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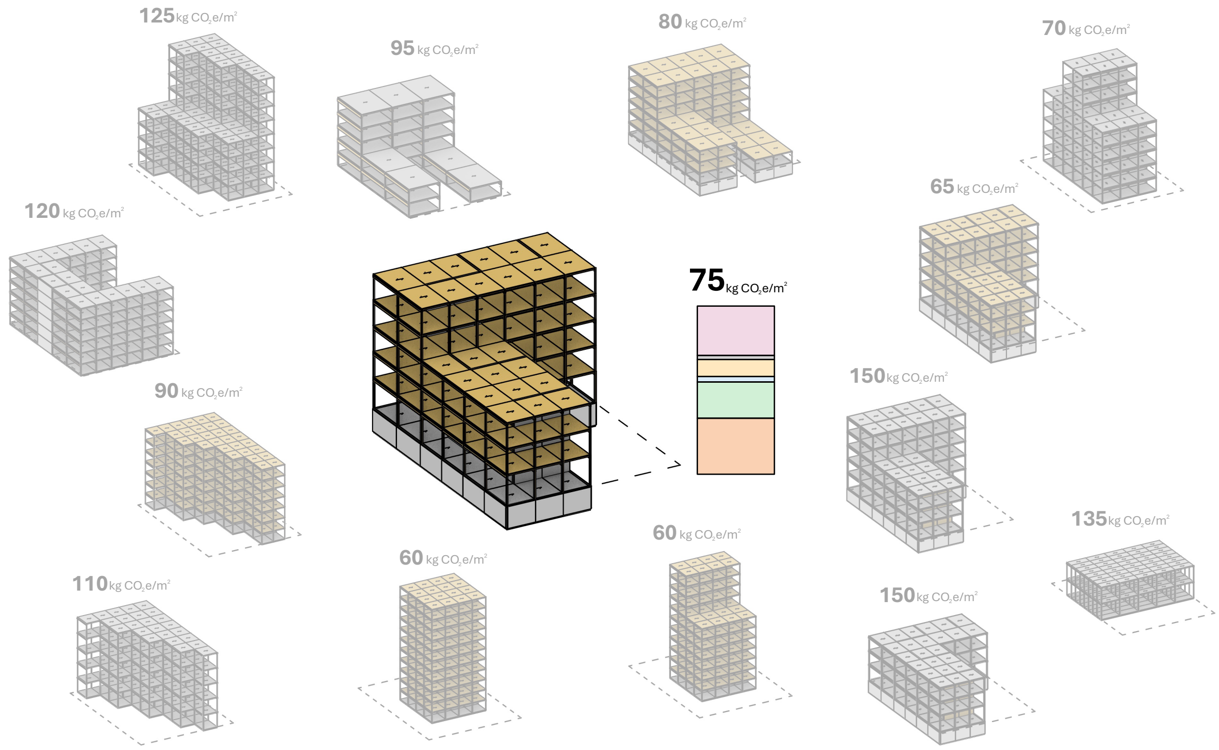

A parametric approach to environmental impact assessment of structural systems in early-stage design

Development of a user-oriented tool for intuitive feedback and informed decision-making

Master's thesis in Master's Programme Structural Engineering and Building Technology

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CHALMERS UNIVERSITY OF TECHNOLOGY
Master's thesis ACEX30
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MASTER'S THESIS ACEX30

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Examensarbete ACEX30
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Cover:
Several design alternatives evaluated using the developed tool, a designer's preferred option highlighted.
Department of Architecture and Civil Engineering
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ABSTRACT

In the context of global warming, the construction industry plays a key role in reducing greenhouse gas emissions. Structural systems can account for up to 60% of a building's emissions during the construction phase. Estimating the environmental impact of structural options early in the design process is essential, as this is when decisions most affect outcomes, despite greater uncertainty. However, structural input is often considered at a later stage, when the overall design is already set, limiting opportunities for integrated, low-impact solutions. This highlights a need for tools that support early-stage structural evaluation alongside architectural design.

This thesis presents a parametric tool for rapid exploration and comparison of structural systems in early-stage design. It integrates parametric modelling, structural design logic and life cycle assessment to support efficient and transparent environmental evaluation. The tool was developed through a user-centred process involving user personas, iterative prototyping, and scripting. It is intended primarily for structural engineers but also facilitates collaboration with architects and other stakeholders.

The tool enables users to generate structural system alternatives and receive summarised evaluations of environmental impact and element dimensions. It prioritises speed, usability and visual clarity. Its modular structure supports flexible geometries and structural elements are preliminarily sized using tabulated values in an extendable database. Based on a simply supported beam–column system, it performs a vertical load-takedown validated through hand calculations.

Two case studies guided development and assessed real-world use. The first focused on parametric functionality with academic and industry feedback. The second, based on a real project, was structured as a collaborative workshop. The user-friendly interface supported interdisciplinary dialogue and rapid iteration. The architect's request to present outputs to the client further highlighted the tool's practical value.

Future research could build on the initial implementation to further explore how the tool supports collaboration and informed decision-making for sustainable design. Development may include extended database content and optimisation features.

Keywords: early-stage design, parametric tool, structural systems, environmental impact, life cycle assessment, structural design, interdisciplinary collaboration.

En parametrisk metod för klimatpåverkan av bärande system i tidiga design skeden
Utveckling av ett användarorienterat verktyg för återkoppling och informerat beslutsfattande

Examensarbete inom masterprogrammet Konstruktionsteknik och byggnadsteknologi

ERIK GUSTAFSSON
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Institutionen för arkitektur och samhällsbyggnadsteknik
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SAMMANFATTNING

Byggbranschen spelar en avgörande roll i att minska utsläppen av växthusgaser i en tid då klimatfrågan är mer aktuell än någonsin. Den bärande stommen kan stå för 60% av en byggnads utsläpp under byggskedet. Därför är det viktigt att kunna bedöma miljöpåverkan från olika stomlösningar redan i tidiga skeden av designprocessen, när möjligheten att påverka är som störst, men osäkerheten också hög. Trots detta inkluderas konstruktionsperspektivet ofta sent i dagens arbetsflöden, vilket försvårar integrerade och klimatmedvetna beslut. Det finns därför ett tydligt behov av verktyg som möjliggör tidig utvärdering av bärande system i samspel med arkitektonisk utformning.

