16, "wind_load_Gebied1_Onbebouwd": 1.69, "wind_load_Gebied1_Bebouwd": 1.49,
           "wind_load_Gebied2_Kust": 1.81, "wind_load_Gebied2_Onbebouwd": 1.42, "wind_load_Gebied2_Bebouwd": 1.25,
           "wind_load_Gebied3_Onbebouwd": 1.17, "wind_load_Gebied3_Bebouwd": 1.03},
    "60": {"wind_load_Gebied1_Kust": 2.19, "wind_load_Gebied1_Onbebouwd": 1.73, "wind_load_Gebied1_Bebouwd": 1.53,
           "wind_load_Gebied2_Kust": 1.83, "wind_load_Gebied2_Onbebouwd": 1.45, "wind_load_Gebied2_Bebouwd": 1.28,
           "wind_load_Gebied3_Onbebouwd": 1.19, "wind_load_Gebied3_Bebouwd": 1.05},
    "65": {"wind_load_Gebied1_Kust": 2.22, "wind_load_Gebied1_Onbebouwd": 1.76, "wind_load_Gebied1_Bebouwd": 1.57,
           "wind_load_Gebied2_Kust": 1.86, "wind_load_Gebied2_Onbebouwd": 1.48, "wind_load_Gebied2_Bebouwd": 1.31,
           "wind_load_Gebied3_Onbebouwd": 1.22, "wind_load_Gebied3_Bebouwd": 1.08},
    "70": {"wind_load_Gebied1_Kust": 2.25, "wind_load_Gebied1_Onbebouwd": 1.80, "wind_load_Gebied1_Bebouwd": 1.60,
           "wind_load_Gebied2_Kust": 1.88, "wind_load_Gebied2_Onbebouwd": 1.50, "wind_load_Gebied2_Bebouwd": 1.34,
           "wind_load_Gebied3_Onbebouwd": 1.24, "wind_load_Gebied3_Bebouwd": 1.10},
    "75": {"wind_load_Gebied1_Kust": 2.27, "wind_load_Gebied1_Onbebouwd": 1.83, "wind_load_Gebied1_Bebouwd": 1.63,
           "wind_load_Gebied2_Kust": 1.90, "wind_load_Gebied2_Onbebouwd": 1.53, "wind_load_Gebied2_Bebouwd": 1.37,
           "wind_load_Gebied3_Onbebouwd": 1.26, "wind_load_Gebied3_Bebouwd": 1.13},
    "80": {"wind_load_Gebied1_Kust": 2.30, "wind_load_Gebied1_Onbebouwd": 1.86, "wind_load_Gebied1_Bebouwd": 1.66,
           "wind_load_Gebied2_Kust": 1.92, "wind_load_Gebied2_Onbebouwd": 1.55, "wind_load_Gebied2_Bebouwd": 1.39,
           "wind_load_Gebied3_Onbebouwd": 1.28, "wind_load_Gebied3_Bebouwd": 1.15},
    "85": {"wind_load_Gebied1_Kust": 2.32, "wind_load_Gebied1_Onbebouwd": 1.88, "wind_load_Gebied1_Bebouwd": 1.69,
           "wind_load_Gebied2_Kust": 1.94, "wind_load_Gebied2_Onbebouwd": 1.58, "wind_load_Gebied2_Bebouwd": 1.42,
           "wind_load_Gebied3_Onbebouwd": 1.30, "wind_load_Gebied3_Bebouwd": 1.17},
    "90": {"wind_load_Gebied1_Kust": 2.34, "wind_load_Gebied1_Onbebouwd": 1.91, "wind_load_Gebied1_Bebouwd": 1.72,
           "wind_load_Gebied2_Kust": 1.96, "wind_load_Gebied2_Onbebouwd": 1.60, "wind_load_Gebied2_Bebouwd": 1.44,
           "wind_load_Gebied3_Onbebouwd": 1.32, "wind_load_Gebied3_Bebouwd": 1.18},
    "95": {"wind_load_Gebied1_Kust": 2.36, "wind_load_Gebied1_Onbebouwd": 1.93, "wind_load_Gebied1_Bebouwd": 1.74,
           "wind_load_Gebied2_Kust": 1.98, "wind_load_Gebied2_Onbebouwd": 1.62, "wind_load_Gebied2_Bebouwd": 1.46,
           "wind_load_Gebied3_Onbebouwd": 1.33, "wind_load_Gebied3_Bebouwd": 1.20},
    "100": {"wind_load_Gebied1_Kust": 2.38, "wind_load_Gebied1_Onbebouwd": 1.96, "wind_load_Gebied1_Bebouwd": 1.77,
            "wind_load_Gebied2_Kust": 1.99, "wind_load_Gebied2_Onbebouwd": 1.64, "wind_load_Gebied2_Bebouwd": 1.48,
            "wind_load_Gebied3_Onbebouwd": 1.35, "wind_load_Gebied3_Bebouwd": 1.22},
    "110": {"wind_load_Gebied1_Kust": 2.42, "wind_load_Gebied1_Onbebouwd": 2.00, "
```

```python
        wind_load_Gebied1_Bebouwd": 1.81,
            "wind_load_Gebied2_Kust": 2.03, "wind_load_Gebied2_Onbebouwd": 1.68, "wind_load_Gebied2_Bebouwd": 1.52,
            "wind_load_Gebied3_Onbebouwd": 1.38, "wind_load_Gebied3_Bebouwd": 1.25},
    "120": {"wind_load_Gebied1_Kust": 2.45, "wind_load_Gebied1_Onbebouwd": 2.04, "wind_load_Gebied1_Bebouwd": 1.85,
            "wind_load_Gebied2_Kust": 2.05, "wind_load_Gebied2_Onbebouwd": 1.71, "wind_load_Gebied2_Bebouwd": 1.55,
            "wind_load_Gebied3_Onbebouwd": 1.41, "wind_load_Gebied3_Bebouwd": 1.28},
    "130": {"wind_load_Gebied1_Kust": 2.48, "wind_load_Gebied1_Onbebouwd": 2.08, "wind_load_Gebied1_Bebouwd": 1.89,
            "wind_load_Gebied2_Kust": 2.08, "wind_load_Gebied2_Onbebouwd": 1.74, "wind_load_Gebied2_Bebouwd": 1.59,
            "wind_load_Gebied3_Onbebouwd": 1.44, "wind_load_Gebied3_Bebouwd": 1.31},
    "140": {"wind_load_Gebied1_Kust": 2.51, "wind_load_Gebied1_Onbebouwd": 2.12, "wind_load_Gebied1_Bebouwd": 1.93,
            "wind_load_Gebied2_Kust": 2.10, "wind_load_Gebied2_Onbebouwd": 1.77, "wind_load_Gebied2_Bebouwd": 1.62,
            "wind_load_Gebied3_Onbebouwd": 1.46, "wind_load_Gebied3_Bebouwd": 1.33},
    "150": {"wind_load_Gebied1_Kust": 2.54, "wind_load_Gebied1_Onbebouwd": 2.15, "wind_load_Gebied1_Bebouwd": 1.96,
            "wind_load_Gebied2_Kust": 2.13, "wind_load_Gebied2_Onbebouwd": 1.80, "wind_load_Gebied2_Bebouwd": 1.65,
            "wind_load_Gebied3_Onbebouwd": 1.48, "wind_load_Gebied3_Bebouwd": 1.35},
    "160": {"wind_load_Gebied1_Kust": 2.56, "wind_load_Gebied1_Onbebouwd": 2.18, "wind_load_Gebied1_Bebouwd": 2.00,
            "wind_load_Gebied2_Kust": 2.15, "wind_load_Gebied2_Onbebouwd": 1.83, "wind_load_Gebied2_Bebouwd": 1.67,
            "wind_load_Gebied3_Onbebouwd": 1.50, "wind_load_Gebied3_Bebouwd": 1.38},
    "170": {"wind_load_Gebied1_Kust": 2.59, "wind_load_Gebied1_Onbebouwd": 2.21, "wind_load_Gebied1_Bebouwd": 2.03,
            "wind_load_Gebied2_Kust": 2.17, "wind_load_Gebied2_Onbebouwd": 1.85, "wind_load_Gebied2_Bebouwd": 1.70,
            "wind_load_Gebied3_Onbebouwd": 1.52, "wind_load_Gebied3_Bebouwd": 1.40},
    "180": {"wind_load_Gebied1_Kust": 2.61, "wind_load_Gebied1_Onbebouwd": 2.24, "wind_load_Gebied1_Bebouwd": 2.06,
            "wind_load_Gebied2_Kust": 2.19, "wind_load_Gebied2_Onbebouwd": 1.88, "wind_load_Gebied2_Bebouwd": 1.72,
            "wind_load_Gebied3_Onbebouwd": 1.54, "wind_load_Gebied3_Bebouwd": 1.42},
    "190": {"wind_load_Gebied1_Kust": 2.63, "wind_load_Gebied1_Onbebouwd": 2.27, "wind_load_Gebied1_Bebouwd": 2.08,
            "wind_load_Gebied2_Kust": 2.20, "wind_load_Gebied2_Onbebouwd": 1.90, "wind_load_Gebied2_Bebouwd": 1.75,
            "wind_load_Gebied3_Onbebouwd": 1.56, "wind_load_Gebied3_Bebouwd": 1.44},
    "200": {"wind_load_Gebied1_Kust": 2.65, "wind_load_Gebied1_Onbebouwd": 2.29, "wind_load_Gebied1_Bebouwd": 2.11,
            "wind_load_Gebied2_Kust": 2.22, "wind_load_Gebied2_Onbebouwd": 1.92, "wind_load_Gebied2_Bebouwd": 1.77,
            "wind_load_Gebied3_Onbebouwd": 1.58, "wind_load_Gebied3_Bebouwd": 1.46},
}

value = get_windload_value(gebied, height, table)
```

A.1.3. Beams

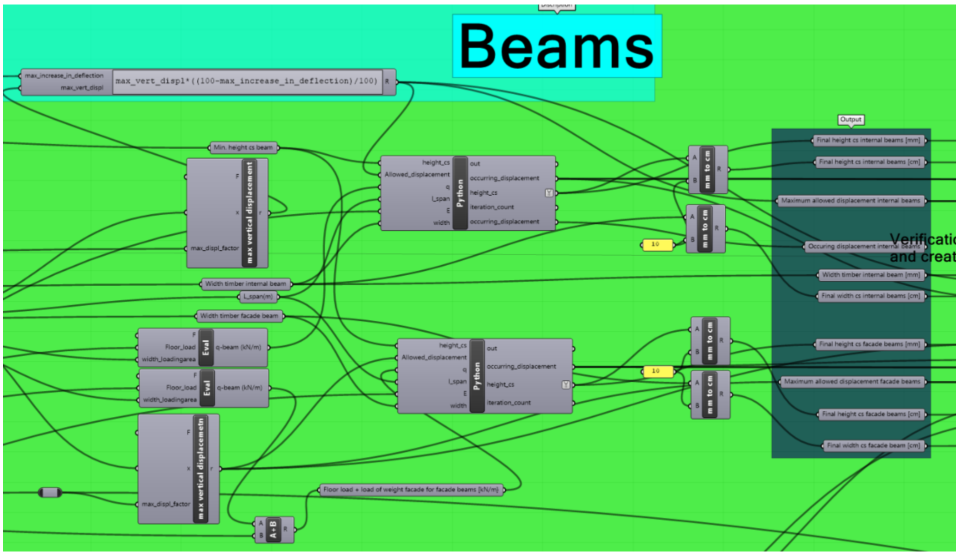

Figure A.2: Grasshopper Component Cross Section Size Determination Beams

```python
def check_deflection(height_cs, Allowed_displacement, E, l_span, q, width):
    # Calculate initial I
    I = (1/12) * width * (height_cs ** 3)
    iteration_count = 0
    # Deflection with I
    occurring_displacement = (5 * q * (l_span * 1000) ** 4) / (384 * E * I)

    # Loop that increases height_cs until the displacement occuring is lower than the maximum allowed
    while occurring_displacement >= Allowed_displacement:
        height_cs += 10
        I = (1/12) * width * (height_cs ** 3)
        occurring_displacement = (5 * q * (l_span * 1000) ** 4) / (384 * E * I)
        iteration_count += 1

    return occurring_displacement, height_cs, iteration_count

# Assign the function's output to the output variables
occurring_displacement, height_cs, iteration_count = check_deflection(height_cs, Allowed_displacement, E, l_span, q, width)
```

A.1.4. Axial deformation columns elongated column method

A.1.5. Axial deformation columns dimensioning

```python
import math

def check_axial_strain(height_cs, Axial_load, E, Max_axial_deformation):
    # Calculate initial A_cs
    A_cs = height_cs**2
    iteration_count = 0
    # Deflection with A_cs
    Axial_strain = 1000*Axial_load / (E * A_cs)
    # Loop to increment height_cs until the displacement exceeds the threshold
    while Axial_strain >= Max_axial_deformation:
        if height_cs >= 2000:
            break
        height_cs += 1
        A_cs = height_cs**2
        Axial_strain = 1000*Axial_load / (E * A_cs)
        iteration_count += 1

    return Axial_strain, height_cs, iteration_count

```

```python

# Assign the function's output to the output variables
Axial_strain, height_cs, iteration_count = check_axial_strain(height_cs, Axial_load, E,
    Max_axial_deformation)

print(Axial_strain)
```

A.1.6. Axial resistance columns dimensioning

```python
import math
def check_axial_compr_stress(height_cs, Axial_load, Strength_class):
    # Calculate initial I
    A_cs = height_cs**2
    iteration_count = 0
    # Deflection with I
    Axial_resistance = Strength_class*A_cs
    # Loop to increment height_cs until the displacement exceeds the threshold
    while Axial_resistance <= Axial_load:
        height_cs += 1
        A_cs = height_cs**2
        Axial_resistance = Strength_class*A_cs
        iteration_count += 1

    return Axial_resistance, height_cs, iteration_count

# Assign the function's output to the output variables
Axial_resistance, height_cs, iteration_count = check_axial_compr_stress(height_cs, Axial_load
    , Strength_class)
```

A.1.7. Buckling resistance columns dimensioning

```python
import math
def check_buckling(height_cs, Axial_load, E, H_column):
    # Calculate initial I
    I = (1/12) * height_cs * (height_cs ** 3)
    iteration_count = 0
    # Deflection with I
    buckling_resistance = (((math.pi**2)*E*I)/((H_column*1000)**2))/1000

    # Loop to increment height_cs until the displacement exceeds the threshold
    while buckling_resistance <= Axial_load:
        height_cs += 5
        I = (1/12) * height_cs * (height_cs ** 3)
        buckling_resistance = (((math.pi**2)*E*I)/((H_column*1000)**2))/1000
        iteration_count += 1
    return buckling_resistance, height_cs, iteration_count

# Assign the function's output to the output variables
buckling_resistance, height_cs, iteration_count = check_buckling(height_cs, Axial_load, E,
    H_column)

def UC_buckling(Axial_load,buckling_resistance):
    UC_buckling=Axial_load/buckling_resistance
    return UC_buckling

UC_buckling=UC_buckling(Axial_load,buckling_resistance)
```

A.1.8. Connection dimensioning

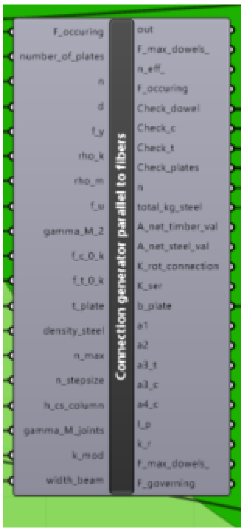

Figure A.4: Grasshopper Component Connection Generator Parallel to fiber

Python code connection orthogonal to fibers dimensioning