I detta examensarbete har ett parametriskt verktyg för snabb utforskning och jämförelse av olika stomalternativ i tidiga skeden utvecklats. Verktyget kombinerar parametrisk modellering, konstruktionsprinciper och livscykelanalys för att möjliggöra en effektiv och transparent bedömning av klimatpåverkan. Utvecklingen har skett utifrån användarnas perspektiv med definierade användarprofiler, iterativt prototyparbete och scriptbaserad implementering. Verktyget är främst riktat till konstruktörer men underlättar också samarbete med arkitekter och andra aktörer i designprocessen. Användaren kan generera olika stomlösningar och få sammanställda resultat kring klimatpåverkan och dimensioner för bärande element. Fokus har varit på användarvänlighet, tydlig visuell återkoppling och hög prestanda. Verktyget är modulärt uppbyggt för att hantera flexibla geometrier och dimensioneringen baseras på tabellvärden lagrade i en utbyggbar databas. Verktyget är baserat på ett antaget system av fritt upplagda bjälklag, balkar och pelare. En lastnedräkning utförs av verktyget och har verifierats med handberäkningar.

Två fallstudier har genomförts för att vägleda arbetet och utvärdera verktygets praktiska användbarhet. Den första fokuserade på den parametriska funktionaliteten och samlade in feedback från handledare inom akademin och branschen. Den andra utgick från ett verkligt byggprojekt i tidigt skede och genomfördes som en workshop där arkitekter och ingenjörer samarbetade. Verktygets potential att stödja tvärdisciplinär dialog och snabb iteration av designalternativ kunde verifieras. Arkitektens användning av resultaten i kommunikationen med beställaren understryker dess praktiska relevans.

Framtida utveckling kan bygga vidare på det implementerade verktyget och att djupare studera hur det kan stödja tvärdisciplinärt samarbete och informerade beslut. Potentiell utveckling av verktyget kan inkludera en utökad databas och optimeringsfunktioner.

Nyckelord: tidiga design skeden, parametriskt verktyg, bärande system, miljöpåverkan, livscykelanalys, konstruktionsteknik, tvärdisciplinärt samarbete.

Preface

This master's thesis was carried out between February and June 2025 as the final part of the Structural Engineering and Building Technology master's programme at Chalmers University of Technology. The study focuses on the development of a parametric computational tool to estimate the environmental impact of structural systems in early-stage building design.

The work has been conducted in collaboration with the engineering consultancy firm VBK Konsulterande Ingenjörer AB in Gothenburg, Sweden. The project was supervised by PhD student Toivo Säwén, at the division of Building Technology, Chalmers University of Technology, and structural engineers Daniel Jonsson and Jonathan Söderqvist at VBK. Dr. Mats Ander at the division of Architectural Theory and Methods at Chalmers University of Technology has been the examiner.

We would like to express our sincere gratitude to our supervisors and examiner for their valuable support and guidance throughout the project. Special thanks also go to the architects Markus Gustafsson and Maja Lindborg at Kaminsky Arkitektur AB for participating in one of the conducted case studies.

Lastly, we would like to express our gratitude to our opponents, David Selse and Erik Wigh, for their thoughtful discussions and constructive feedback throughout the process. We are also grateful to our family for their encouragement and support throughout our studies.

Gothenburg, June 2025
Erik Gustafsson & Sebastian Oguz

Contents

List of abbreviations

AEC	Architecture, engineering and construction
BIM	Building information modelling
BREP	Boundary representations
CAD	Computer-aided-design
CLT	Cross-laminated timber
CSV	Comma separated values
EKS	Europeiska konstruktionsstandarder
EPD	Environmental product declarations
EWP	Engineered wood product
FEM	Finite element method
GFA	Gross floor area
GHG	Green house gases
GWP	Global warming potential
JSON	JavaScript object notation
LCA	Life cycle assessment
OOP	Object-oriented programming
SDL	Superimposed dead load
SLS	Serviceability limit states
UCD	User-centred design
UI	User interface
ULS	Ultimate limit states

1 Introduction

This master's thesis explores how parametric modelling, structural engineering and environmental assessments can be integrated to develop a tool for evaluating design options in the early stages of a building project.

This chapter provides the background of the thesis, defines its aim and objectives, outlines its governing delimitations and presents the structure of the thesis.

1.1 Background

The construction industry is contributing greatly to emissions of greenhouse gases (GHG), both globally and in Sweden. As described by Boverket (2025), approximately 22% of Sweden's domestic GHG emissions originate from the construction industry (2022). The structural system is generally contributing the most to the total GHG emissions from a building project (Malmqvist et al., 2023). Among all building members, such as facades, internal walls and roofs, the structural system can account for up to 60 % of the total GHG emissions from the construction phase. Fossilfritt Sverige (2024) describes that the Swedish industry has committed to achieving net-zero GHG emissions by 2045, with a milestone of reducing emissions by 50% by 2030, compared to 2015 levels.

Fossilfritt Sverige (2024) points out key factors such as the need for increased collaboration throughout the entire design and construction process, where stakeholders work together in ways that support lower greenhouse gas emissions. Another key factor is the role of digitalisation in streamlining the transition to a industry with lower environmental impact, emphasising the importance of effective digital information flows related to materials and energy.

Establishing GHG emissions as a design driver in early-stage decision-making requires the ability to quantify it early in the design process, which can lead to more effective reductions (Fang et al., 2023). The most common method for assessing the environmental sustainability of buildings is to perform a life cycle assessment (LCA). The early stages of building design offer the greatest potential to reduce GHG emissions (Fang et al., 2023). However, applying LCA during these stages is not straightforward, as decisions related to material selection and structural member sizing are typically delayed to structural engineers in later phases (Basbagill et al., 2013). For LCA to become a meaningful decision-making tool early in the design process, designers must gain a better understanding of which parameters most significantly influence a building's environmental impact and which decisions have lesser effects (Basbagill et al., 2013). Despite these challenges, there is potential value in integrating LCA during early design to explore and compare alternative structural systems. This thesis focuses on the structural system of buildings and investigates how LCA and structural analysis can be combined to estimate the environmental impact of design options.

The design process of building design is often divided into four phases, conceptual design, schematic design, detailed design and construction (Ekvall, 2019). Depending on the design discipline, involvement in the building project varies, architects are typically involved early, while structural engineers and other specialists become involved at later stages. During the first phase, conceptual design, the architecture team are often working independently, making major decisions regarding global factors such as overall geometry and massing (Mueller, 2014). Structural considerations are minimal at this stage, with structural engineers generally becoming involved in the schematic design phase to begin developing possible solutions. However, the potential to influence the performance of the structural system is reduced at this stage compared to earlier phases, which highlights the importance of integrating structural design already in the conceptual design stage, as an interdisciplinary work.

The uncertainty of a building's environmental impact typically decreases as the project progresses, as illustrated in Figure 1.1. This thesis seeks to develop a parametric tool that can be used in early stage design; in stages with greater design freedom but with less design knowledge. Such a computational tool can enhance the design process to strive for sustainability and performance driven design solutions (Fusari et al., 2024). By developing a tool that integrates structural design principles, parametric modelling and LCA methods, designers can more efficiently evaluate the impact of decisions related to materials, geometry and building systems. Translating the complexity of structural design in an intuitive manner, such a tool would need to be user-centric, making it easy to assess the outcomes of early design choices and enhancing the decision-making process (Fusari et al., 2024).

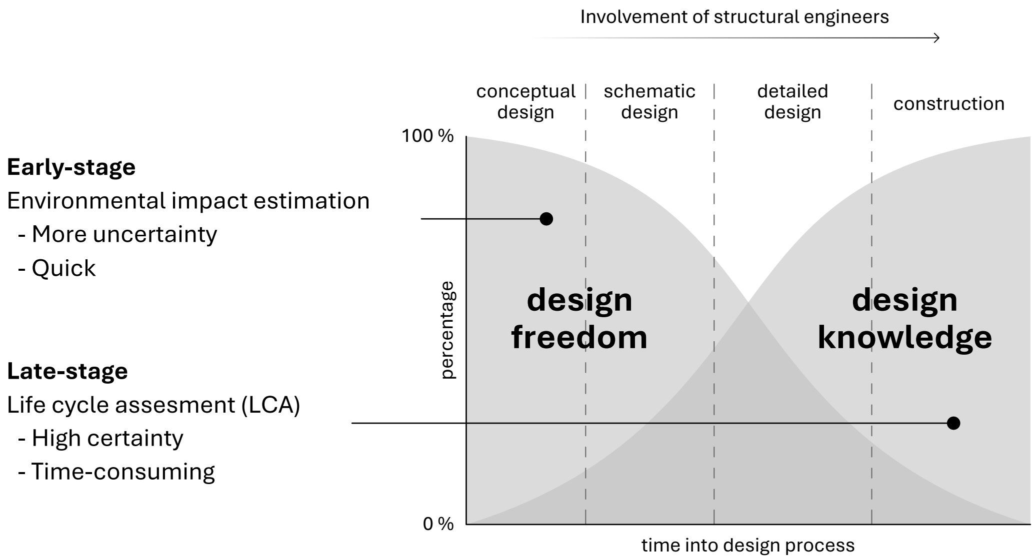


Figure 1.1: Relation between design freedom and design knowledge in building design, adopted from (Mueller, 2014), (Fang et al., 2023) and (Ekvall, 2019).

A key knowledge gap lies in the traditional workflow between architects and structural engineers during the early stages of building design, where involvement of structural engineers traditionally happen gradually, as the project proceeds, as illustrated in Figure 1.1. Typically, architects work independently in these initial phases, exploring multiple design options through rapid iterations. This stage is characterised by high design freedom and holds the greatest potential to influence the building's overall environmental impact.

Despite the fact that the structural system can contribute up to 60% of a building's GHG emissions during the construction phase, it is often not thoroughly evaluated until later in the process, when the design is more fixed and the opportunity for change is reduced (Fang et al., 2023). To address this, the designers need tools and workflows that allow them to rapidly assess the environmental impact of various structural design alternatives in terms of material selection, geometry and system configuration. Without such capabilities, structural input risks being disconnected from the iterative, fast-paced nature of early-stage architectural design, limiting the potential for integrated, low-impact solutions (Mueller, 2014).

1.1.1 Previous prototype

During the spring of 2024, a first prototype of a parametric tool was developed in a master's thesis by Flyman (2024), together with the structural engineering company VBK Konsulterande Ingenjörer AB. This version was a proof of concept but needs to be developed further to cover more aspects and functionality to make it more applicable in real design processes. This tool was based on a column-beam system with a limited number of structural element types and materials, focusing mainly on vertical load takedown and preliminary sizing of slabs, beams and columns. The tool computes the environmental impact and highlights the interplay between different parameters and their combined effect on the total GHG emissions. This version was set to be a starting point for this thesis.

1.1.2 Literature study

A critical theoretical basis for this thesis is built upon an introductory review of literature related to early-stage strategies for reducing embodied carbon in structural systems. Fang et al. (2023) provide an extensive literature review that synthesises academic and industry sources to identify and evaluate a broad spectrum of strategies. These are categorised into baseline, holistic design and material-specific approaches. Baseline strategies often involve estimating embodied carbon through material quantities and statistical prediction models. Holistic design strategies emphasise parametric optimisation and multi-criteria decision-making, while material-specific strategies target the reduction of material usage and selection of low-carbon alternatives. Additionally, the importance of reuse and adaptive reuse of structural elements is underscored.

The review highlights the practical challenges in implementing these strategies, such as data availability, the complexity of tools and the need to balance cost, performance and environmental impact. Most notably, Fang et al. (2023) emphasise the necessity of accessible, user-friendly and data-driven tools that support early-stage decision-making in sustainable structural design. This highlights a gap between theoretical sustainability strategies and their implementation in practice.

Complementing this, Fusari et al. (2024) explore how computational tools can be integrated into structural design to evaluate and reduce embodied carbon. The study introduces the Smart Massing Tool (SMT), a Grasshopper plug-in for early-stage assessments, and ECO2, a Revit-based tool for detailed analysis using building information modelling (BIM) data. These tools address the critical gap in existing software regarding integration, flexibility and usability. Findings underscore the strengths of parametric tools in enabling rapid design comparisons, supporting customisation and improving user experience. Notably, users found it helpful to flip through previously saved design alternatives, featuring different typologies, materials and compile a matrix of options containing key embodied carbon data for side-by-side evaluation. This feature was seen as particularly valuable in supporting informed comparisons during early-stage exploration. Challenges such as interoperability and the need for broader geographical data integration are also acknowledged.

Together, the reviewed literature provides a strong foundation for identifying the methodological and practical needs in current sustainable design practice. It motivates the development of a parametric, user-oriented tool that supports structural and environmental evaluation in early design, a direction this thesis builds upon.

1.2 Aim

The aim of this thesis is to develop a parametric computational tool that supports the exploration and comparison of structural systems in early-stage building design, with a focus on estimating environmental impact in terms of GHG emissions. The tool combines parametric modelling, structural engineering principles, LCA and includes preliminary design of structural members. It should enable structural engineers to develop design proposals efficiently and promote transparent, informed collaboration with other stakeholders in the design process.