```
import rhinoscriptsyntax as rs
import math


t_1 = t_plate
t_2 = t_1  # All plates have the same thickness

def f_u_d(f_u,gamma_M_steel):
    f_u_d=f_u/gamma_M_steel
    return f_u_d

f_u_d=f_u_d(f_u,gamma_M_2)

def a1_parallel_to_grain(alpha, d):
    # Assuming alpha is in degrees and needs to be converted to radians
    alpha = math.radians(alpha)
    a1 = (4 + abs(math.cos(alpha))) * d
    return a1

a1 = a1_parallel_to_grain(alpha, d)
print('a1=',a1)

def a2(alpha,d):
    alpha = math.radians(alpha)
    a2=(3 + abs(math.sin(alpha))) * d
    return a2

a2 = a2(alpha,d)
print('a2=',a2)

def a3_t(alpha, d):
    # Assuming alpha is in degrees and needs to be converted to radians
    alpha = math.radians(alpha)
    a3_t = (7 + (5 * abs(math.cos(alpha)))) * d
    return a3_t

a3_t = a3_t(alpha, d)
print('a3_t=',a3_t)

def a3_c(d):
    a3_c= 7*d
    return a3_c

```

```
a3_c = a3_c(d)
print('a3_c=',a3_c)

def a4_c(d):
    a4_c= 3*d
    return a4_c

a4_c = a4_c(d)
print('a4_c=',a4_c)

def calc_b_plate(n, a2, a3_c,a3_t):
    b_plate=(n - 1) * a2 + a3_c+ a3_t
    return b_plate

b_plate = calc_b_plate(n, a2, a3_c,a3_t)
print b_plate

def calc_h_plate(n,a1,a4_c):
    h_plate=(n-1)*a1+2*a4_c
    return h_plate

h_plate= calc_h_plate(n,a1,a4_c)
print h_plate

def calc_f_h_d(d, rho_k,gamma_M_joints):
    f_h=0.082 * (1 - 0.01 * d) * rho_k/gamma_M_joints
    return f_h
   #d= diameter of dowel

f_h = calc_f_h_d(d, rho_k,gamma_M_joints)
print(f_h)

def calc_M_y_k(f_u_d, d):
    return 0.3 * f_u_d * d**2.6
    #d= diameter of dowel

M_y = calc_M_y_k(f_u_d, d)
print(M_y)

def calc_F_y(t_1, t_2, d, f_h, M_y):
    ModeI=0.25 * (2*t_1 + t_2)*d*f_h
    ModeIIa=(-0.5 * t_1 + 0.25 * t_2 + (0.5 * (t_1**2) + (M_y / (d * f_h)))**0.5) * d * f_h
    ModeIIb=(4 * M_y * d * f_h)**0.5
    ModeIIIa=(0.5 * t_1 + 0.5 * (t_1**2 + 2 * M_y / (d * f_h))**0.5) * d * f_h
    ModeIIIb=((M_y / (d * f_h))**0.5 + 0.5 * t_1) * d * f_h
    ModeIIIc=((M_y / (d * f_h))**0.5 + 0.25 * t_2) * d * f_h
    ModeIIId=(-0.5 * t_1 + (0.5 * t_1**2 + M_y / (d * f_h))**0.5 + (M_y / (d * f_h))**0.5) *
        d * f_h
    F_governing = min(ModeI,ModeIIa,ModeIIb,ModeIIIa,ModeIIIb,ModeIIIc,ModeIIId)
    return F_governing,ModeI,ModeIIa,ModeIIb,ModeIIIa,ModeIIIb,ModeIIIc,ModeIIId

F_governing,ModeI,ModeIIa,ModeIIb,ModeIIIa,ModeIIIb,ModeIIIc,ModeIIId = calc_F_y(t_1, t_2, d,
     f_h, M_y)

print(F_governing,ModeI,ModeIIa,ModeIIb,ModeIIIa,ModeIIIb,ModeIIIc,ModeIIId)

def calc_n_eff(n, a1, d):
    return min(n, n**0.9 * (a1 / (13 * d))**0.25)
    #d= diameter of dowel

n_eff_ = calc_n_eff(n, a1, d)

def calc_A_net_timber(b_plate, n, d, width_beam):
    return 0.5*d*math.pi*(n**2)*width_beam

A_net_timber_val = calc_A_net_timber(b_plate, n, d,width_beam)

def calc_A_net_steel(b_plate, n, d,t_plate):
    return 0.5*d*math.pi*(n**2)*t_plate*2

A_net_steel_val = calc_A_net_steel(b_plate, n, d, t_plate)
```

```
def calc_F_max_dowels(n_eff, F_governing, n):
    return 4* n_eff * F_governing * n
F_max_dowels_ = calc_F_max_dowels(n_eff_, F_governing, n)

def calc_F_max_c(f_c_90_k, A_net_timber, gamma_M_joints):
    F_max_c_k= f_c_90_k * A_net_timber
    F_max_c_= k_mod*F_max_c_k/gamma_M_joints
    return F_max_c_

F_max_c_ = calc_F_max_c(f_c_90_k, A_net_timber_val,gamma_M_joints)

def calc_F_max_t(f_t_90_k, A_net_timber, gamma_M_joints):
    F_max_t_k= f_t_90_k * A_net_timber
    F_max_t_= k_mod*F_max_t_k/gamma_M_joints
    return F_max_t_

F_max_t_ = calc_F_max_t(f_t_90_k, A_net_timber_val,gamma_M_joints)

def calc_F_max_plates(f_y, t_plate, b_plate, f_u, A_net_steel, gamma_M_2):
    return min(f_y * t_plate * b_plate, (0.9 * f_u * A_net_steel) / gamma_M_2)

F_max_plates_ = calc_F_max_plates(f_y, t_plate, b_plate, f_u_d, A_net_steel_val, gamma_M_2)

def check_capacity(F_occuring, F_max_dowels_, F_max_c_, F_max_t_, F_max_plates_, n,
    n_stepsize):
    while F_max_dowels_ < F_occuring or F_max_c_ < F_occuring or F_max_t_ < F_occuring or
        F_max_plates_ < F_occuring:
        if n >= n_max:
            break
        n += n_stepsize

        # Update values that depend on n
        b_plate = calc_b_plate(n, a2, a3_c,a3_t)
        n_eff_ = calc_n_eff(n, a1, d)
        A_net_timber_val = calc_A_net_timber(b_plate, n, d,width_beam)
        A_net_steel_val = calc_A_net_steel(b_plate, n, d,t_plate)

        F_max_dowels_ = calc_F_max_dowels(n_eff_, F_governing, n)
        F_max_c_ = calc_F_max_c(f_c_90_k, A_net_timber_val,gamma_M_joints)
        F_max_t_ = calc_F_max_t(f_t_90_k, A_net_timber_val, gamma_M_joints)
        F_max_plates_ = calc_F_max_plates(f_y, t_plate, b_plate, f_u_d, A_net_steel_val,
            gamma_M_2)

    Check_dowel = F_occuring / F_max_dowels_
    Check_c = F_occuring / F_max_c_
    Check_t = F_occuring / F_max_t_
    Check_plates = F_occuring / F_max_plates_
    return Check_dowel, Check_c, Check_t, Check_plates, n

Check_dowel, Check_c, Check_t, Check_plates, n= check_capacity(F_occuring, F_max_dowels_,
    F_max_c_, F_max_t_, F_max_plates_, n, n_stepsize)

#Makes sure values are not only used in new calculations but displayed out of code block
n_eff_ = calc_n_eff(n, a1, d)
F_max_dowels_ = calc_F_max_dowels(n_eff_, F_governing, n)
b_plate = calc_b_plate(n, a2, a3_c,a3_t)
A_net_timber_val = calc_A_net_timber(b_plate, n, d,width_beam)
A_net_steel_val = calc_A_net_steel(b_plate, n, d,t_plate)

print("Check_dowel:", Check_dowel)
print("Check_c:", Check_c)
print("Check_t:", Check_t)
print("Check_plates:", Check_plates)
print("Final n:", n)
print("A_net_timber:", A_net_timber_val)
print("A_net_steel:", A_net_steel_val)



def calculate_K_ser(rho_m, d):
```

```
    K_ser = 2*((rho_m*10**9) ** 1.5 * (d*10**-3) / 23) #The times two is added due to the steel.
    return K_ser

K_ser=calculate_K_ser(rho_m, d)

print(K_ser)

def calculate_distances_squared(n, a1):
    # Calculate center index (assuming the center is exactly at the midpoint)
    center_index = (n - 1) / 2.0

    x_sum = 0
    y_sum = 0

    # Loop through all points in the grid
    for i in range(n):
        for j in range(n):
            # Calculate the x and y distances to the center
            x_distance =2*( abs(i - center_index) * (a1*10**-3))**2
            y_distance =2*(abs(j - center_index) * (a1*10**-3))**2

            # Square the distances and accumulate
            x_sum += x_distance
            y_sum += y_distance

    return x_sum, y_sum

# Call the function
x_sum, y_sum = calculate_distances_squared(n, a1)

# Outputs

def calculate_k_r(K_ser,x_sum,y_sum):
    k_r=K_ser*(x_sum+y_sum)# it is time 10^6 to change it from Nmm/rad to kNm/rad,mmh look again when fresh
    return k_r

k_r=calculate_k_r(K_ser,x_sum,y_sum)
print(k_r) # output is kNm/rad

def calculate_weight_connection(d,n,t_plate,b_plate,h_cs_column,density_steel, number_of_plates,width_beam):
    kg_steel_dowels=(width_beam)*((((math.pi / 4) * (d ** 2))*n**2)*10**-9 * density_steel)
    kg_steel_plates=(2*number_of_plates*(t_plate*b_plate*b_plate)-(((math.pi / 4) * (d ** 2))*n**2))*10**-9 *density_steel
    total_kg_steel=kg_steel_dowels+kg_steel_plates
    return total_kg_steel

total_kg_steel=calculate_weight_connection(d,n,t_plate,b_plate,h_cs_column,density_steel, number_of_plates,width_beam)

print("the total amount of steel per connection is", total_kg_steel,"kg")
```

Python code connection parallel to fibers dimensioning

```
import rhinoscriptsyntax as rs
import math

alpha=0
t_1 = t_plate
t_2 = t_1  # All plates have the same thickness

def f_u_d(f_u,gamma_M_steel):
    f_u_d=f_u/gamma_M_steel
    return f_u_d

f_u_d=f_u_d(f_u,gamma_M_2)

def a1_parallel_to_grain(alpha, d):
    # Assuming alpha is in degrees and needs to be converted to radians
```

```
    alpha = math.radians(alpha)
    a1 = (4 + abs(math.cos(alpha))) * d
    return a1

a1 = a1_parallel_to_grain(alpha, d)
print('a1=',a1)

def a2(alpha,d):
    a2=(3 + abs(math.sin(alpha))) * d
    return a2

a2 = a2(alpha,d)
print('a2=',a2)

def a3_t(alpha, d):
    # Assuming alpha is in degrees and needs to be converted to radians
    alpha = math.radians(alpha)
    a3_t = (7 + (5 * abs(math.cos(alpha)))) * d
    return a3_t

a3_t = a3_t(alpha, d)
print('a3_t=',a3_t)

def a3_c(d):
    a3_c= 7*d
    return a3_c

a3_c = a3_c(d)
print('a3_c=',a3_c)

def calc_b_plate(n, a2, a3_c,a3_t):
    b_plate=(n - 1) * a2 + a3_c+ a3_t
    return b_plate

b_plate = calc_b_plate(n, a2, a3_c,a3_t)
print b_plate

def calc_f_h_d(d, rho_k,gamma_M_joints):
    f_h=0.082 * (1 - 0.01 * d) * rho_k/gamma_M_joints
    return f_h
   #d= diameter of dowel

f_h = calc_f_h_d(d, rho_k,gamma_M_joints)
print(f_h)

def calc_M_y_k(f_u_d, d):
    return 0.3 * f_u_d * d**2.6
    #d= diameter of dowel

M_y = calc_M_y_k(f_u_d, d)
print(M_y)

def calc_F_y(t_1, t_2, d, f_h, M_y):
    ModeI=0.25 * (2*t_1 + t_2)*d*f_h
    ModeIIa=(-0.5 * t_1 + 0.25 * t_2 + (0.5 * (t_1**2) + (M_y / (d * f_h)))**0.5) * d * f_h
    ModeIIb=(4 * M_y * d * f_h)**0.5
    ModeIIIa=(0.5 * t_1 + 0.5 * (t_1**2 + 2 * M_y / (d * f_h))**0.5) * d * f_h
    ModeIIIb=((M_y / (d * f_h))**0.5 + 0.5 * t_1) * d * f_h
    ModeIIIc=((M_y / (d * f_h))**0.5 + 0.25 * t_2) * d * f_h
    ModeIIId=(-0.5 * t_1 + (0.5 * t_1**2 + M_y / (d * f_h))**0.5 + (M_y / (d * f_h))**0.5) *
        d * f_h
    F_governing = min(ModeI,ModeIIa,ModeIIb,ModeIIIa,ModeIIIb,ModeIIIc,ModeIIId)
    return F_governing,ModeI,ModeIIa,ModeIIb,ModeIIIa,ModeIIIb,ModeIIIc,ModeIIId

F_governing,ModeI,ModeIIa,ModeIIb,ModeIIIa,ModeIIIb,ModeIIIc,ModeIIId = calc_F_y(t_1, t_2, d,
     f_h, M_y)

print(F_governing,ModeI,ModeIIa,ModeIIb,ModeIIIa,ModeIIIb,ModeIIIc,ModeIIId)

def calc_n_eff(n, a1, d):
    return min(n, n**0.9 * (a1 / (13 * d))**0.25)
```

```
85      #d= diameter of dowel
86
87  n_eff_ = calc_n_eff(n, a1, d)
88
89  def calc_A_net_timber(b_plate, n, d, width_beam):
90      return 0.5*d*math.pi*(n**2)*width_beam
91
92  A_net_timber_val = calc_A_net_timber(b_plate, n, d,width_beam)
93
94  def calc_A_net_steel(b_plate, n, d,t_plate):
95      return 0.5*d*math.pi*(n**2)*t_plate*2
96
97  A_net_steel_val = calc_A_net_steel(b_plate, n, d, t_plate)
98
99  def calc_F_max_dowels(n_eff, F_governing, n):
100     return 4 * n_eff * F_governing * n
101 F_max_dowels_ = calc_F_max_dowels(n_eff_, F_governing, n)
102
103 def calc_F_max_c(f_c_0_k, A_net_timber, gamma_M_joints):
104     F_max_c_k= f_c_0_k * A_net_timber
105     F_max_c_= k_mod*F_max_c_k/gamma_M_joints
106     return F_max_c_
107
108 F_max_c_ = calc_F_max_c(f_c_0_k, A_net_timber_val,gamma_M_joints)
109
110 def calc_F_max_t(f_t_0_k, A_net_timber, gamma_M_joints):
111     F_max_t_k= f_t_0_k * A_net_timber
112     F_max_t_= k_mod*F_max_t_k/gamma_M_joints
113     return F_max_t_
114
115 F_max_t_ = calc_F_max_t(f_t_0_k, A_net_timber_val,gamma_M_joints)
116
117 def calc_F_max_plates(f_y, t_plate, b_plate, f_u, A_net_steel, gamma_M_2):
118     return min(f_y * t_plate * b_plate, (0.9 * f_u * A_net_steel) / gamma_M_2)
119
120 F_max_plates_ = calc_F_max_plates(f_y, t_plate, b_plate, f_u_d, A_net_steel_val, gamma_M_2)
121
122 def check_capacity(F_occuring, F_max_dowels_, F_max_c_, F_max_t_, F_max_plates_, n,
        n_stepsize):
123     while F_max_dowels_ < F_occuring or F_max_c_ < F_occuring or F_max_t_ < F_occuring or
            F_max_plates_ < F_occuring:
124         if n >= n_max:
125             break
126         n += n_stepsize
127
128         # Update values that depend on n
129         b_plate = calc_b_plate(n, a2, a3_c,a3_t)
130         n_eff_ = calc_n_eff(n, a1, d)
131         A_net_timber_val = calc_A_net_timber(b_plate, n, d,width_beam)
132         A_net_steel_val = calc_A_net_steel(b_plate, n, d,t_plate)
133
134         F_max_dowels_ = calc_F_max_dowels(n_eff_, F_governing, n)
135         F_max_c_ = calc_F_max_c(f_c_0_k, A_net_timber_val,gamma_M_joints)
136         F_max_t_ = calc_F_max_t(f_t_0_k, A_net_timber_val, gamma_M_joints)
137         F_max_plates_ = calc_F_max_plates(f_y, t_plate, b_plate, f_u_d, A_net_steel_val,
                gamma_M_2)
138
139     Check_dowel = F_occuring / F_max_dowels_
140     Check_c = F_occuring / F_max_c_
141     Check_t = F_occuring / F_max_t_
142     Check_plates = F_occuring / F_max_plates_
143     return Check_dowel, Check_c, Check_t, Check_plates, n
144
145 Check_dowel, Check_c, Check_t, Check_plates, n = check_capacity(F_occuring, F_max_dowels_,
        F_max_c_, F_max_t_, F_max_plates_, n, n_stepsize)
146 #In the line above (133 and two lines above that,131, i had to remove A_net_steel_val and
        A_net_timber_val. This is not the case with the beam part. Except 90 to 0 degree change
147 # no difference is present. Output seems in both case correct, but might be a possible bug
        location.
148
149 #Makes sure values are not only used in new calculations but displayed out of code block
```