Research question:
How can a parametric tool with an intuitive user interface and rapid feedback support more informed decision-making and improve understanding of the structural system's environmental impact in early-stage design?

1.3 Objectives

The tool should provide an intuitive user experience, support flexible geometry inputs and include various structural members. It should be designed to be quick and user-friendly enough to facilitate collaboration among multiple disciplines in the early design phase.

The development of the parametric tool is guided through the following objectives:

- **Study** the work that was done by Flyman (2024) and investigate how it can be improved to fulfil the aim of this thesis.
- **Analyse** existing methods for evaluating the environmental impact of structural systems in early design stages.
- **Develop** a parametric workflow that integrates structural and environmental assessments that allows for flexible geometry input.
- **Implement** the workflow as a user-friendly tool within a computational design environment.

- **Evaluate** the tool's effectiveness and reliability by applying it to case studies and comparing results with traditional approaches.

The tool developed in this thesis will focus specifically on assessing structural systems in early design phases. It aims to rapidly provide the design team with insights into the environmental impact of their design choices, particularly regarding the geometry and material selection of the structural system.

1.4 Delimitations

This thesis focuses on estimating the embodied carbon of structural systems in early-stage building design. The objective is not to perform a full LCA, but rather to enable comparative assessments between design alternatives, thereby supporting informed decision-making during early design stages.

The environmental impact assessment is limited to global warming potential (GWP) within the construction stages, A1–A5 (European Committee for Standardization, 2011). These stages typically account for the majority of embodied emissions in structural systems and are therefore considered most relevant for the scope of this work.

The study is limited to structural performance under normal loading conditions. Only ultimate- and serviceability limit states (ULS and SLS) are considered, in accordance with Eurocode and the Swedish national annex (EKS 12). Moreover, aspects such as accidental loads, fire safety and dynamic effects are excluded. Structural calculations are done analytically and preliminary design is based on tabulated values.

The tool includes load-bearing walls, primarily for vertical load transfer and GWP calculation. However, no verification of horizontal stability is performed and lateral load resistance is not assessed. Snow load is included, but simplified as a uniform distributed load, without accounting for roof geometry.

The thesis focuses on common building types and materials used in Sweden such as multi-residential and office buildings. Only reinforced concrete, steel and timber are considered as structural materials. The structural systems are assumed to be column-beam-slab systems, with members modelled as simply supported in an orthogonal topology. This simplification enables a modular load path and sizing approach, suitable for early-stage comparison but not representative of fully optimised designs.

Tool development is carried out using Rhinoceros 3D and Grasshopper, with custom components written in Python. This restricts the implementation to a specific software environment, although the core logic could be transferable.

1.5 Thesis structure

The thesis is organised into the chapters listed below, progressing from theoretical background and methodology to results, discussion and conclusion. The results are presented across Chapters 4 to 6, covering the preparatory work, tool development and user testing phases.

- **Chapter 2: Theory** outlines the theoretical foundation for structural systems, environmental impact and parametric workflows. It introduces key principles related to structural concepts, geometry generation and environmental impacts relevant to early-stage design.
- **Chapter 3: Methodology** presents the methods used throughout the thesis, including the iterative development process, modelling assumptions, user personas and how case studies were carried out.
- **Chapter 4: Prepatory work** analyses an earlier prototype, identifying transferable functionalities and limitations, as well as an framework study. It concludes with a concept proposal for the continued development.
- **Chapter 5: Tool Development** detailed the development process of WP, the tool developed within the scope of this thesis. It describes the input logic, structural system logic, environmental calculations, database structure, output features and user interface, concluding with verification.
- **Chapter 6: User testing** presents the outcomes of two case studies with engineers and architects. It includes observations, tool results and user feedback gathered from practical applications in real design contexts.
- **Chapter 7: Discussion** reflects on WP's performance, its integration into practice and lessons learned. It discusses design support, comparison with literature and outlines directions for future work.
- **Chapter 8: Conclusion** summarises the key findings and contributions of the thesis.

2 Theory

This chapter introduces the theoretical background and key concepts that underpin the thesis. It covers structural systems and their components as well as the principles used in early structural design. In addition, it presents workflows for computational and parametric design, with a focus on tools such as Rhino, Grasshopper and Python scripting. The chapter also outlines methods for assessing environmental impact through life cycle assessment (LCA), with an emphasis on embodied carbon in structural systems. Together, these sections provide the technical and methodological basis for the tool's development and its role in supporting sustainable decision-making in early-stage design.

2.1 A structure

A structure refers to the framework of elements designed to support and transfer loads safely to the ground. Buildings are composed of structural elements such as columns, beams, slabs and walls, which make up the structural system. All these elements work together to carry loads such as the structure's self-weight, superimposed dead loads and live loads to the ground.

A building's structure can be divided into two main parts: the superstructure and the substructure as shown in Figure 2.1. The superstructure refers to all elements above ground level, including columns, slabs, load-bearing walls and bracing members, which support the floors, roof and internal finishes while providing overall stability to the building (LETI, 2020). The substructure consists of the building's foundations and, where present, underground basements. Typically made of reinforced concrete, the substructure is crucial as it carries the load transferred from the superstructure to the ground and is often the most structurally demanding part of the building's design (LETI, 2020).

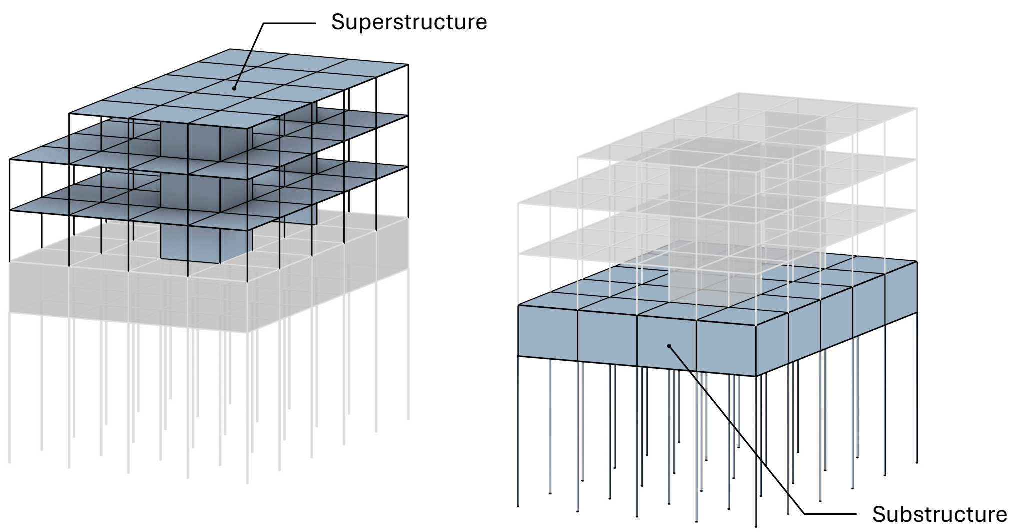


Figure 2.1: Superstructure highlighted to the left, substructure highlighted to the right.