```python
n_eff_ = calc_n_eff(n, a1, d)
F_max_dowels_ = calc_F_max_dowels(n_eff_, F_governing, n)
b_plate = calc_b_plate(n, a2, a3_c,a3_t)
A_net_timber_val = calc_A_net_timber(b_plate, n, d,width_beam)
A_net_steel_val = calc_A_net_steel(b_plate, n, d,t_plate)

print("Check_dowel:", Check_dowel)
print("Check_c:", Check_c)
print("Check_t:", Check_t)
print("Check_plates:", Check_plates)
print("Final n:", n)
print("A_net_timber:", A_net_timber_val)
print("A_net_steel:", A_net_steel_val)



def calculate_K_ser(rho_m, d):
    K_ser = 2*((rho_m*10**9) ** 1.5 * (d*10**-3) / 23) #The times two is added due to the steel.
    return K_ser

K_ser=calculate_K_ser(rho_m, d)

print(K_ser)

def calculate_distances_squared(n, a1):
    # Calculate center index (assuming the center is exactly at the midpoint)
    center_index = (n - 1) / 2.0

    x_sum = 0
    y_sum = 0

    # Loop through all points in the grid
    for i in range(n):
        for j in range(n):
            # Calculate the x and y distances to the center
            x_distance =2*( abs(i - center_index) * (a1*10**-3))**2
            y_distance =2*(abs(j - center_index) * (a1*10**-3))**2

            # Square the distances and accumulate
            x_sum += x_distance
            y_sum += y_distance

    return x_sum, y_sum

# Call the function
x_sum, y_sum = calculate_distances_squared(n, a1)

# Outputs

def calculate_k_r(K_ser,x_sum,y_sum):
    k_r=K_ser*(x_sum+y_sum)# it is time 10^6 to change it from Nmm/rad to kNm/rad,mmh look again when fresh
    return k_r

k_r=calculate_k_r(K_ser,x_sum,y_sum)
print(k_r) # output is kNm/rad

def calculate_weight_connection(d,n,t_plate,b_plate,h_cs_column,density_steel,number_of_plates,width_beam):
    kg_steel_dowels=(h_cs_column)*((((math.pi / 4) * (d ** 2))*n**2)*10**-9 * density_steel)
    kg_steel_plates=(2*number_of_plates*(t_plate*b_plate*b_plate)-(((math.pi / 4) * (d ** 2))*n**2))*10**-9 *density_steel
    total_kg_steel=kg_steel_dowels+kg_steel_plates
    return total_kg_steel

total_kg_steel=calculate_weight_connection(d,n,t_plate,b_plate,h_cs_column,density_steel,number_of_plates,width_beam)

print("the total amount of steel per connection is", total_kg_steel,"kg")
```

A.1.9. Core dimensioning

```
def check_deflection(height_cs, thickness, Allowed_displacement, E, h, q):
    # Calculate initial I
    I = ((1/12)*height_cs*(height_cs**3))-((1/12)*(height_cs-thickness)*((height_cs-thickness
        )**3))
    iteration_count = 0
    # Deflection with I
    occurring_displacement = (q*(h*1000)**4)/(8*E*I*10**12)
    # Loop to increment width until the displacement exceeds the threshold
    while occurring_displacement >= Allowed_displacement:
        height_cs += 0.3
        I = ((1/12)*height_cs*(height_cs**3))-((1/12)*(height_cs-thickness)*((height_cs-
            thickness)**3))
        occurring_displacement = (q*(h*1000)**4)/(8*E*I*10**12)
        iteration_count += 1

    return occurring_displacement, height_cs, iteration_count

# Assign the function's output to the output variables
occurring_displacement,height_cs, iteration_count =  check_deflection(height_cs, thickness,
    Allowed_displacement, E, h, q)
```

A.1.10. Python code fictive Elastic modulus determination

```
def calculate_E_f(concrete_class, alpha_n, rho):
    formulas = {
        'C12/15': {
            'alpha_n_leq_0_45': lambda alpha_n, rho: (1.30 + 410 * rho + (9.0 - 130 * rho) *
                alpha_n) * 10**3,
            'alpha_n_gt_0_45_leq_0_9': lambda alpha_n, rho: (6.8 + 517 * rho) * (1 - 0.5 *
                alpha_n) * 10**3,
            'min_value': 2900 * 10**3
        },
        'C16/20': {
            'alpha_n_leq_0_45': lambda alpha_n, rho: (1.45 + 415 * rho + (11.5 - 145 * rho) *
                 alpha_n) * 10**3,
            'alpha_n_gt_0_45_leq_0_9': lambda alpha_n, rho: (8.5 + 514 * rho) * (1 - 0.5 *
                alpha_n) * 10**3,
            'min_value': 3250 * 10**3
        },
        'C20/25': {
            'alpha_n_leq_0_45': lambda alpha_n, rho: (1.60 + 420 * rho + (14.0 - 160 * rho) *
                 alpha_n) * 10**3,
            'alpha_n_gt_0_45_leq_0_9': lambda alpha_n, rho: (10.0 + 510 * rho) * (1 - 0.5 *
                alpha_n) * 10**3,
            'min_value': 3600 * 10**3
        },
        'C25/30': {
            'alpha_n_leq_0_45': lambda alpha_n, rho: (1.75 + 425 * rho + (16.5 - 175 * rho) *
                 alpha_n) * 10**3,
            'alpha_n_gt_0_45_leq_0_9': lambda alpha_n, rho: (11.7 + 506 * rho) * (1 - 0.5 *
                alpha_n) * 10**3,
            'min_value': 3950 * 10**3
        },
        'C30/37': {
            'alpha_n_leq_0_45': lambda alpha_n, rho: (1.96 + 432 * rho + (20.0 - 196 * rho) *
                 alpha_n) * 10**3,
            'alpha_n_gt_0_45_leq_0_9': lambda alpha_n, rho: (14.0 + 501 * rho) * (1 - 0.5 *
                alpha_n) * 10**3,
            'min_value': 4450 * 10**3
        },
        'C35/45': {
            'alpha_n_leq_0_45': lambda alpha_n, rho: (2.20 + 440 * rho + (24.0 - 220 * rho) *
                 alpha_n) * 10**3,
            'alpha_n_gt_0_45_leq_0_9': lambda alpha_n, rho: (16.7 + 495 * rho) * (1 - 0.5 *
                alpha_n) * 10**3,
            'min_value': 5000 * 10**3
        },
        'C40/50': {
            'alpha_n_leq_0_45': lambda alpha_n, rho: (2.35 + 445 * rho + (26.5 - 235 * rho) *
                 alpha_n) * 10**3,
```

```
            'alpha_n_gt_0_45_leq_0_9': lambda alpha_n, rho: (18.3 + 491 * rho) * (1 - 0.5 *
                alpha_n) * 10**3,
            'min_value': 5350 * 10**3
        },
        'C45/55': {
            'alpha_n_leq_0_45': lambda alpha_n, rho: (2.50 + 450 * rho + (29.0 - 250 * rho) *
                 alpha_n) * 10**3,
            'alpha_n_gt_0_45_leq_0_9': lambda alpha_n, rho: (20.0 + 487 * rho) * (1 - 0.5 *
                alpha_n) * 10**3,
            'min_value': 5700 * 10**3
        },
        'C50/60': {
            'alpha_n_leq_0_45': lambda alpha_n, rho: (2.65 + 455 * rho + (31.5 - 265 * rho) *
                 alpha_n) * 10**3,
            'alpha_n_gt_0_45_leq_0_9': lambda alpha_n, rho: (21.6 + 484 * rho) * (1 - 0.5 *
                alpha_n) * 10**3,
            'min_value': 6050 * 10**3
        },
        'C55/67': {
            'alpha_n_leq_0_45': lambda alpha_n, rho: (2.86 + 462 * rho + (34.6 - 258 * rho) *
                 alpha_n) * 10**3,
            'alpha_n_gt_0_45_leq_0_9': lambda alpha_n, rho: (23.8 + 480 * rho) * (1 - 0.5 *
                alpha_n) * 10**3,
            'min_value': 6400 * 10**3
        },
        'C60/75': {
            'alpha_n_leq_0_45': lambda alpha_n, rho: (3.10 + 470 * rho + (37.0 - 170 * rho) *
                 alpha_n) * 10**3,
            'alpha_n_gt_0_45_leq_0_9': lambda alpha_n, rho: (25.5 + 480 * rho) * (1 - 0.5 *
                alpha_n) * 10**3,
            'min_value': 6400 * 10**3
        },
        'C70/85': {
            'alpha_n_leq_0_45': lambda alpha_n, rho: (3.10 + 470 * rho + (41.5 - 170 * rho) *
                 alpha_n) * 10**3,
            'alpha_n_gt_0_45_leq_0_9': lambda alpha_n, rho: (28.1 + 480 * rho) * (1 - 0.5 *
                alpha_n) * 10**3,
            'min_value': 6400 * 10**3
        },
        'C80/95': {
            'alpha_n_leq_0_45': lambda alpha_n, rho: (3.10 + 470 * rho + (46.5 - 170 * rho) *
                 alpha_n) * 10**3,
            'alpha_n_gt_0_45_leq_0_9': lambda alpha_n, rho: (31.1 + 480 * rho) * (1 - 0.5 *
                alpha_n) * 10**3,
            'min_value': 6400 * 10**3
        },
        'C90/105': {
            'alpha_n_leq_0_45': lambda alpha_n, rho: (3.10 + 470 * rho + (51.0 - 170 * rho) *
                 alpha_n) * 10**3,
            'alpha_n_gt_0_45_leq_0_9': lambda alpha_n, rho: (33.7 + 480 * rho) * (1 - 0.5 *
                alpha_n) * 10**3,
            'min_value': 6400 * 10**3
        }
    }

    cylindrical_strengths = {
        'C12/15': 12,
        'C16/20': 16,
        'C20/25': 20,
        'C25/30': 25,
        'C30/37': 30,
        'C35/45': 35,
        'C40/50': 40,
        'C45/55': 45,
        'C50/60': 50,
        'C55/67': 55,
        'C60/75': 60,
        'C70/85': 70,
        'C80/95': 80,
        'C90/105': 90
    }
```

```
    f_cd = cylindrical_strengths[concrete_class] / gamma_c

    if alpha_n <= 0.45:
        formula = formulas[concrete_class]['alpha_n_leq_0_45']
        E_f = formula(alpha_n, rho)
        min_value = formulas[concrete_class]['min_value']
        if E_f < min_value:
            E_f = min_value
    elif 0.45 < alpha_n <= 0.9:
        formula = formulas[concrete_class]['alpha_n_gt_0_45_leq_0_9']
        E_f = formula(alpha_n, rho)
    else:
        raise ValueError("alpha_n should be between 0 and 0.9")


    return E_f, f_cd


cylindrical_strengths = {
        'C12/15': 12,
        'C16/20': 16,
        'C20/25': 20,
        'C25/30': 25,
        'C30/37': 30,
        'C35/45': 35,
        'C40/50': 40,
        'C45/55': 45,
        'C50/60': 50,
        'C55/67': 55,
        'C60/75': 60,
        'C70/85': 70,
        'C80/95': 80,
        'C90/105': 90
    }

f_cd = cylindrical_strengths[concrete_class] / gamma_c
def calculate_alpha_n(N_ed, f_cd, A_c, A_st, A_sc, f_yd):
    alpha_n = N_ed / (f_cd * A_c + (A_st + A_sc) * f_yd)
    return alpha_n

# Example usage
h_core_cs_mm = h_core_cs * 1000
t_wall_mm = t_wall * 1000
A_sc = A_st
A_c = 2 * h_core_cs * t_wall
f_yd = f_yk / gamma_s  # Design yield strength

alpha_n = calculate_alpha_n(N_ed, f_cd, A_c, A_st, A_sc, f_yd)
E_f, f_cd = calculate_E_f(concrete_class, alpha_n, rho)

print(E_f)
print(f_cd)
print(alpha_n)
print(rho)
```

A.1.11. Core assessment

Python Code core shear assessment

```
import math

# calculates v_Ed
def v_Ed(V_Ed, d, b):
    v_Ed=V_Ed / (d * b * 2)
    return v_Ed

# calculates v_min
def v_min(k, f_ck):
    v_min=0.035 * k**(3/2) * (math.sqrt(f_ck))**(1/2)
    return v_min

```

```python
# calculates k
def k(d):
    k=min(1 + math.sqrt(200 / d), 2)
    return k
# calculates effective depth of the section
def rho_l(b, d):
    return None  # Since A_s is removed, this always returns None now

# calculates minimal reinforcement ratio
def rho_w_min(f_ck, f_yk):
    rho_w_min=(0.08 * math.sqrt(f_ck))/f_yk
    return rho_w_min

# calculates v_Rd_c_stress
def v_Rd_c_stress(k, rho_w_min, f_yk, f_ck):
    v_Rd_c_stress = max(0.12 * k * (1000 * rho_w_min * math.sqrt(f_ck))**(1/3), v_min(k, f_ck))
    return v_Rd_c_stress

# calculates the total shear resistance
def V_Rd_c(v_Rd_c_stress, b, d):
    V_Rd_c=v_Rd_c_stress * b * d
    return V_Rd_c

# checks the capacity of the section
def check_capacity(V_Ed, v_Rd_c_stress, f_ck_max, f_ck_stepsize, f_ck, t_wall, d, b):
    while V_Ed / V_Rd_c(v_Rd_c_stress(k(d), rho_w_min(f_ck, f_yk), f_yk, f_ck), b, d) > uc_max:
        if f_ck >= f_ck_max or t_wall >= t_max:
            break
        f_ck += f_ck_stepsize
    else:
        return V_Ed / V_Rd_c(v_Rd_c_stress(k(d), rho_w_min(f_ck, f_yk), f_yk, f_ck), b, d), f_ck, t_wall
    # If it still doesn't suffice, increase the thickness of the core wall
    while V_Ed / V_Rd_c(v_Rd_c_stress(k(d), rho_w_min(f_ck, f_yk), f_yk, f_ck), b, d) > uc_max:
        t_wall += 0.01  # Increase thickness by 1 cm (adjust as needed)
        d = t_wall * 0.81
        if t_wall >= t_max:
            break
    return V_Ed / V_Rd_c(v_Rd_c_stress(k(d), rho_w_min(f_ck, f_yk), f_yk, f_ck), b, d), f_ck, t_wall
d = t_wall * 0.81  # Initial depth

# Check capacity
result, final_f_ck, final_t_wall = check_capacity(V_Ed, v_Rd_c_stress, f_ck_max, f_ck_stepsize, f_ck, t_wall, d, b)

if result <= 1:
    print("V_Ed / V_Rd_c:", result)
    print("Final used f_ck:", final_f_ck)
    print("Final used t_wall:", final_t_wall)
    print(rho_l(b, d))  # just for checking if it works properly
else:
    print("Capacity not sufficient.")
    print("V_Ed / V_Rd_c:", result)
    print("Final used f_ck:", final_f_ck)
    print("Final used t_wall:", final_t_wall)
    print(rho_l(b, d))  # just for checking if it works properly
```

Python Code core torsion assessment

```python
import math


d = t_wall * 0.81  # Initial depth of section

gamma_c = 1.5


```

```python
# Function to calculate area
def calc_area(height_core):
    return height_core ** 2

# Function to calculate perimeter (u) and effective thickness (t_eff)
def calc_u_and_t_eff(A):
    u = (A ** 0.5) * 4 #assuming a rectangular cs
    t_eff = A / u
    return u, t_eff

# Function to calculate f_ctd
def calc_f_ctd(f_ck, gamma_c):
    f_ctk_005 = 0.7 * 0.3 *f_ck**( 2/3)
    f_ctd = f_ctk_005 / gamma_c
    return f_ctd

# Function to calculate T_Rd_C
def T_Rd_C(A_k, f_ctd, t_eff):
    T_Rd_C=2 * A_k * f_ctd * t_eff
    return T_Rd_C

# Function to check capacity
def check_capacity(T_Ed, f_ck, t_eff, f_ck_max, f_ck_stepsize, t_wall, height_core):
    A = calc_area(height_core)
    u, t_eff = calc_u_and_t_eff(A)
    A_k = ((A ** 0.5) - t_eff) ** 2

    while T_Ed / T_Rd_C(A_k, calc_f_ctd(f_ck, gamma_c), t_eff) > uc_max:
        if f_ck >= f_ck_max or t_wall >= t_max:  # Ensuring t_wall does not exceed 1 meter
            break
        f_ck += f_ck_stepsize
        A = calc_area(height_core)
        u, t_eff = calc_u_and_t_eff(A)
        A_k = ((A ** 0.5) - t_eff) ** 2
    else:
        return T_Ed / T_Rd_C(A_k, calc_f_ctd(f_ck, gamma_c), t_eff), f_ck, height_core, A, t_eff, A_k

    # If it still doesn't suffice, increase the height of the core wall
    while T_Ed / T_Rd_C(A_k, calc_f_ctd(f_ck, gamma_c), t_eff) > uc_max:
        if height_core >= h_core_max:
            break
        height_core += 0.01  # Increase height by 1 cm (adjust as needed)
        A = calc_area(height_core)
        u, t_eff = calc_u_and_t_eff(A)
        A_k = ((A ** 0.5) - t_eff) ** 2

    return T_Ed / T_Rd_C(A_k, calc_f_ctd(f_ck, gamma_c), t_eff), f_ck, height_core, A, t_eff, A_k

# Check capacity
result, final_f_ck, final_height_core, final_A, final_t_eff, final_A_k = check_capacity(T_Ed, f_ck, t_eff, f_ck_max, f_ck_stepsize, t_wall, height_core)