Designing the structural system requires analysis of the applied loads, including both vertical and horizontal permanent- and variable actions. A simplified approach may isolate vertical loads from horizontal ones. In such cases, a load takedown can be performed, where all vertical loads are calculated and summed from the top of the structure down to the foundation. Through such analysis, loads on each structural member can be determined and in turn, the design of the member can be performed. This is performed in accordance with applicable building code (e.g., Eurocode) to verify that the member is sufficiently sized and designed to withstand the actions on it.

The building's structure can be designed in many different ways regarding aspects such as structural systems, materials and geometry. The following subsections will cover these aspects.

2.1.1 Structural systems

In addition to providing structural stability and transferring loads safely to the ground, structural systems must also meet architectural requirements. This includes supporting functional layouts, allowing spatial flexibility, and contributing to the building's architecture. Different structural systems are suitable for various building types and uses and several factors must be considered when selecting the appropriate system. These factors may include the building's purpose, span requirements, material availability, environmental impact, cost and construction methods. A building can be constructed out of multiple different types of structural systems or out of one type of structural system, divided into multiple zones. One of the most common structural system is the column-beam system, which is explained in the following section.

2.1.1.1 Column-beam systems

This is a system where columns support beams that in turn supports slabs. In this system, slabs are often spanning in one direction and are built as simply supported. Becker (2014) describes that column-beam systems are often a combination of a vertical support system (columns) and horizontal spanning systems (slabs and beams) as shown in Figure 2.2. The vertical members are typically subjected to axial forces while the horizontal members are generally subjected to bending moments and shear forces.

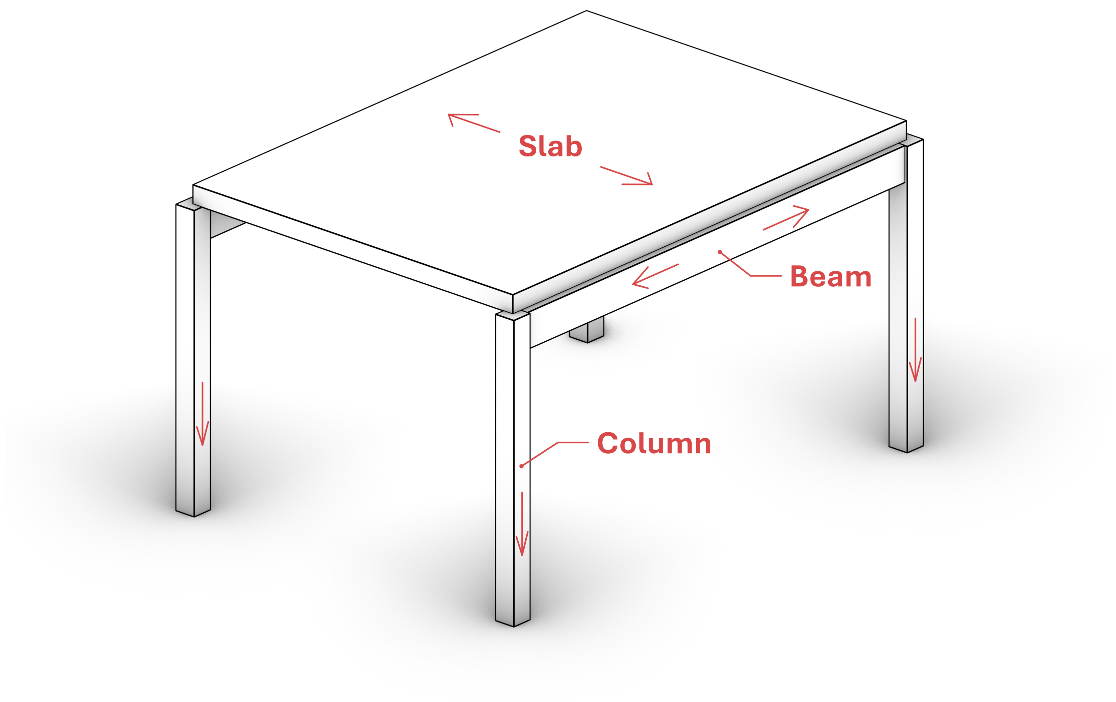


Figure 2.2: Conceptual illustration of a column-beam system, where force paths are shown.

In combination of columns and beams, this system can incorporate load-bearing walls which can act as both vertical and horizontal structural elements.

2.1.2 Structural members

Focusing on the column-beam structural system, this section briefly presents the structural members this system.

2.1.2.1 Slabs

Slabs are horizontal structural elements designed to support loads such as self-weight of flooring and interior installations or live load from occupancy. When functioning as a roof, slabs also carry loads from roof constructions, snow and other environmental factors. Slabs are typically supported by beams, but may also rest directly on walls or columns. Common slab types include solid plates (e.g., filigree slabs), hollow sections (e.g., hollow-core slabs) and composite configurations (e.g., CLT rib floors combining plate and beam action). Figure 2.3 shows an overview of common slab types. A key factor influencing slab type selection is the span length, which directly affects structural efficiency and material choice. Verifications commonly performed in slab design include flexural strength checks, deflection control and vibration checks.

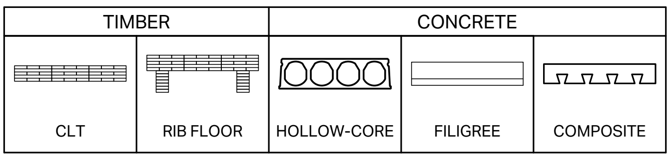


Figure 2.3: Commonly used slab types in building construction in Sweden.

2.1.2.2 Beams

Beams are a part of the horizontal spanning system that typically supports slabs and transfers the load to the vertical support system. Among common beam types, shown in Figure 2.4, some examples are steel sections (e.g., HEA-beam), glulam timber and reinforced concrete beams. Verifications commonly performed in beam design include flexural- and shear strength checks, torsional stability and deflection control.