if result <= uc_max:
    print("T_Ed / T_Rd_C:", result)
    print("Final used f_ck:", final_f_ck)
    print("Final used height_core:", final_height_core)
    print("Final t_eff:", final_t_eff)
    print("Final A:", final_A)
    print("Final A_k:", final_A_k)
else:
    print("Capacity not sufficient.")
    print("T_Ed / T_Rd_C:", result)
    print("Final used f_ck:", final_f_ck)
    print("Final used height_core:", final_height_core)
    print("Final t_eff:", final_t_eff)
    print("Final A:", final_A)
    print("Final A_k:", final_A_k)
```

A.2. Flowcharts and overview script

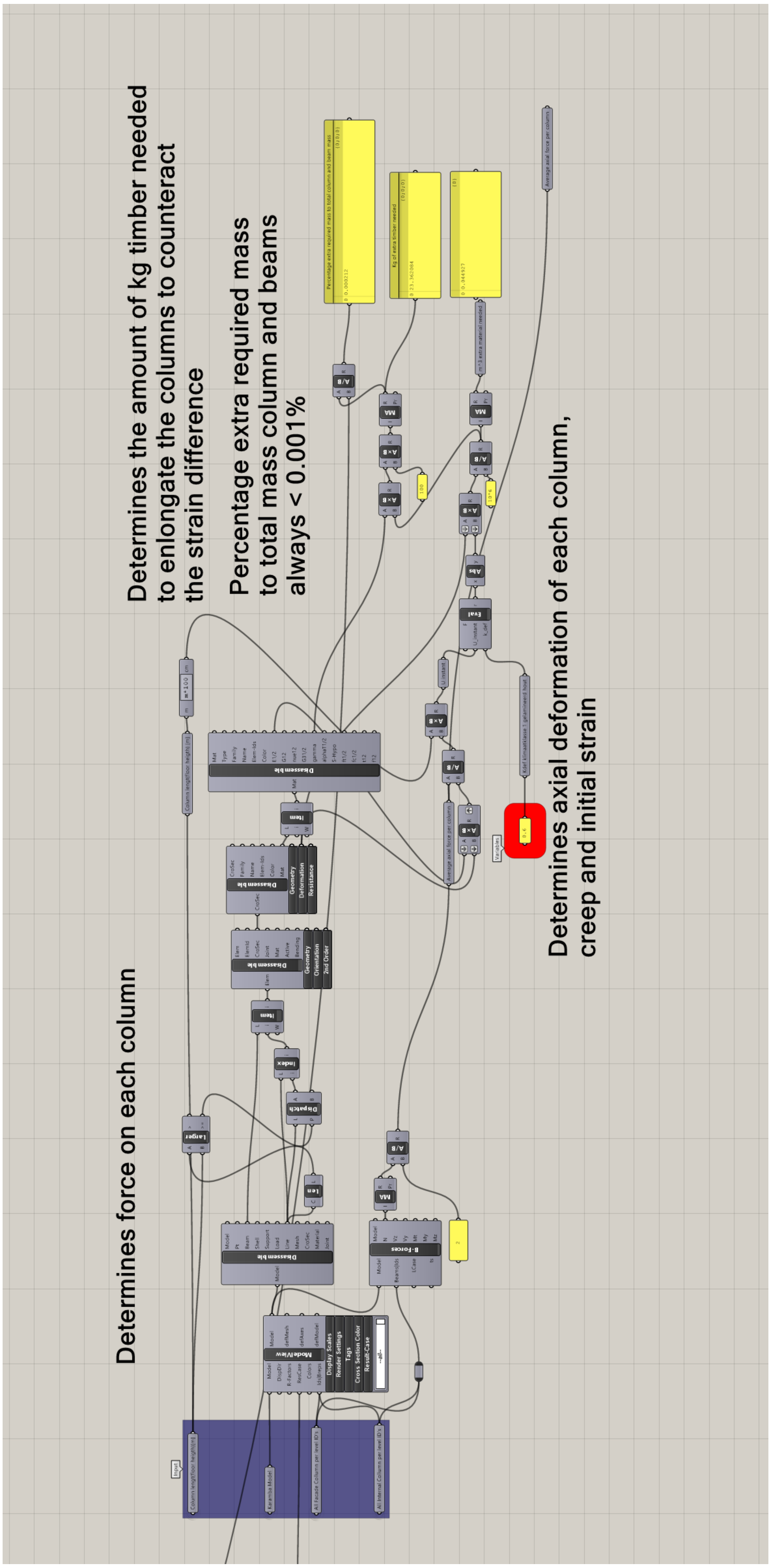

Figure A.3: Axial Strain and extra material for elongation needed determination

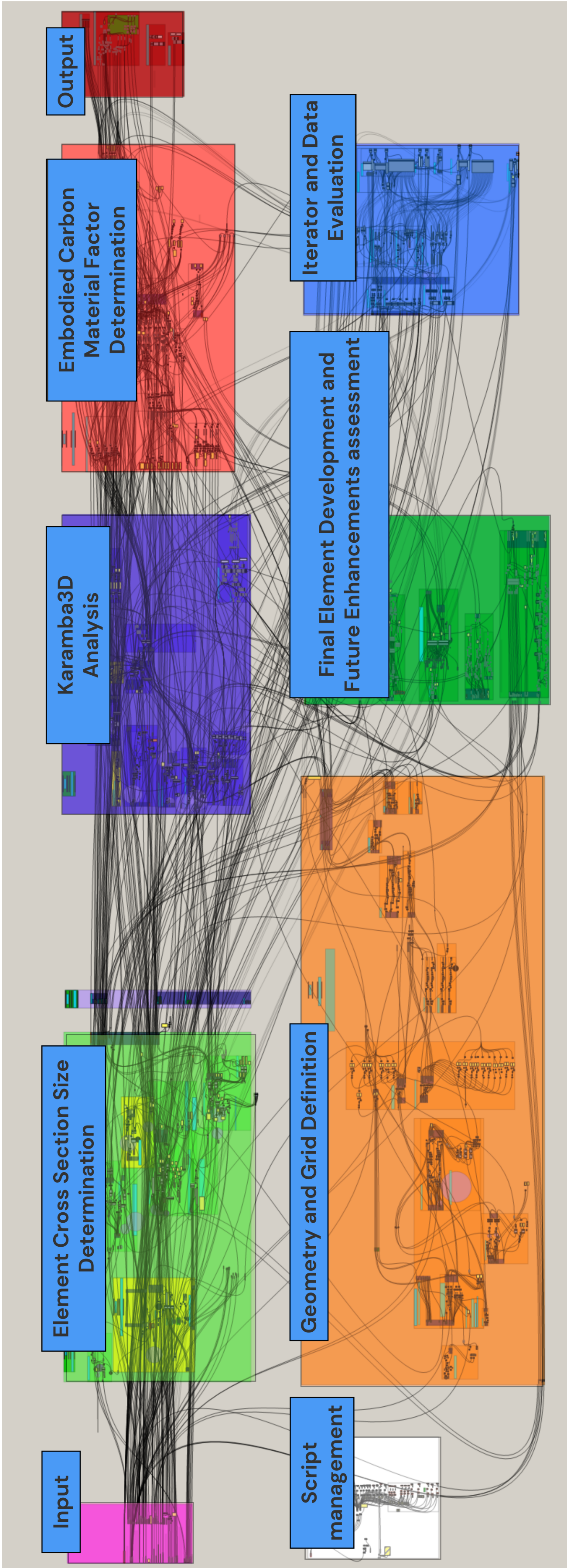

Figure A.5: Script Overview sideways

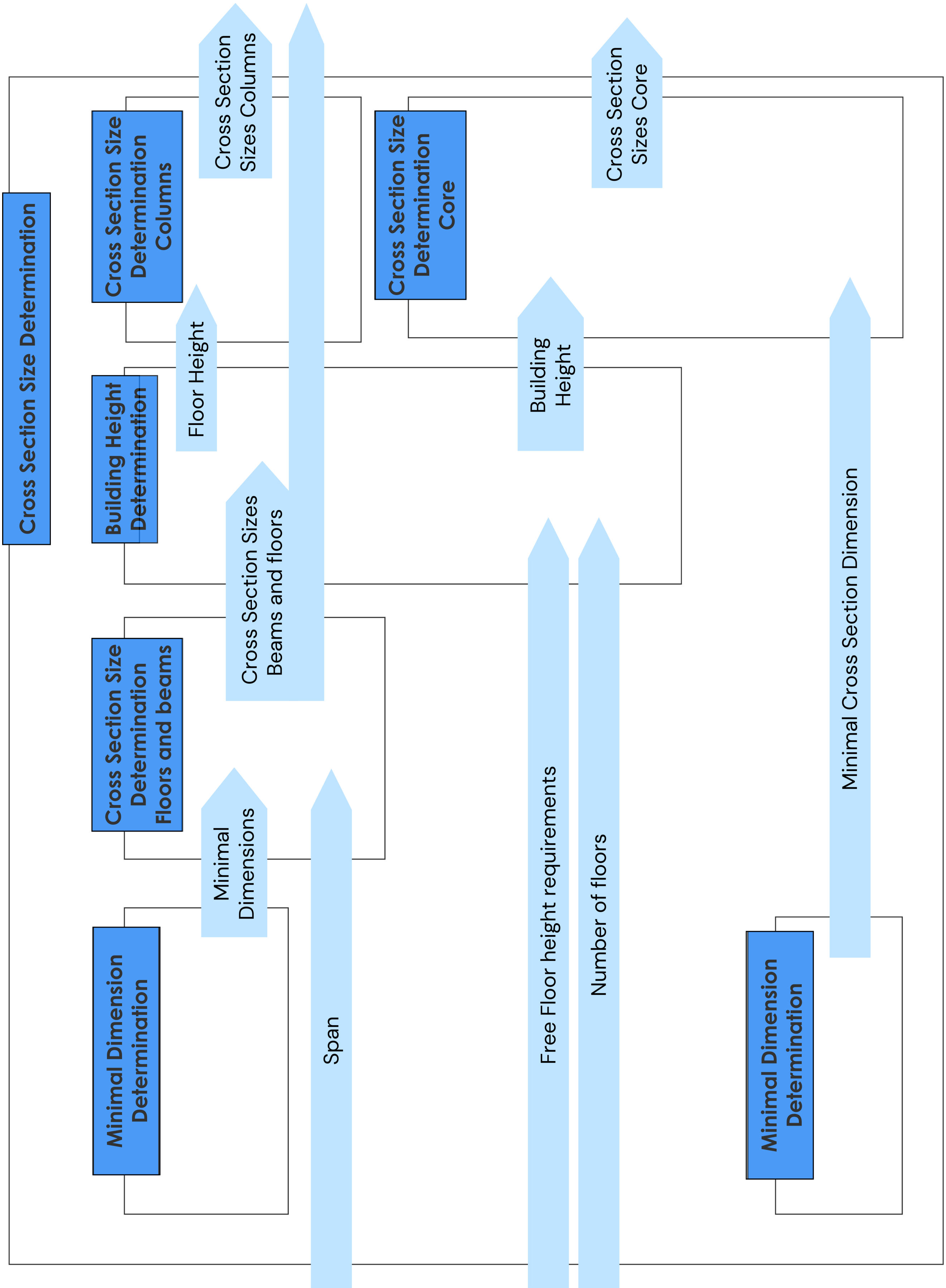

Figure A.6: Cross Section Size Determination Flowchart Minimalistic

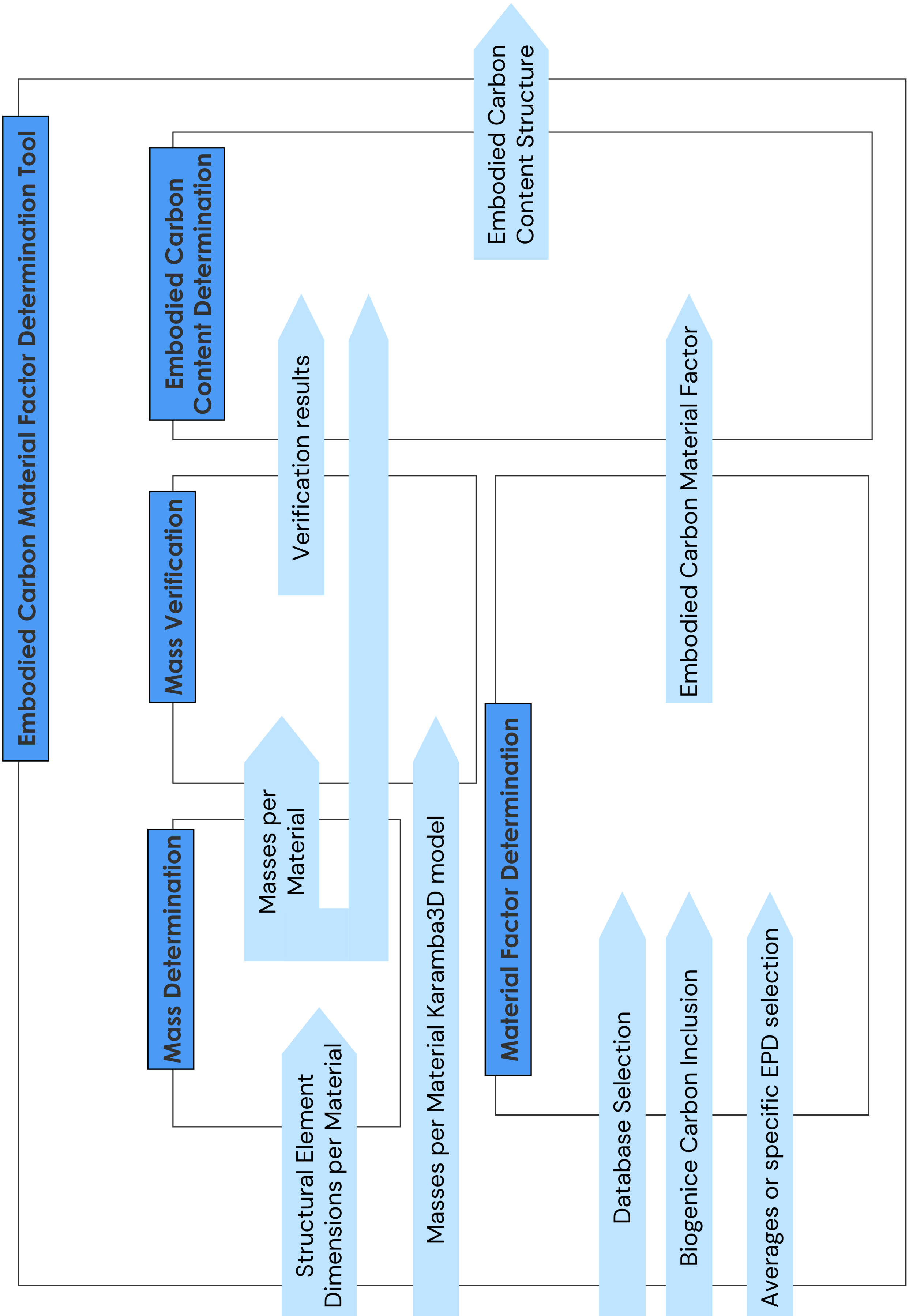

Figure A.7: Embodied Carbon Material Factor Determination Tool Flowchart Minimalistic

B

Embodied carbon database

This appendix contains all EPD's or other sources from the NMD and ICE database used in the framework.

B.1. Timber

B.1.1. NMD

Title	Description
KLH - CLT (Cross Laminated Timber) S-P-04195	EPD for CLT
X-LAM (Cross laminated timber) 1.1.00280.2022	EPD for X-lam
CLT (Cross Laminated Timber) S-P-09949	EPD for CLT
Glulam (Glued Laminated Timber) EPD-2023-4701	EPD for Glulam
Cat 3. Europees naaldhout; duurzame bosbouw	Generic Value Softwood
Cat 3. Hout gelamineerd europees naaldhout, duurzame bosbouw	Generic Value Softwood
Cat 1. Circulair gelamineerd hout ligger De Groot Vroomshoop	EPD for Glulam

Table B.1: Timber EPD's and other sources used out of the NMD

B.1.2. ICE

Reference Details	Description
EPD Number: BREG EN EPD 000083 published by BRE, 2017	EPD for MEDITE PREMIER
EPD Number: BREG EN EPD 000124 published by BRE, 2017	EPD for Wood for good, 1m3 of kiln dried planed or machined sawn timber used as structural timber.
EPD Number: EPD-EHW-20130013-IBC1-DE published by IBU - Institut Bauen & Umwelt e.V., 2013	EPD for Gypsum fiber board
EPD Number: EPD-EHW-20130012-IBC1-DE published by IBU - Institut Bauen & Umwelt e.V., 2013	EPD for Laminate floor (DPL)
EPD Number: EPD-MWS-20130229-IBD1-DE published by IBU - Institut Bauen & Umwelt e.V., 2013	EPD for Nadura floors NB 400 and wall panels NP 300
EPD Number: EPD-SCP-20150324-IBC1-DE published by IBU - Institut Bauen & Umwelt e.V., 2016	EPD for Scheucher Parkett multi-layer parquet Wood
EPD Number: EPD-WEI-20150284-IBD1-DE published by IBU - Institut Bauen & Umwelt e.V., 2015	EPD for Multilayered Flooring
EPD Number: EPD-STI-20160090-IBC1-DE published by IBU - Institut Bauen & Umwelt e.V., 2016	EPD for Admonter solid wood multilayer products
EPD Number: EPD-MWS-2060176-CBC1-DE published by IBU - Institut Bauen & Umwelt e.V., 2016	EPD for Master Longlife parquet
EPD Number: EPD-EGG-20150313-IBD1-EN published by IBU - Institut Bauen & Umwelt e.V., 2015	EPD for Eurolight coated board
EPD Number: EPD-EGG-20150045-IBA1-EN published by IBU - Institut Bauen & Umwelt e.V., 2015	EPD for MDF coated Wood
EPD Number: EPD-EGG-20150312-IBD1-EN published by IBU - Institut Bauen & Umwelt e.V., 2015	EPD for Eurolight raw lightweight boards

EPD Number: EPD-EGG-20140035-IBB1-DE published by IBU - Institut Bauen & Umwelt e.V., 2014	**EPD for Eurodecor - coated chipboard**
EPD Number: EPD-EGG-20140196-IBA1-EN published by IBU - Institut Bauen & Umwelt e.V., 2014	**EPD for EGGER DHF is a vapour-permeable, moisture-resistant wood fibreboard**
EPD Number: EPD-KRO-20150067-IBD2-DE published by IBU - Institut Bauen & Umwelt e.V., 2015	**EPD for SWISS KRONO OSB Wood**
EPD Number: EPD-EGG-20140246-IBA2-DE published by IBU - Institut Bauen & Umwelt e.V., 2017	**EPD for sawn timber green**
EPD Number: EPD-EGG-20140003-IBD1-DE published by IBU - Institut Bauen & Umwelt e.V., 2014	**EPD for Eurospan raw chipboard**
Oekobau, Federal Ministry of the Interior, Building and Community, 2017	**A German database for LCA of buildings by the Federal Ministry of the Interior, Building and Community.**
EPD Number: EPD-EGG-20140247-IBA2-DE published by IBU - Institut Bauen & Umwelt e.V., 2017	**EPD for sawn timber dried**
EPD Number: EPD-EGG-20140248-IBA2-EN published by IBU - Institut Bauen & Umwelt e.V., 2017	**EPD for sawn timber planed**
EPD Number: S-P-00070 published by Environdec, 2048	**EPD for particleboard**
EPD Number: S-P-00083 published by Environdec, 2016	**EPD for outdoor treated wood**
EPD Number: S-P-00272 published by Environdec, 2017	**EPD for particleboards and melamine faced boards**
EPD Number: S-P-00273 published by Environdec, 2017	**EPD for MDF and melamine faced boards**
EPD Number: S-P-00560 published by Australasian EPD Programme , 2017	**EPD for softwood lumber from Australia, including rough and dresssed. Includes data on treated for outdoor use, with a wide range of preservatives.**

EPD Number: S-P-00561 published by Australasian EPD Programme , 2017	**EPD for hardwood lumber from Australia, including rough and dresssed. Includes data on treated for outdoor use, with a wide range of preservatives.**
EPD Number: S-P-00562 published by Australasian EPD Programme , 2017	**EPD for particleboard from Australia**
Cross Laminated Timber, Wood for Good Lifecycle Database, 2013	**LCA of CLT, UK market**
Fresh sawn softwood, Wood for Good Lifecycle Database, 2013	**LCA of fresh sawn softwood, UK market**
Kiln dried hardwood, Wood for Good Lifecycle Database, 2013	**LCA of kiln dried hardwood, UK market**
Glued Laminated Timber, Wood for Good Lifecycle Database, 2013	**LCA of glued laminated timber, UK market**
High Density Fibreboard (HDF), Wood for Good Lifecycle Database, 2013	**LCA of high density fibreboard (HDF), UK market**
Laminated Veneer Lumber (LVL), Wood for Good Lifecycle Database, 2013	**LCA of Laminated Veneer Lumber (LVL), UK Market**
Medium Density Fibreboard (MDF), Wood for Good Lifecycle Database, 2013	**LCA of Medium Density Fibreboard (MDF), UK market.**
Melamine Coated Particleboard, Wood for Good Lifecycle Database, 2013	**LCA of Melamine Coated Particleboard, UK market**
Particleboard (Uncoated), Wood for Good Lifecycle Database, 2013	**LCA of Particleboard (Uncoated), UK market**
Planed Softwood, Wood for Good Lifecycle Database, 2013	**LCA of planed softwood, UK market**
Plywood, Wood for Good Lifecycle Database, 2013	**LCA of plywood, UK market**
Timber frame - Closed panel system, Wood for Good Lifecycle Database, 2013	**LCA of timber frame - Closed panel system, UK market**
Timber frame - Open panel system, Wood for Good Lifecycle Database, 2013	**LCA of timber frame - Open panel system, UK market**
EPD Number: S-P-00563 published by Australasian EPD Programme , 2015	**EPD for Medium Density fibreboard (MDF), Version 1.1 (2017)**
EPD Number: S-P-00564 published by Australasian EPD Programme , 2015	**EPD for Plywood, Version 1.1 (2017)**
EPD Number: S-P-00565 published by Australasian EPD Programme , 2017	**EPD for Glued Laminated Timber, Version 1**

EPD Number: S-P-00853 published by Australasian EPD Programme , 2017	**EPD for Innowood composite (plastic-) timber products**
EPD Number: S-P-00865 published by Environdec, 2016	**EPD for Laminated Beams and Profiles**
EPD Number: S-P-01070 published by Environdec, 2017	**EPD for particleboard, Japan**
EPD Number: S-P-01072 published by Environdec, 2017	**EPD for JJI-Joist, which is an engineered oriented strand board (OSB) webbed timber I-joist**
EPD Number: S-P-01314 published by Environdec, 2018	**EPD for EGO-CLT Cross Laminated Timber wood panel**
EPD Number: 4787319688.101.1 published by UL Environment, 2016	**EPD for North American Cellulosic Fiberboard**
EPD Number: 13CA24184.104.1 published by UL Environment, 2013	**EPD for North American Glued Laminated Timber**
EPD Number: 4787549627.101.1 published by UL Environment, 2016	**EPD for Hardboard/Engineered Wood Siding and Trim (EWST), North American**
EPD Number: 13CA24184.106.1 published by UL Environment, 2013	**EPD for Wood I-Joists, North American**
EPD Number: 4784193543.101.1 published by UL Environment, 2016	**EPD for North American Laminated Strand Lumber**
EPD Number: 13CA24184.105.1 published by UL Environment, 2013	**EPD for North American Laminated Veneer Lumber**
EPD Number: 4788663642.101.1 published by UL Environment, 2018	**EPD for North American Medium Density Fiberboard**
EPD Number: 13CA24184.101.1 published by UL Environment, 2013	**EPD for North American Oriented Strand Board**
EPD Number: 4788663642.102.1 published by UL Environment, 2018	**EPD for North American Particleboard**
EPD Number: 13CA24184.107.1 published by UL Environment, 2013	**EPD for North American Redwood Decking**
EPD Number: 13CA24184.102.1 published by UL Environment, 2013	**EPD for North American Softwood Lumber**
EPD Number: 13CA24184.103.1 published by UL Environment, 2013	**EPD for North American Softwood Plywood**
EPD Number: EPDIE-18-01 published by EPD Ireland, 2018	**EPD for OSB2**
EPD Number: EPDIE-18-02 published by EPD Ireland, 2018	**EPD for OSB3**
EPD Number: EPDIE-18-03 published by EPD Ireland, 2018	**EPD for OSB3 T&G**

EPD Number: EPDIE-18-04 published by EPD Ireland, 2018	**EPD for Flame retardant (FR) OSB3**
EPD Number: EPDIE-18-06 published by EPD Ireland, 2018	**EPD for OSB2 T&G**
EPD Number: EPDIE-18-07 published by EPD Ireland, 2018	**EPD for Site Protect OSB3**
EPD Number: EPDIE-18-11 published by EPD Ireland, 2018	**EPD for Site Protect Plus OSB3**
	EPD for EGGER OSB-Boards
	EPD for Kronoply OSB
	EPD for Metsä Wood Finnjoist, I-joist
	EPD for Kerto LVL, Laminated Veneer Lumber (Metsä Wood)
	EPD for Masonite I-beam
	EPD for OSB 4 Superfinish ECO
	EPD for OSB

B.2. Concrete

B.2.1. NMD

Title	Description
Cat 3. (25% CEM I, 75% CEM II, 40 kg staal/ m3) Massieve wanden, dragend, Beton, in het werk gestort, C2025; incl. wapening	Generic Value Concrete incl. reinforcement
Cat 3. (25% CEM I, 75 CEM II, 40 kg staal/ m3) Massieve wanden, dragend, Beton, in het werk gestort, C3037; incl. wapening	Generic Value Concrete incl. reinforcement

Table B.2: Concrete EPD's and other sources used out of the NMD

B.2.2. ICE

Reference Details	Description
EPD Number: BREG EN EPD No: 000104 published by BRE Environmental Product Declaration, 2016	EPD for readymix concrete
EPD Number: BREG EN EPD No: 000106 published by BRE Environmental Product Declaration, 2016	EPD for self compacting readymix concrete
EPD Number: BREG EN EPD 000104 published by BRE, 2016	EPD for Readymix concrete, Tarmac
EPD Number: BREG EN EPD 000107 published by BRE, 2016	EPD for TOPFORCE (Fibre Reinforced Readymix Concrete), Tarmac
EPD Number: EPD-SLG-20150317-CAE1-DE published by IBU - Institut Bauen & Umwelt e.V., 2015	EPD for Concrete plaster standard stone gray with intent
EPD Number: EPD-BBS-20120030-IBG1-DE published by IBU - Institut Bauen & Umwelt e.V., 2012	EPD for Concrete light shaft system
EPD Number: EPD-KRO-20160234-CCA1-DE published by IBU - Institut Bauen & Umwelt e.V., 2017	EPD for Concrete paving stone with black and white mottled header
EPD Number: EPD-KRO-20160221-CCA1-DE published by IBU - Institut Bauen & Umwelt e.V., 2017	EPD for Concrete paving stone with fine chippings
EPD Number: environdec EPD S-P-01259 published by Environdec, 2018	EPD for Autoclaved Aerated Concrete
EPD Number: BREG EN EPD 000192 published by Bre, 2018	EPD for Hanson, C28/35 CIIIA Ready Mix Concrete
EPD Number: BREG EN EPD 000193 published by Bre, 2018	EPD for Hanson, C32/40 CIIIA Ready Mix Concrete
EPD Number: BREG EN EPD 000194 published by Bre, 2018	EPD for Hanson, GEN3 CIIIA Ready Mix Concrete
EPD Number: BREG EN EPD 000195 published by Bre, 2018	EPD for Hanson, C28/35 CIIIB Ready Mix Concrete
EPD Number: BREG EN EPD 000196 published by Bre, 2018	EPD for Hanson, C32/40 CIIIB Ready Mix Concrete

EPD Number: environdec EPD S-P-01060 published by Environdec, 2017	EPD for concrete railway sleepers SB35F
Oekobau, Federal Ministry of the Interior, Building and Community, 2017	A German database for LCA of buildings by the Federal Ministry of the Interior, Building and Community.
EPD Number: environdec EPD S-P-00682 published by Environdec, 2015	EPD for Enviroblock Dense Blocks
EPD Number: environdec EPD S-P-00634 published by Environdec, 2007	EPD for KLASSIC CEMENT POSTs
EPD Number: environdec EPD S-P-00683 published by Environdec, 2015	EPD for Enviroblock Lightweight Blocks
EPD Number: BREG EN EPD 000197 published by Bre, 2018	EPD for Hanson, UK Average Ready Mix Concrete
EPD Number: BREG EN EPD 000191 published by BRE, 2018	EPD for Hanson, GEN3 CEMI Ready Mix Concrete
EPD Number: BREG EN EPD 000190 published by BRE, 2018	EPD for Hanson, C32/40 CEMI Ready Mix Concrete
EPD Number: BREG EN EPD 000189 published by BRE, 2018	EPD for Hanson, C28/35 CEMI Ready Mix Concrete
EPD Number: BREG EN EPD 000154 published by BRE, 2015	EPD for Ready mix concrete
EPD Number: EPD-BPC-20180013-CCD1-EN published by IBU - Institut Bauen & Umwelt e.V., 2018	EPD for UK manufactured single leaf concrete cladding panel
EPD Number: EPD-BPC-20170093-CCD1-EN published by IBU - Institut Bauen & Umwelt e.V., 2017	EPD for UK Manufactured Precast Aerated Concrete Blocks
EPD Number: EPD-BPC-20170092-CCD1-EN published by IBU - Institut Bauen & Umwelt e.V., 2017	EPD for UK Manufactured Precast Concrete Blocks
EPD Number: EPD-BPC-20170094-CCD1-EN published by IBU - Institut Bauen & Umwelt e.V., 2017	EPD for UK Manufactured 1 tonne of Generic Precast Concrete Paving Products (Blocks, Slabs, Channels and Kerbs)
EPD Number: EPD-BPC-20170091-CCD1-EN published by IBU - Institut Bauen & Umwelt e.V., 2017	EPD for UK Manufactured DN600 Concrete Pipe with Class B Bedding
EPD Number: EPD-BPC-20160005-CCD1-EN published by IBU - Institut Bauen & Umwelt e.V., 2017	EPD for UK Manufactured Precast Hollowcore Flooring
EPD Number: EPD-BPC-20170148-CCD1-EN published by IBU - Institut Bauen & Umwelt e.V., 2017	EPD for UK manufactured Precast Concrete Ground Beam
EPD Number: EPD-RMC-20180095-CBG1-EN published by IBU - Institut Bauen & Umwelt e.V., 2018	EPD for UK manufactured generic ready-mixed concrete

B.3. Steel

B.3.1. NMD

Title	Description
Voorspanstaal	Generic Value for prestressing steel

Table B.3: Steel EPD's and other sources used out of the NMD

B.3.2. ICE

Reference Details	Description
Worldsteel - LCI Data for Steel Products, LCI 2017, Worldsteel, 2017	LCI of the world steel market
EPD Number: BREG EN EPD 000078 published by BRE, 2015	EPD for Hot Rolled Flat Steel, Recycled. From a specific manufacturer in Turkey.
EPD Number: BREG EN EPD 000079 published by BRE, 2015	EPD for Hot Rolled Flat Steel, Recycled. From a specific manufacturer in Turkey.
EPD Number: BREG EN EPD 000080 published by BRE, 2016	EPD for Reinforcing steel bar, recycled. From a specific manufacturer in Turkey.
EPD Number: BREG EN EPD 000121 published by BRE, 2015	EPD for Gratings & Kerb drainage, Saint-Gobain PAM UK
EPD Number: BREG EN EPD 000122 published by BRE, 2016	EPD for Surface boxes, Saint-Gobain PAM UK
EPD Number: BREG EN EPD 000125 published by BRE, 2016	EPD for Steel rebar, recycled. Sector Average produced by UK CARES at manufacturing facilities in France, Spain, Turkey and Portugal.
EPD Number: BREG EN EPD 000126 published by BRE, 2016	EPD for Steel rebar, recycled. From a specific manufacturer in France.
EPD Number: BREG EN EPD 000128 published by BRE, 2016	EPD for Steel rebar, recycled. From a specific manufacturer in Spain.
EPD Number: BREG EN EPD 000129 published by BRE, 2016	EPD for Steel rebar, recycled. From a specific manufacturer in Turkey.
EPD Number: BREG EN EPD 000130 published by BRE, 2016	EPD for Steel rebar, recycled. From a specific manufacturer in Turkey.
EPD Number: BREG EN EPD 000131 published by BRE, 2016	EPD for Steel rebar (Direct reduced iron production route). . From a specific manufacturer in Abu Dhabi.
EPD Number: BREG EN EPD 000132 published by BRE, 2016	EPD for non-alloy structural steel (Direct reduced iron production route). . From a specific manufacturer in Au Dhabi.
EPD Number: environdec EPD S-P-01158 published by Environdec, 2017	EPD for Steel Pipe Piles, dimensions 88,9*6,3mm. Per 6 m
EPD Number: environdec EPD S-P-01159 published by Environdec, 2017	EPD for SS (Structural Steel) Piles
EPD Number: environdec EPD S-P-01160 published by Environdec, 2017	EPD for SSdr (Structural Steel) Piles
EPD Number: environdec EPD S-P-01317 published by Environdec, 2018	EPD for ECO-ASFALT® Plus
EPD Number: EPD-EF-5.0 published by IBU - Institut Bauen & Umwelt e.V., 2013	EPD for Schiebetor_TT

EPD Number: BREG EN EPD 000208 published by BRE, 2018	**EPD for Steel rebar, recycled. From a specific manufacturer in Abu Dhabi.**
EPD Number: environdec EPD S-P-00903 published by Environdec, 2016	**EPD for Steel pipes**
EPD Number: environdec EPD S-P-00904 published by Environdec, 2016	**EPD for steel core piles**
EPD Number: environdec EPD S-P-01064 published by Environdec, 2017	**EPD for Oil Country Tubular Goods, steel.**
EPD Number: BREG EN EPD 000133 published by BRE, 2016	**EPD for Steel rebar. From a specific manufacturer in Turkey.**
EPD Number: BREG EN EPD 000134 published by BRE, 2016	**EPD for Steel rebar, recycled. From a specific manufacturer in Turkey.**
EPD Number: BREG EN EPD 000135 published by BRE, 2016	**EPD for Steel rebar, recycled. From a specific manufacturer in Turkey.**
EPD Number: BREG EN EPD 000137 published by BRE, 2016	**EPD for Steel rebar. From a specific manufacturer in Spain.**
EPD Number: BREG EN EPD 000138 published by BRE, 2016	**EPD for Stainless steel rebar. From a specific manufacturer in the UK.**
EPD Number: BREG EN EPD 000139 published by BRE, 2016	**EPD for Steel rebar. From a specific manufacturer in Qatar.**
EPD Number: published by IBU - Institut Bauen & Umwelt e.V., 2013	**EPD for Fire doors_T60, ASx; 1 m²**
EPD Number: environdec EPD S-P-00869 published by Environdec, 2017	**EPD for Steel Profiles and Accessories**
EPD Number: environdec EPD S-P-00854 published by Environdec, 2016	**EPD for HOT ROLLED STRUCTURAL AND RAIL - 1 tonne of rail products**
EPD Number: environdec EPD S-P-00855 published by Environdec, 2016	**EPD for REINFORCING ROD, BAR AND WIRE - LOW RELAXATION STRAND AND LOW RELAXATION WIRE**
EPD Number: environdec EPD S-P-00856 published by Environdec, 2016	**EPD for HOT ROLLED STRUCTURAL PRODUCTS - STRUCTURAL**
EPD Number: environdec EPD S-P-00857 published by Environdec, 2016	**EPD for REINFORCING MESH**
EPD Number: EPD-FRA-0.5 published by IBU - Institut Bauen & Umwelt e.V., 2013	**EPD for Fire sliding door _T30HM**
EPD Number: EPD-FVS-20130195-IBG2-DE published by IBU - Institut Bauen & Umwelt e.V., 2013	**EPD for Stainless steel door fittings**
EPD Number: EPD-KAL-20130273-IBA1-DE published by IBU - Institut Bauen & Umwelt e.V., 2014	**EPD for Steel Enamel Baths and Shower Trays**
EPD Number: EPD-TMZ-0.3 published by IBU - Institut Bauen & Umwelt e.V., 2012	**EPD for Front door_HM; 1 m² area**
EPD Number: EPD-LD-GB-24.0 published by IBU - Institut Bauen & Umwelt e.V., 2017	**EPD for sectional door-Lindab-LDC_steel**
EPD Number: EPD-COD-25.0 published by IBU - Institut Bauen & Umwelt e.V., 2016	**EPD for Industrial and Garage Doors Condoor-PG3-Steel 40mm; 1 m² area**
EPD Number: EPD-FTO-0.7 published by IBU - Institut Bauen & Umwelt e.V., 2012	**EPD for Fire door_T30**
Oekobau, Federal Ministry of the Interior, Building and Community, 2017	**A German database for LCA of buildings by the Federal Ministry of the Interior, Building and Community.**
EPD Number: environdec EPD S-P-01025 published by Environdec, 2017	**EPD for stretched coil electroelded mesh cold rolled.**
EPD Number: environdec EPD S-P-00782 published by Environdec, 2017	**EPD for c® Gyproc® Steel Profiles and Accessories**

EPD Number: environdec EPD S-P-00776 published by Environdec, 2015	EPD for TEKNO EVO steel piles.
EPD Number: environdec EPD S-P-00701 published by Environdec, 2018	EPD for Steel reinforcing bar manufactured from iron ore
EPD Number: environdec EPD S-P-00700 published by Environdec, 2018	EPD for Steel reinforcing bar manufactured from steel scrap
EPD Number: environdec EPD S-P-00697 published by Environdec, 2017	EPD for Steel Profiles
EPD Number: environdec EPD S-P-00696 published by Environdec, 2017	EPD for [Reinforcing Steel Bar
EPD Number: environdec EPD S-P-00559 published by Environdec, 2015	EPD for Steel – Welded Beams and Columns
EPD Number: environdec EPD S-P-00558 published by Environdec, 2015	EPD for steel plate. . From a specific manufacturer in Australia.
EPD Number: environdec EPD S-P-00308 published by Environdec, 2015	EPD for Steel reinforcement products for concrete. From a specific manufacturer in Denmark.
EPD Number: environdec EPD S-P-00307 published by Environdec, 2015	EPD for Steel reinforcement products for concrete. From a specific manufacturer in Finland.
EPD Number: environdec EPD S-P-00306 published by Environdec, 2015	EPD for Steel reinforcement products for concrete. From a specific manufacturer in Norway.
EPD Number: environdec EPD S-P-00305 published by Environdec, 2015	EPD for Steel reinforcement products for concrete. From a specific manufacturer in Sweden.
EPD Number: environdec EPD S-P-00256 published by Environdec, 2017	EPD for hot-drawn reinforcing steel for concrete in bars and coils. From a specific manufacturer in Italy.
EPD Number: environdec EPD S-P-00255 published by Environdec, 2015	EPD for for hot-rolled reinforcing steel for concrete in bar and coils. From a specific manufacturer in Italy.
EPD Number: environdec EPD S-P-00254 published by Environdec, 2017	EPD for hot-rolled reinforcing steel for concrete in bars and coils. From a specific manufacturer in Italy.
EPD Number: environdec EPD S-P-00253 published by Environdec, 2015	EPD for Steel Deformed Bars for Concrete Reinforcement. From a specific manufacturer in Italy.
EPD Number: environdec EPD S-P-00252 published by Environdec, 2017	EPD for steel merchant bars. From a specific manufacturer in Italy.
EPD Number: environdec EPD N. S-P-00257 published by Environdec, 2017	EPD for hot-drawn reinforcing steel for concrete in bars. . From a specific manufacturer in Italy.
EPD Number: BREGENEPD000178 published by BRE, 2013	EPD for SIP Kingspan

EPD Number: BREGENEPD000166 published by BRE, 2016	**EPD for SIP Kingspan**
EPD Number: BREG EN EPD000136 published by BRE, 2016	**EPD for Steel rebar, recycled**
EPD Number: BREG EN EPD 000198 published by BRE, 2018	**EPD for steel rebar**
EPD Number: BREG EN EPD 000182 published by BRE, 2018	**EPD for Non-Alloy Structural Steel, recycled**
EPD Number: BREG EN EPD 000181 published by BRE, 2018	**EPD for Steel rebar, recycled**
EPD Number: BREG EN EPD 000180 published by BRE, 2018	**EPD for Steel rebar, recycled**
EPD Number: BREG EN EPD 000179 published by BRE, 2017	**EPD for SIP Kingspan**
EPD Number: BREG EN EPD 000177 published by BRE, 2017	**EPD for SIP Kingspan**
EPD Number: BREG EN EPD 000143 published by BRE, 2016	**EPD for Steel rebar**
EPD Number: BREG EN EPD 000142 published by BRE, 2016	**EPD for Steel rebar**
EPD Number: BREG EN EPD 000141 published by BRE, 2016	**EPD for Steel rebar**
EPD Number: BREG EN EPD 000140 published by BRE, 2016	**EPD for Steel rebar**

C

Non-structural verification's for structural element sizing formulas

Three non-structural aspects that influence structural element sizing are taken into account; stairs& elevator requirements, daylight and the sound insulation between floor levels.

C.1. Airborn sound insulation

For the sounds insulation between floor levels only airborne sound insulation is considered. This specific type of sound insulation is often an issue with timber floors and solving this type of sound insulation is done with mass addition while contact sound insulation can be improved with tactics like floating screeds. The mass addition for airborne sound insulation is done in the form of concrete. This concrete is added to the floors until airborne sound insulation standards have been met. The sound waves are assumed to be perpendicular and the floor layers bonded sufficiently to be viewed as a homogeneous mass, making Rayleigh's law applicable. The structure is assumed to have no sound leaks.