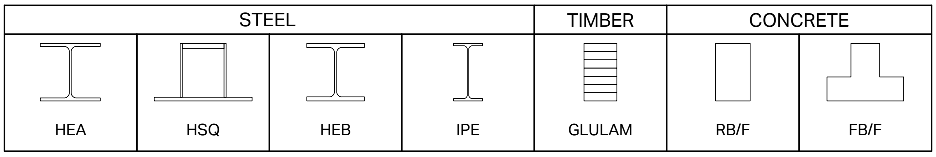


Figure 2.4: Commonly used beam types in building construction in Sweden.

2.1.2.3 Columns

Columns are a part of the vertical support system, transferring load down to foundations, typically subjected to axial forces. Common column types are steel sections (e.g., HEA-profile), glulam timber and reinforced concrete columns, Figure 2.5 illustrates an overview of profiles. Verifications typically cover axial strength checks and resistance against instability due to buckling.

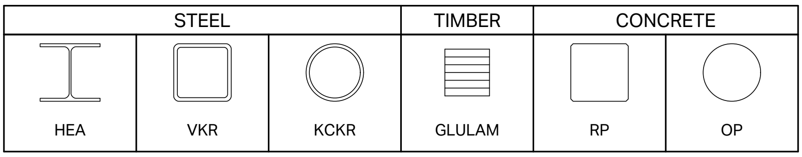


Figure 2.5: Commonly used column types in building construction in Sweden.

2.1.2.4 Walls

In the context of structural members, walls are load-bearing. They may primarily carry vertical load but can also be a part of a horizontal stabilisation system, carrying lateral loads. Additionally, if the wall is a part of a substructure, it might be carrying lateral load from soil or groundwater. Walls can be constructed out of reinforced concrete, cross-laminated timber (CLT) or as a light partition wall, constructed as a composite of studs and sheets. Depending on the loads that a wall is subjected to, different verifications need to be done, e.g., stability checks, shear flow transfer and flexural strength.

2.1.2.5 Foundations

The foundation transfers all loads, both vertical and horizontal, from the structure to the ground. The choice of foundation type depends on parameters such as soil conditions, groundwater level and the magnitude of structural loads. Common types of foundations include slab foundations, strip footings and piles.

Piles are used when suitable bearing capacity cannot be reached near the ground surface and must be transferred into deeper ground. They can be constructed in various ways, with square reinforced concrete piles and circular steel piles being the most common, as illustrated in Figure 2.6. In practice, piles are rarely installed exactly as planned, which introduces eccentricities that must be accounted for in design. For this reason, it is common to install multiple piles under columns, as columns have limited capacity to accommodate load eccentricity. In contrast, a single pile may be sufficient under a wall, since the wall's continuous nature can better accommodate shifted load paths.

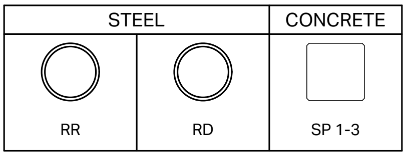


Figure 2.6: Commonly used pile types in building construction in Sweden.

2.1.3 Structural materials

In Sweden, there are typically three main structural materials used in building construction: concrete, steel and timber. Concrete is generally not used on its own but is instead combined with steel reinforcement to form reinforced concrete, which improves its tensile performance. These materials differ significantly in their mechanical properties, structural behaviour, environmental impact and practical applications. Buildings with a high proportion of timber have been shown to have significantly lower environmental impact compared to those where steel or reinforced concrete are the predominant structural materials (Malmqvist et al., 2023). Understanding the characteristics of each material, such as their strength in tension and compression, stiffness, anisotropy and constructibility, is essential for evaluating their suitability in sustainable structural design. Among a number of different mechanical properties of materials, Young's modulus is a constant that describe a material's elastic properties in uniaxial loading.

2.1.3.1 Reinforced concrete

Reinforced concrete is a composite material made from concrete and steel reinforcement. The concrete provides high compressive strength, while the embedded steel bars (rebars) resist tensile forces, overcoming concrete's characteristic weakness in tension. It behaves as an isotropic material in practice, though reinforcement layouts can introduce directional behaviour. Reinforced concrete is prone to long-term effects such as creep and shrinkage. Cracking of concrete is a common phenomenon that can affect its durability and performance over time. To control cracks, methods such as prestressing the reinforcement can be used. A slab element with prestressed reinforcement alongside with a column element with regular reinforcement is illustrated in Figure 2.7.

The concrete itself, unreinforced, has a range of the Young's modulus typically between 30-40 GPa. Its compressive- and tensile strength ranges typically between 20-60 MPa and 2-5 MPa respectively.

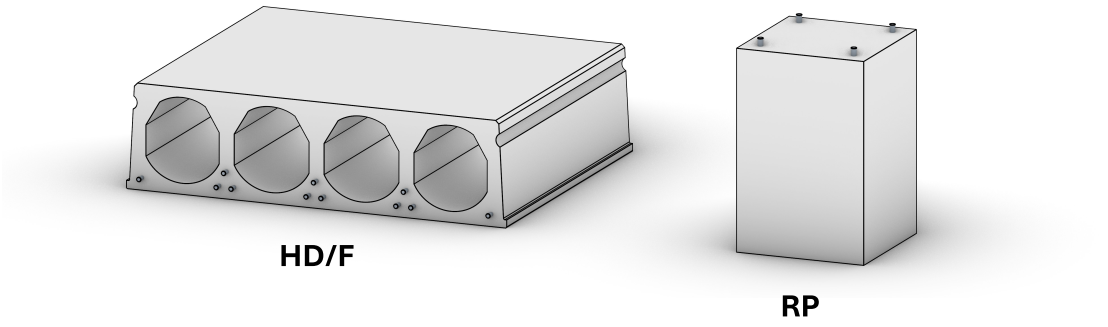


Figure 2.7: Common concrete profiles used as structural members in building construction in Sweden. A pre-stressed hollow-core slab element (HD/F) to the left and a rectangular column (RP) to the right.

2.1.3.2 Steel

Steel is assumed as a homogeneous and isotropic material, offering high strength in both tension and compression. It allows for prefabrication and rapid assembly, and is available both as standardised profiles and in custom configurations. In Figure 2.8, commonly used structural steel profiles are illustrated. Connections are a critical aspect of steel structures and are typically made using either bolts or welding, each with implications for performance and construction. However, steel is prone to corrosion if not properly protected and loses strength at elevated temperatures, which necessitates the use of fire protection measures in many applications.