The mass is determined for the lowest possible occurring frequency to ensure sufficient sounds insulation for all possible occurring frequency's. The lowest possible frequency taken into account is 50 Hz.

$$R_{\perp} = 20 \cdot \log\left(\frac{2\pi \cdot f \cdot m \cdot \cos 0}{2\rho_{air} \cdot c_{air}}\right) \tag{C.1}$$

C.2. Elevator and staircase capacity

The needed elevator capacity is calculated as a function of the total height of the building, the number of floors, desired area per person in the elevator and the desired waiting time. All elevators are able to reach all floors and the required capacity is determined for peak hours.

For the stair requirements the needed capacity for emergency escape is taken. According to Dutch building regulations the throughput capacity for an emergency escape route is given per meter width of that route. Using the amount of people in the building the required width to evacuate these people is determined.

- N: Number of floors
- P: Total population of the building
- T: Peak hour traffic percentage (e.g., 0.10 for 10%)
- C: Elevator car capacity (number of people)
- S: Elevator speed (meters per second)
- D: Door opening/closing time (seconds)
- L: Loading time per floor (seconds)

- WT: Desired average waiting time (seconds)
- floor_height: Height of one floor (meters)

$$\text{Peak Hour Traffic (PHT):} \quad \text{PHT} = P \times T \tag{C.2}$$

$$\text{Average Travel Height (H):} \quad H = \frac{N-1}{2} \times \text{floor\_height} \tag{C.3}$$

$$\text{Round-Trip Time (RT):} \quad \text{RT} = \left(\frac{2H}{S}\right) + \left(D \times \frac{H}{\text{floor\_height}}\right) + \left(L \times \frac{H}{\text{floor\_height}}\right) \tag{C.4}$$

$$\text{Handling Capacity (HC):} \quad \text{HC} = \left(\frac{3600}{\text{RT}}\right) \times C \tag{C.5}$$

$$\text{Number of Elevators Required (E):} \quad E = \frac{\text{PHT}}{\text{HC}} \tag{C.6}$$

With the average round trip time (RT) and the calculated amount of elevators (E) it is calculated how long on average people will have to wait. If this is above the maximum desired waiting time (WT) elevators are added until a desired waiting time has been reached.

Based on the desired number of people per elevator and the amount of space required per person the total area of elevators required is calculated.

The amount of people that have to use the elevator is determined by dividing the sum of the floor area by the amount of floor area a single person requires in a office. These values can all be adapted by the user if desired. The value now taken is based on minimum demands from the ARBO and NEN 1824 rounded upwards to include travel space.

For the stair requirements the needed capacity for emergency escape is taken. The throughput capacity for a stairwell with a height difference of more than 1m and a tread size of at least 0.17 m is 90 people per meter of width[6]. The number of people per floor are calculated as described above and this number is taken to determine the necessary width of the stair. An intertwined stairwell is assumed so the calculated width does not have to be doubled.

C.3. Daylight

For daylight the rule of thumb for daylight entry is used. The rule of thumb states that direct sunlight reaches a distance of one times the free height away from the facade, with indirect sunlight extending up to two times this distance. Beyond this, daylight is not considered to be present. Since in the central area of the floor plan the core is placed and often other non-light dependent functions it is acceptable to have a part of the floor plan with no daylight. To ensure acceptable daylight factors in the rest of the building, it is recommended that the width and length of the building's floor plan do not exceed six times the free height value. This ensures that the majority of the building's interior remains within an decent range for daylight.

D

Element Cross Seciont Size Determination Section Formulas

The core is schematized as a clamped column being loaded with a lateral q-load.

$$w = \frac{ql^4}{8E_f I} \tag{D.1}$$

To account for loss of stiffness due to cracks occurring under possible tensile forces a fictive stiffness, E_f, is calculated using table D.1 out of EN-1992-1-1.

Concrete Class	Formula for $\alpha_n \leq 0.45$	Formula for $0.45 < \alpha_n \leq 0.9$
C12/15	$(1.30 + 410\rho + (9.0 - 130\rho)\alpha_n) \times 10^3 < 2900$	$(6.8 + 517\rho)(1 - 0.5\alpha_n) \times 10^3$
C16/20	$(1.45 + 415\rho + (11.5 - 145\rho)\alpha_n) \times 10^3 < 3250$	$(8.5 + 514\rho)(1 - 0.5\alpha_n) \times 10^3$
C20/25	$(1.60 + 420\rho + (14.0 - 160\rho)\alpha_n) \times 10^3 < 3600$	$(10.0 + 510\rho)(1 - 0.5\alpha_n) \times 10^3$
C25/30	$(1.75 + 425\rho + (16.5 - 175\rho)\alpha_n) \times 10^3 < 3950$	$(11.7 + 506\rho)(1 - 0.5\alpha_n) \times 10^3$
C30/37	$(1.96 + 432\rho + (20.0 - 196\rho)\alpha_n) \times 10^3 < 4450$	$(14.0 + 501\rho)(1 - 0.5\alpha_n) \times 10^3$
C35/45	$(2.20 + 440\rho + (24.0 - 220\rho)\alpha_n) \times 10^3 < 5000$	$(16.7 + 495\rho)(1 - 0.5\alpha_n) \times 10^3$
C40/50	$(2.35 + 445\rho + (26.5 - 235\rho)\alpha_n) \times 10^3 < 5350$	$(18.3 + 491\rho)(1 - 0.5\alpha_n) \times 10^3$
C45/55	$(2.50 + 450\rho + (29.0 - 250\rho)\alpha_n) \times 10^3 < 5700$	$(20.0 + 487\rho)(1 - 0.5\alpha_n) \times 10^3$
C50/60	$(2.65 + 455\rho + (31.5 - 265\rho)\alpha_n) \times 10^3 < 6050$	$(21.6 + 484\rho)(1 - 0.5\alpha_n) \times 10^3$
C55/67	$(2.86 + 462\rho + (34.6 - 258\rho)\alpha_n) \times 10^3 < 6400$	$(23.8 + 480\rho)(1 - 0.5\alpha_n) \times 10^3$
C60/75	$(3.10 + 470\rho + (37.0 - 170\rho)\alpha_n) \times 10^3 < 6400$	$(25.5 + 480\rho)(1 - 0.5\alpha_n) \times 10^3$
C70/85	$(3.10 + 470\rho + (41.5 - 170\rho)\alpha_n) \times 10^3 < 6400$	$(28.1 + 480\rho)(1 - 0.5\alpha_n) \times 10^3$
C80/95	$(3.10 + 470\rho + (46.5 - 170\rho)\alpha_n) \times 10^3 < 6400$	$(31.1 + 480\rho)(1 - 0.5\alpha_n) \times 10^3$
C90/105	$(3.10 + 470\rho + (51.0 - 170\rho)\alpha_n) \times 10^3 < 6400$	$(33.7 + 480\rho)(1 - 0.5\alpha_n) \times 10^3$

Table D.1: Fictive elastic modulus E_f for symmitrically reinforced, rectangular cross section loaded with bending and axial forces.

With a max allowable deflection as a function of the height. The factor of 750 is taken to account for any rotation in the foundation and possible loss of stiffness due to opening in the core walls.

$$w_{max} = \frac{h}{750} \tag{D.2}$$

Out of this the necessary second moment of inertia is calculated and since a square core is assumed. This gives the needed dimensions of the core.

The beams are dimensioned using a maximum deflection as well. Assuming hinged connections the deflection is calculated using the following formula;

$$w = \frac{5ql^4}{384EI} \tag{D.3}$$

For the maximum deflection separated values might have to be used for the facade beams and the inner beams. This is due to movement restraints of the facade elements that are more strict than the maximum deflections of the SLS. These factors have yet to be determined.

According to NEN-EN 1995-1-1 the maximum deflections can be chosen out of the range shown in table D.2.

$$w_{net,fin} = w_{inst} + w_{creep} - w_c = w_{fin} - w_c \tag{D.4}$$

$w_c = Upwarddeflection$

-	w_{inst}	$w_{net,fin}$	w_{fin}
Beam on two supports	$l/300 - l/500$	$l/250 - l/350$	$l/150 - l/300$
Cantilever beam	$l/150 - l/250$	$l/125 - l/175$	$l/75 - l/150$

Table D.2: Range maximum allowed deflection timber beams NEN-EN 1995-1-1

A deflection of $l/300$ is the default value.

$$w_{max} = \frac{Span}{300} \tag{D.5}$$

The floor is dimensioned by taking a one meter wide section and following the same calculation as with the beams.

$$w = \frac{5ql^4}{384EI} \tag{D.6}$$

$$w_{max} = \frac{Span}{300} \tag{D.7}$$

The columns are dimensioned based on maximum compression, Eulers buckling formula and axial strain.

$$F_{buckling} = \frac{\pi^2 EI}{L^2} \tag{D.8}$$

$$N \cdot L = E \cdot A \tag{D.9}$$

For the force on the column the most heavily loaded column on the ground floor is taken. This load is estimated by taking the number of floors, the loaded area the column has to carry and the applied permanent and live loads. The dead weight of the columns them self is not taken into account.

The floors thickness is determined in a similar manner as the beam with maximum deflection. A one meter wide strip is taken as a 1 meter wide beam and the dimensioning method of the beam with maximum deflection is than applied.

D.0.1. Dynamic Behavior Floors

For simply supported clt slabs it is desired to keep the natural frequency above 9 Hz [57]. The natural frequency of the floor can be calculated using equation D.10

$$n_{1x} = \frac{\pi}{2 \cdot l^2} \cdot \sqrt{\frac{(EI)_{eff}}{\rho \cdot A}} \quad \text{(D.10)}$$

$l = the\ floor\ span\ [m]$
$\rho = thecharacteristicdensity\ [kg/m^2]$
$(EI)_{eff} = effective\ bendingstiffness\ [Nm^2/m]$

With this formula a minimum thickness for the CLT floors is determined as the starting point for the static calculations.

D.0.2. Connection design - Development

Column-beam connection

The bolts, steel plates or the timber itself may be governing.

For the dowel type fasteners all failure mechanism must be checked. It is assumed that both the steel and timber elements of the joint can reach full plastic capacity. For single steel on timber dowel connections eurocode provides the failure mechanisms shown in figure D.1. For the joints in this case mechanism f,g and h would be relevant.

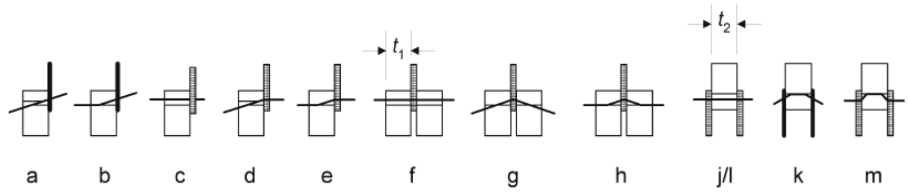

Figure D.1: Failure mechanisms dowels NEN-EN 1995-1-1

In case of two slotted plates the eurocode provides no formulas. For those case the failure mechanism determined by Pedersen can be used [48]. The failure mechanisme are shown in figure D.2 and the accompyning formulas in figure D.3.

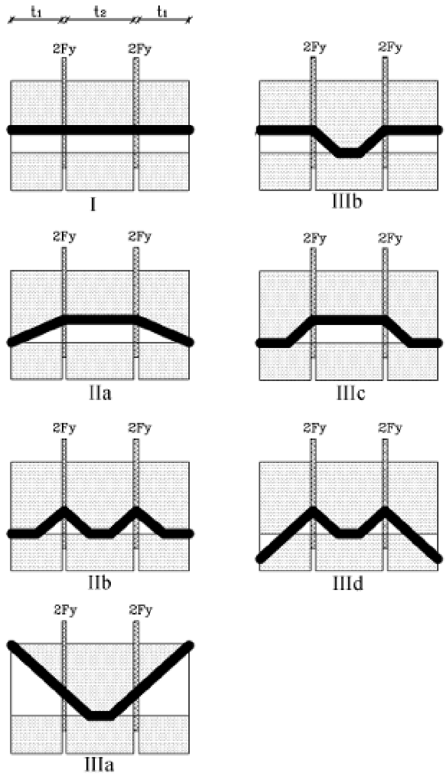

Figure D.2: Failure mechanismes slotted-in steel plates with four shear planes[48]

$$
F_y = min \begin{cases}
\frac{1}{4}(2t_1 + t_2) d\, f_h & \text{Mode I} \\
\left(-\frac{1}{2}t_1 + \frac{t_2}{4} + \sqrt{\frac{1}{2}t_1^2 + \frac{M_y}{d\, f_h}}\right) d\, f_h & \text{Mode IIa} \\
\sqrt{4M_y\, d\, f_h} & \text{Mode IIb} \\
\left(\frac{1}{2}t_1 + \frac{1}{2}\sqrt{t_1^2 + \frac{2M_y}{d\, f_h}}\right) d\, f_h & \text{Mode IIIa} \\
\left(\sqrt{\frac{M_y}{d\, f_h}} + \frac{1}{2}t_1\right) d\, f_h & \text{Mode IIIb} \\
\left(\sqrt{\frac{M_y}{d\, f_h}} + \frac{1}{4}t_2\right) d\, f_h & \text{Mode IIIc} \\
\left(-\frac{1}{2}t_1 + \sqrt{\frac{1}{2}t_1^2 + \frac{M_y}{d\, f_h}} + \sqrt{\frac{M_y}{d\, f_h}}\right) d\, f_h & \text{Mode IIId}
\end{cases}
$$

Figure D.3: Failure mechanismes slotted-in steel plates with four shear planes equations[48]

The lowest value for F_y is taken as $F_{governing}$. Additional needed formulas for this step are D.11 and D.12.

$$f_{h,k} = 0.082\,(1 - 0.01 \cdot d) \cdot \rho_k \tag{D.11}$$

$$M_{y,k} = 0.3 \cdot f_{u,k} \cdot d^{2.6} \tag{D.12}$$

The governing failure mechanism is than taken in equation D.14 to determine the governing failure load.

$$n_{eff} = min(n_{columns}; n_{columns}^{0.9} \cdot (\frac{a_1}{13d})^{0.25}) \tag{D.13}$$

$$F_{\text{max,dowels}} = 4 \cdot n_{\text{eff}} \cdot F_{\text{governing}} \cdot n_{\text{rows}} \tag{D.14}$$

For the timber verification equations D.18 andD.17 are used.

$$F_{\text{max},c,k} = f_{c,0,k} \cdot A_{\text{net,timber}} \tag{D.15}$$

$$F_{\text{max},c,d} = k_{mod} \cdot \frac{F_{\text{max},c,k}}{\gamma_M} \tag{D.16}$$

$\gamma_M = 1.3$
$K_{\text{mod}} = 0.6$

$$F_{\text{max},t,k} = f_{t,0,k} \cdot A_{\text{net,timber}} \tag{D.17}$$

$$F_{\text{max},t,d} = k_{mod} \cdot \frac{F_{\text{max},c,k}}{\gamma_M} \tag{D.18}$$

$\gamma_M = 1.3$
$K_{\text{mod}} = 0.6$ For the verification of the steel plates equation D.19 is used.

$$F_{\text{max,plates}} = \min\left(f_y \cdot t_{\text{plate}} \cdot b_{\text{plate}}; \frac{0.9 \cdot f_u A_{\text{net}}}{\gamma_{M,2}}\right) \tag{D.19}$$

Slotted-in steel plate connections provide in reality not a fully hinged joint. But a semi-rigid connection. In the model the connections are considered fully hinged. The rotational stiffness of these joints can be determined using formulas D.20 and D.21.

$$K_{ser} = \rho_m^{1.5} \cdot \frac{d}{23} \tag{D.20}$$

$$K_{rot,connection} = K_{ser} \cdot I_p \tag{D.21}$$

The slip factor that is used is the slip factor for the fasteners. This calculation has to be multiplied by the number of shear planes occurring. Using the density of timber. To take the interaction of timber and steel into account the density of the timber should be doubled [48]. This feature is optional in the structure generator tool, but by default the joints are considered to be fully hinged. This is done to exclude any possible favourable contributions from the joints in the calculations as an extra safety measure in the design.

All bolts are assumed to be pre drilled and larger than 5mm. To keep the connections as small as possible the minimum spacings are taken. The minimum spacings and distances are taken according to the values provided in NEN-EN 1995-1-1. Shown in table D.3

To ensure bolts will not be governing in 90% of the cases, bolt class M10.9 is assumed with yielding strength of 900 MPa and an ultimate limit strenght of 1000 MPa. The bolt size will also be taken at a size that in 90% of the cases it will be sufficient. Although in some cases overdimensioned the overall influence on the embodied carbon of the design is assumed to be relatively low and it is not the purpose of this tool to automate connection design but to give a reasonable estimate of the embodied carbon of the connection.

Type of Distance and Comments	Angle α	With Pre-Drilled Holes $\geq 5mm$
Intermediate Distance a_1 (Parallel to grain)	$0° \leq \alpha \leq 360°$	$(4 + \|\cos\alpha\|)d$
Intermediate Distance a_2 (Perpendicular to grain)	$0° \leq \alpha \leq 360°$	$(3 + \|\sin\alpha\|)d$
Distance a_3, t (Loaded end)	$-90° \leq \alpha \leq 90°$	$(7 + 5\|\cos\alpha\|)d$
Distance a_3, c (Unloaded end)	$90° \leq \alpha \leq 270°$	$7d$
Distance a_4, t (Loaded edge)	$0° \leq \alpha \leq 180°$	$d \geq 5$ mm : $(3 + 4\|\sin\alpha\|)d$
Distance a_4, c (Unloaded edge)	$180° \leq \alpha \leq 360°$	$3d$

Table D.3: Minimal intermediate, end and edge distances NEN-EN 1995-1-1

D.0.3. Assumptions and simplifications

- All bolts are symmetrically spaced in a square configuration.
- Two plates are assumed with a standard thickness of 10 mm. This thickness is not iterated but can be manually adapted.
- Timber strength class is as of now not parametrized and assumed to be C40.
- It is not verified if the generated joints fit in the beams and columns.
- Climate class 1 and all load on joint is taken as permanent.

D.0.4. Differential Vertical Shortening Creep - Development

$$u_{creep} = u_{instant} \cdot (1 + k_{def}) \tag{D.22}$$

k_{def} is defined by the climate class and type of engineered wood product.

Climate class 1	Moisture compliant with temperature of 20 degrees and a relative humidity that exceeds 65% for only a few weeks per year	average maximum moisture content timber of 12%
Climate class 2	Moisture compliant with temperature of 20 degrees and a relative humidity that exceeds 85% for only a few weeks per year	average maximum moisture content timber of 20%
Climate class 3	Higher moisture content than class 2	average moisture content timber >20%

Table D.4: Climate classes EC5

D.0.5. Foundation Design - Development

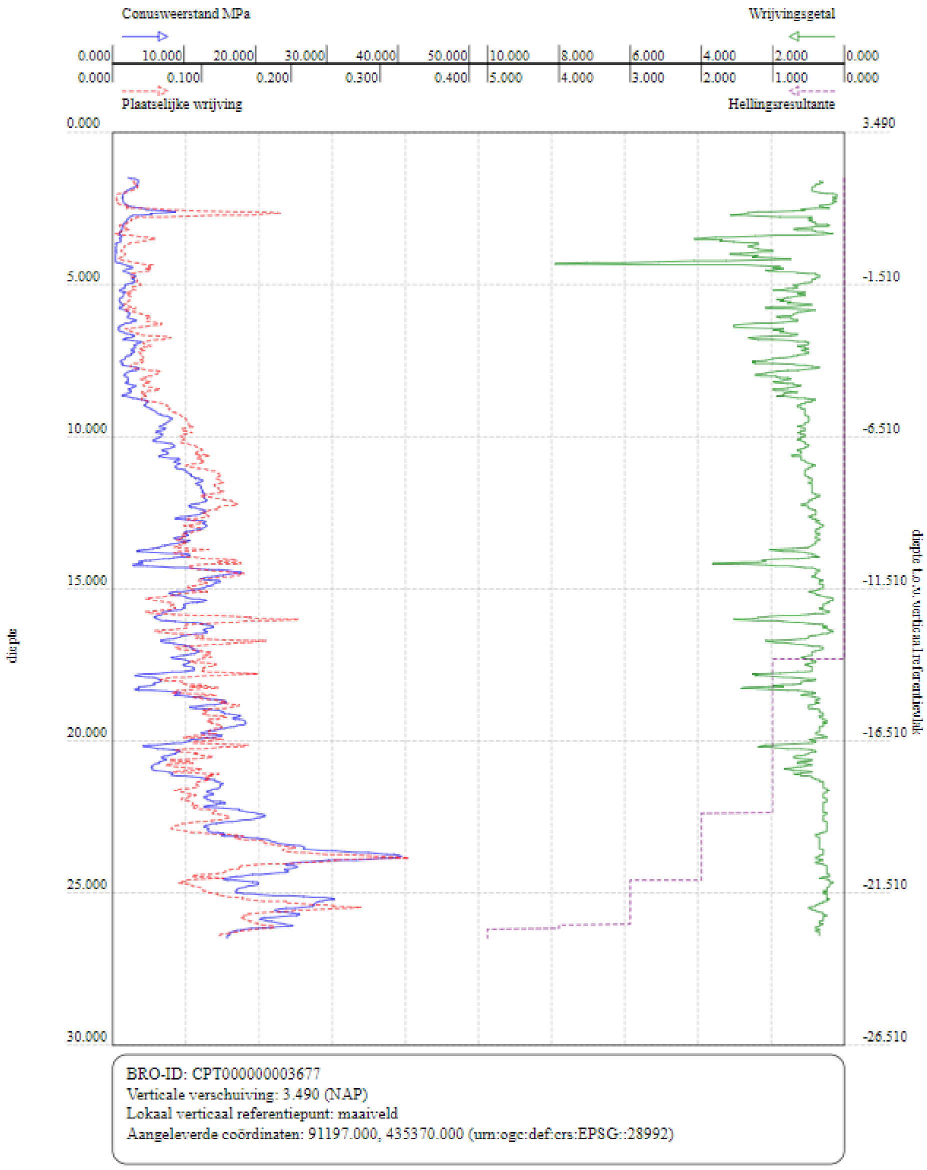

Figure D.4: Connection types and their placements

D.0.6. Detailed Core modelling - Assessment

Torsion

The structures generated are currently limited to symmetrical structures. The amount of torsion expected is therefore quite limited. Due to uneven wind loads torsion however may still arise and therefore the core should be checked for torsional resistance. Including this verification will make the step to unsymmetrical and more complicated structures in later steps more accessible.

It is striven for that the torsional resistance alone is sufficient for carrying the torsional resistance. The torsional resistance is calculated using the equations shown below.

$$T_{Rd,C} = 2 \cdot A_k \cdot f_{ctd} \cdot t_{\text{eff,i}} \tag{D.23}$$

$$t_{\text{eff}} = \max\left\{\frac{A}{u} : (C + \Phi_{\text{sw}} + \frac{\Phi_{\text{sl}}}{2}) \cdot 2\right\} \tag{D.24}$$

$$f_{ctd} = \frac{f_{ctk,0.05}}{\gamma_c} = \frac{(0.7 \cdot 0.3 \cdot f_{ck}^{2/3})}{1.5} \tag{D.25}$$

If the concrete is not able to carry the torsional force by itself, the equation below can be used to calculate the maximum torsional resistance if reinforcement is placed.

$$T_{Rd,\text{max}} = 2 \cdot \nu \cdot f_{Cd} \cdot A_k \cdot t_{\text{eff}} \cdot \sin(\theta) \cdot \cos(\theta) \tag{D.26}$$

$$\nu = 0.6\left(1 - \frac{f_{ck}}{250}\right) \tag{D.27}$$

Shear

$$v_{Ed} = \frac{V_{Ed}}{d \cdot b \cdot 2} \tag{D.28}$$

b is the width of the beam and here the width of the core.

$$v_{\text{min}} = 0.035 \cdot k^{3/2} \cdot (\sqrt{f_{Ck}})^{1/2} \tag{D.29}$$

$$v_{R_{d,C}} = 0.12 \cdot k(1000 \cdot \rho_l \cdot \sqrt{f_{ck}})^{1/3} \tag{D.30}$$

$$k = 1 + \sqrt{\frac{200}{d}} \leq 2 \tag{D.31}$$

$$\rho_l = \frac{A_s}{b \cdot d} \tag{D.32}$$

$$\rho_{w,min} = \frac{(0.08 \cdot \sqrt{f_{ck}})}{f_{yk}} \tag{D.33}$$

$$V_{Rd,C} = (max(v_{Rd,c}, v_{min})) \cdot b \cdot d \tag{D.34}$$

Torsion + Shear

$$\frac{T_{Ed}}{T_{Rd,c}} + \frac{V_{Ed}}{V_{Rd,c}} \leq 1 \tag{D.35}$$

Bending

$$M_{Rd,s} = z \cdot F_s = z \cdot A_s \cdot f_{yd} \tag{D.36}$$

$$M_{Rd,c} = z \cdot F_c = z \cdot 0.453 \cdot f_{ck} \cdot x_u \tag{D.37}$$

Tension Side

$$\sigma = \frac{+M}{w} - \frac{N_{\text{selfweight}}}{A} - \frac{N_{\text{column load}}}{A} \tag{D.38}$$

Compression Side

$$\sigma = \frac{-M}{w} - \frac{N_{\text{selfweight}}}{A} - \frac{N_{\text{column load}}}{A} \tag{D.39}$$

E

Validation appendix

E.1. User Experience

To assess the quality and added value of the tool developed during this thesis, a questionnaire has been created. Most questions are on a scale of 1-10, with 1 being the lowest and 10 being the highest.

1. **Ease of Use**
   On a scale of 1 to 10, how easy was the tool to navigate and use?
   Optional: Please provide any feedback on the user interface or workflow.
2. **Effectiveness in Integrating Embodied Carbon**
   How effective do you find the tool in integrating Embodied Carbon considerations into the early design phase? (1 = Not effective, 10 = Very effective)
   Optional: What aspects of Embodied Carbon integration could be improved?
3. **Accuracy of Results**
   How accurate do you believe the Embodied Carbon estimates generated by the tool are? (1 = Not accurate, 10 = Highly accurate)
   Optional: Where do you think the tool might introduce inaccuracies?
4. **Speed and Performance**
   On a scale of 1 to 10, how would you rate the speed and performance of the tool during your use?
   Optional: Did you encounter any delays or inefficiencies?
5. **Ability to Handle Early Design Stage Uncertainty**
   How well does the tool handle uncertainty typical in the early design stages (e.g., unknown materials, unclear specifications)? (1 = Poorly, 10 = Very well)
6. **Customization and Flexibility**
   On a scale of 1 to 10, how flexible is the tool in allowing customizations and adjustments to inputs like material factors or assumptions?
   Optional: Where could the tool offer more flexibility?
7. **Communication Across Disciplines**
   How well do you think this tool facilitates communication or collaboration between different disciplines (e.g., structural engineers, architects, sustainability experts)? (1 = Not well, 10 = Very well)
8. **Comparison to Existing Tools**
   Compared to other tools you have used for assessing Embodied Carbon in early design phases, how would you rate this tool on Usability, accuracy and verifiability (3 answers)? (1 = Worse, 10 = Superior)
9. **Clarity of Output/Reports**
   On a scale of 1 to 10, how clear and useful are the reports or outputs generated by the tool?
   Optional: What could make the reports or outputs more insightful or actionable?

10. **Overall Satisfaction**
    Overall, how satisfied are you with the tool in terms of its added value to the design process? (1 = Not satisfied, 10 = Very satisfied)
    Optional: What is the most significant improvement you would suggest for the tool?

F
Verification Results

F.1. Structural

F.1.1. Joints

	Dowels	UC Dowels	UC Compression Timber	UC Tension Timber	UC Plates	Mass
Column	4	0.237	0.031	0.034	0.005	11.195 kg
Beam	5	0.116	0.123	0.891	0.010	45.514 kg
Connecting plate	-	-	-	-	-	0

Table F.1: Methodology Verification Joint Variant 1 Excel Results Redone

	Dowels	UC Dowels	UC Compression Timber	UC Tension Timber	UC Plates	Mass
Column	4	0.237	0.031	0.034	0.019	26.571
Beam	6	0.116	0.123	0.890	0.015	81.431
Connecting plate	-	-	-	-	-	0

Table F.2: Methodology Verification Joint Variant 1 Tool Results Redone

	Dowels	UC Dowels	UC Compression Timber	UC Tension Timber	UC Plates	Mass
Column	4	0.370	0.021	0.023	0.008	13.740 kg
Beam	8	0.105	0.108	0.783	0.012	76.406 kg
Connecting plate	-	-	-	-	-	16.287 kg

Table F.3: Methodology Verification Joint Variant 2 Excel Results Redone

	Dowels	UC Dowels	UC Compression Timber	UC Tension Timber	UC Plates	Mass
Column	4	0.370	0.021	0.023	0.029	29.116 kg
Beam	8	0.105	0.108	0.783	0.019	126.483 kg
Connecting plate	-	-	-	-	-	23.343 kg

Table F.4: Methodology Verification Joint Variant 2 Tool Results Redone

	Dowels	UC Dowels	UC Compression Timber	UC Tension Timber	UC Plates	Mass
Column	4	0.533	0.016	0.017	0.012	17.91 kg
Beam	10	0.099	0.100	0.722	0.014	115.263 kg
Connecting plate	-	-	-	-	-	52.595 kg

Table F.5: Methodology Verification Joint Variant 3 Excel Results Redone

	Dowels	UC Dowels	UC Compression Timber	UC Tension Timber	UC Plates	Mass
Column	4	0.533	0.016	0.017	0.042	33.289 kg
Beam	10	0.099	0.100	0.722	0.024	181.538
Connecting plate	-	-	-	-	-	94.2

Table F.6: Methodology Verification Joint Variant 3 Tool Results Redone

G

Safety factors, material properties and loads

G.1. Safety factors

Partial factor	Value	description
γ_c	1.5	Concrete partial factor
γ_s	1.15	Reinforcement steel partial factor
γ_M	1.3	Sawn timber,joints
γ_M	1.25	Metal connection plates
k_{mod}	0.6	Climate class 1, Permanent loading

G.2. Material properties

Material Property FeB500 reinforcement steel	Value	**Unit**
Tensile strength $f_{t;k}$	500	[N/mm^2]
Design value tensile strength $f_{y;k}$ [N/mm^2]	435	[N/mm^2]
Concrete Density	2500	[kg/m^3]

G.3. Loads

G.3.1. Windload

Area type II, Rural is assumed. $C_f = 2.1$ and $C_sC_d = 1.0$. The windspeed is determined as a function of the height out of the design table from the Quick Reference and is assumed constant.

G.4. Load Combinations

The Structure Generator Tool evaluates multiple scenarios within a single iteration with a single load case, performing verifications for floor loads, wind loads, and both ULS and SLS simultaneously. In practice, separate calculations would be required for each specific scenario. Applying this to the Structure Generator Tool would necessitate generating separate structures for each scenario and verification type, then extracting the structural element dimensions from each load case. Afterward, the largest required dimension for each element category would need to be identified and combined into a single structure. This approach would significantly increase both the calculation time and complexity of the tool. Therefore, it was decided to exclude this process from the tool. This is a simplification which requires further investigation. All created structures fall within CC2, load case applied is shown below.

$$1.2G + 1.5Q_{k,1} \tag{G.1}$$

Consequence Class	**Description**	**K_FI**
CC1	Low consequence	0.9
CC2	Medium consequence	1.0
CC3	High consequence	1.1

H

Connection Design

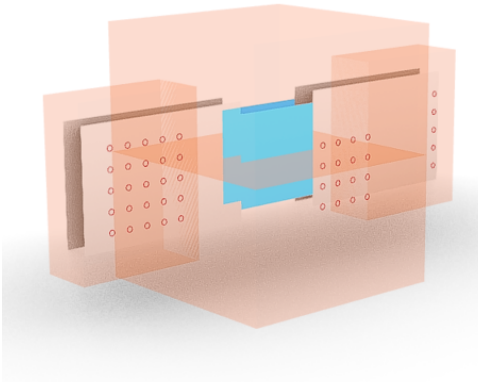

Figure H.1: Connection design perspective view

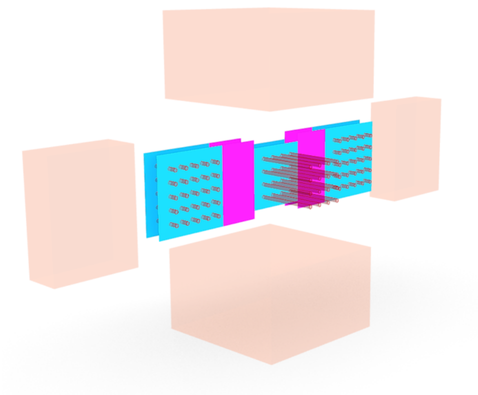

Figure H.2: Connection design perspective view exploded

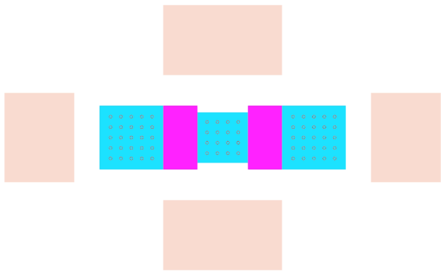

Figure H.3: Connection design front view exploded

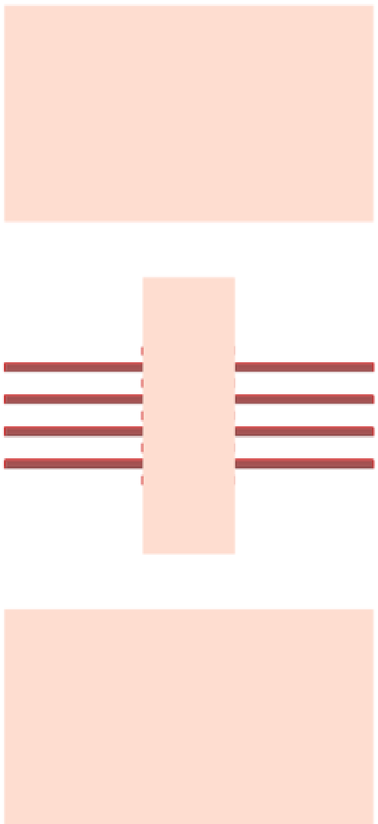

Figure H.4: Connection design side view exploded

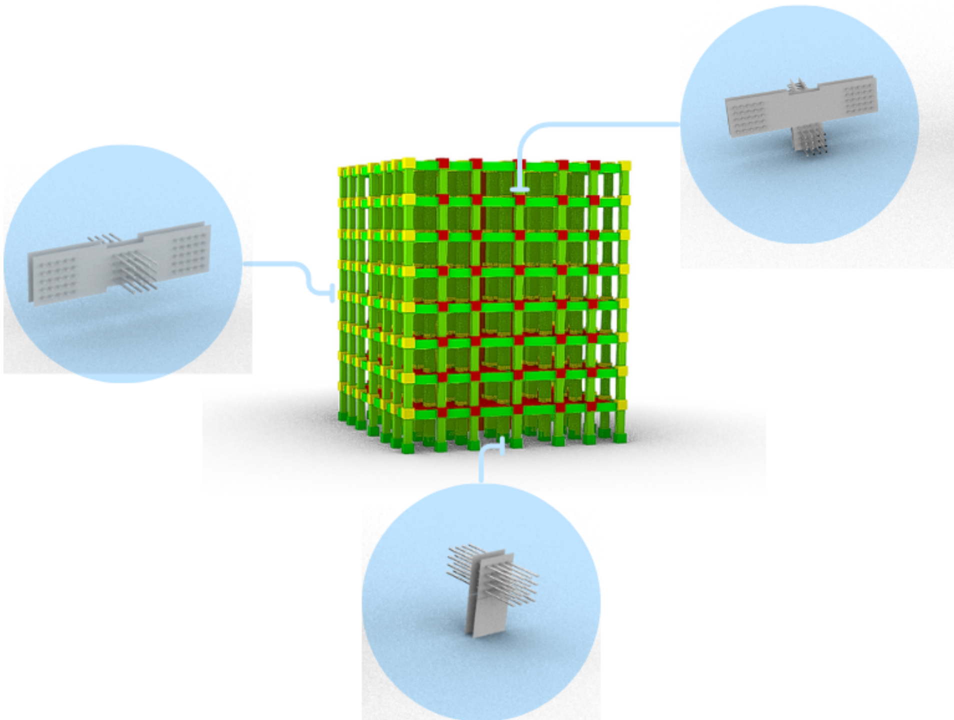

Figure H.5: Connection types and their placements