Young's modulus for commonly used structural steel is 210 GPa, while its yield strength ranges between 235-500 MPa depending on the steel grade.

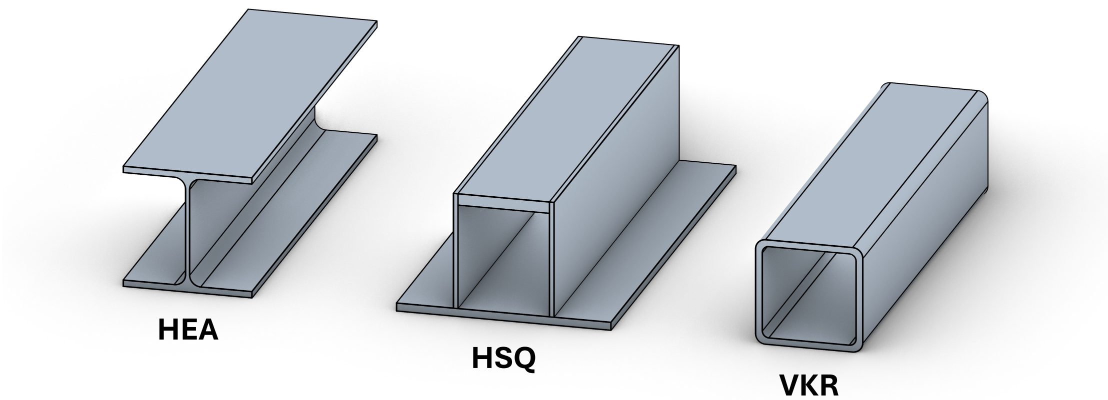


Figure 2.8: Common steel profiles used as structural members in building construction in Sweden.

2.1.3.3 Timber

Timber is a natural, orthotropic material, meaning its properties differ along the grain, across the grain and radially. Engineered wood products (EWP) such as glue laminated timber (glulam) and cross-laminated timber (CLT), as illustrated in Figure 2.9, enable the use of larger cross-sections, customised members and higher structural strength. EWPs also reduce the impact of natural defects in timber, such as knots and skewed fibres. Timber is a renewable resource with a lower carbon footprint compared to concrete and steel. Timber is sensitive to moisture and is also affected by long-term phenomena such as creep.

For the glulam grade GL32c, observing the properties parallel to the grains, the Young's modulus is 13.5 GPa. The compressive- and tensile strength is, in the same direction, 24.5 MPa and 19.5 MPa respectively. However, observing the same properties but perpendicular to the grains, the Young's modulus is 0.3 GPa and the compressive- and tensile strengths are 2.5 MPa and 0.5 MPa respectively.

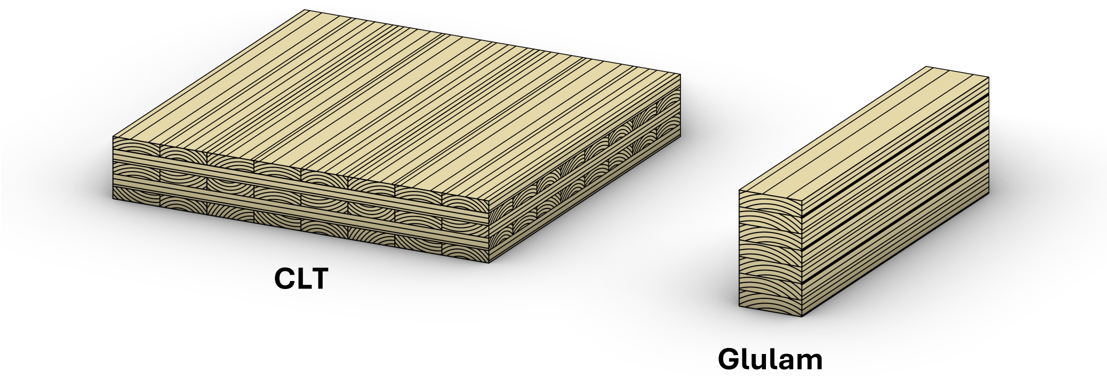


Figure 2.9: Common structural timber members in building construction in Sweden.

2.1.4 Structural grid

A fundamental early decision in structural design is defining support positions, typically organised through a structural grid. This grid determines the placement of vertical elements like columns or load-bearing walls, shaping both the structural logic and architectural layout of the building. The grid is a global parameter of a building and has a significant impact on the total environmental impact (Gholam, 2020).

Most grids are orthogonal, consisting of square or rectangular bays with perpendicular connections, as illustrated in Figure 2.10. This geometry simplifies both design and construction (Becker, 2014). Repetition of identical members reduces complexity in detailing, fabrication and assembly. While often uniform, orthogonal grids can accommodate varied bay sizes and be combined or adjusted to meet specific spatial or programmatic needs.

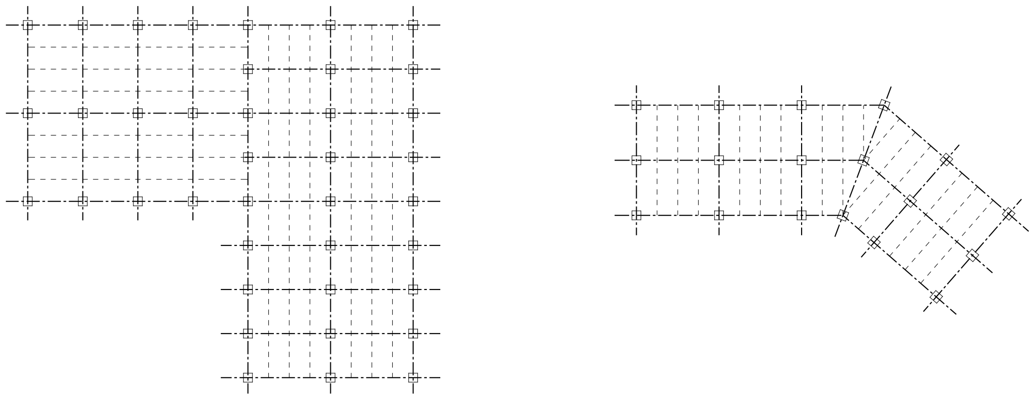


Figure 2.10: Two examples of orthogonal grids. Adopted from Becker (2014).

The grid layout is influenced by site constraints, spatial program and material choices. Large open spaces demand structural systems capable of spanning greater distances, while material selection impacts allowable spans and the dimensions of structural components. In some cases, structural elements like columns may also contribute to the architectural expression or define spatial organisation.

In early design stages, orthogonal grids are particularly valuable due to their simplicity and ease of comprehension. Moreover, they facilitate construction by enabling repetition, as such grids often consist of identical members, thereby reducing the number of unique elements that need to be designed, an aspect that can offer economic as well as construction benefits. (Becker, 2014). Orthogonal grids may become limiting when applied to buildings with complex geometries, such as organic shapes in plan, elevation, or both, where a more flexible grid layout may offer greater design and structural benefits.

2.1.5 Stability

The stability of a building is checked with lateral actions applied to it, such as wind, unintended inclination and seismic loads. To design a sufficient stability system, there are several concepts that can be implemented. Shear walls, braced frames and moment frames are the most common ones, illustrated in Figure 2.11.

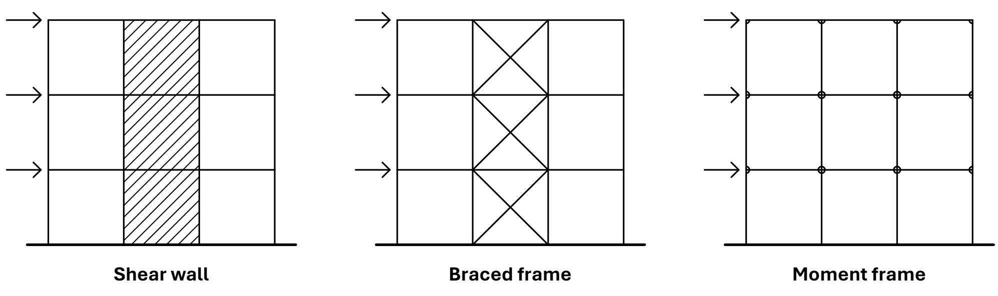


Figure 2.11: Examples of three lateral stability systems.

These stabilising systems often act throughout the entire height of the building, from the foundation to the roof. Shear walls act as a surface active member, where the wall resists lateral load. Braced frames are a frame with diagonal bracing, often acting in tension to transfer the lateral loads applied to it. Lastly, the moment frames act through rigid connections between the horizontal and vertical members.

2.2 Workflows for parametric and computational design

This section outlines commonly used workflows in parametric and computational design, with a particular focus on tools such as Rhinoceros 3D, Grasshopper and basic programming approaches.

2.2.1 Rhinoceros 3D

Rhinoceros 3D, commonly referred to as Rhino, is a Non-Uniform Rational B-Spline-based (NURBS) 3D modelling software that enables users to create highly complex geometries (McNeel, n.d.). While it is widely used in architectural and industrial design, it is also gaining traction in structural design practice due to its parametric capabilities and strong interoperability with other commonly used engineering tools such as CAD-software, BIM-software and FEM-software. The modelling process in Rhino can be approached in two primary ways: direct modelling and parametric modelling. Direct modelling involves manually defining geometry, allowing for quick conceptual sketches such as simple volumes. In contrast, parametric modelling introduces a set of constraints and adjustable parameters, which enhances automation and flexibility in the design workflow. Although parametric modelling requires a more extensive initial setup, it offers significant time savings when iterating through multiple design variations (Jabi, 2013).

2.2.2 Grasshopper

Rhino supports numerous plug-ins, one of the most widely used is being Grasshopper, which enables visual scripting for parametric modelling. Instead of traditional programming, Grasshopper employs a node-based interface, where components are linked together to define workflows. This approach facilitates rapid prototyping, algorithmic design and generative modelling, making it highly valuable for architectural, structural and environmental simulations.

Säwén et al. (2022) presents a study where a characterisation framework of parametric LCA tools was developed. This study investigates 13 existing tools and found that the most common approach among them was to use Grasshopper to model geometry and materials, to perform LCA analysis and present the results. This approach was identified to be a convenient method or large-scale adoption. This underlines the strength of Grasshopper and its extensive ecosystem of plug-ins in the context of LCA and quantification of environmental impact of buildings.

2.2.3 Python

In addition to its built-in components, Grasshopper allows scripting in languages such as Python and C#, expanding its capabilities for advanced customisation and automation. Python is widely used due to its clear syntax and extended list of available libraries.

When conducting LCA in early-stage structural design, automation plays a crucial role in streamlining material selection, geometric modifications and performance evaluations. By leveraging Python, users can optimise workflows, enhance data exchange between software environments and enable dynamic environmental impact assessments.

2.2.3.1 Object-oriented programming

The concept of object-oriented programming (OOP) is fundamental in many programming languages, including Python. It provides a structured and logical way to organise code, often mirroring how real-world objects are perceived (Phillips, 2018). OOP is particularly useful for building applications that solve complex problems in a scalable, reusable and maintainable way. Core concepts in OOP include classes, objects and inheritance. A class defines a blueprint for an object, while an object is an instance of that class, containing attributes (data) and methods (functions) relevant to it.

For example, a script might define a class called Box to represent a real-world box. The object could have attributes such as height, length, depth and volume. Once the object is created, e.g myBox, accessing the height is as simple as calling myBox.height, which might return 20, indicating the box has a height of 20 units.

2.2.3.2 COMPAS

COMPAS is an open-source, Python-based computational framework developed to support research and collaboration in architecture, engineering, digital fabrication and construction (COMPAS Association, n.d.-a). It is maintained by the COMPAS Association, a public-benefit organisation originating from ETH Zürich, and is continuously updated through contributions from an active developer community. The framework provides a range of core functionalities, including geometry processing, data management and interoperability with design environments such as Rhino and Grasshopper. These capabilities make COMPAS a flexible and powerful framework for implementing custom workflows and integrating geometry generation directly within Python scripts.

The core COMPAS library includes a dedicated geometry module, *compas.geometry*, that facilitates scripting and manipulation of geometric data through a wide range of classes and functions (COMPAS Association, n.d.-b). This module enables the creation and management of common geometric types such as primitives (e.g., points, lines, circles), surfaces and boundary representations (BREPs). Each geometry class comes with its own set of attributes and methods, along with inherited functionality from parent classes, allowing for consistent and object-oriented handling of geometry in Python-based workflows.

COMPAS also provides tools for working with data structures through the *compas.datastructures* module, offering a structured way to store and access information related to both topological and geometrical components. Among the available classes, VolMesh is particularly well-suited for representing three-dimensional geometric systems composed of polyhedral cells. A VolMesh is a volumetric mesh structure where individual cells represent polyhedra bounded by faces, edges and vertices, illustrated in Figure 2.12. This data structure supports the assignment of custom attributes at the cell, face, edge and vertex levels, enabling flexible and granular control over geometry and metadata.

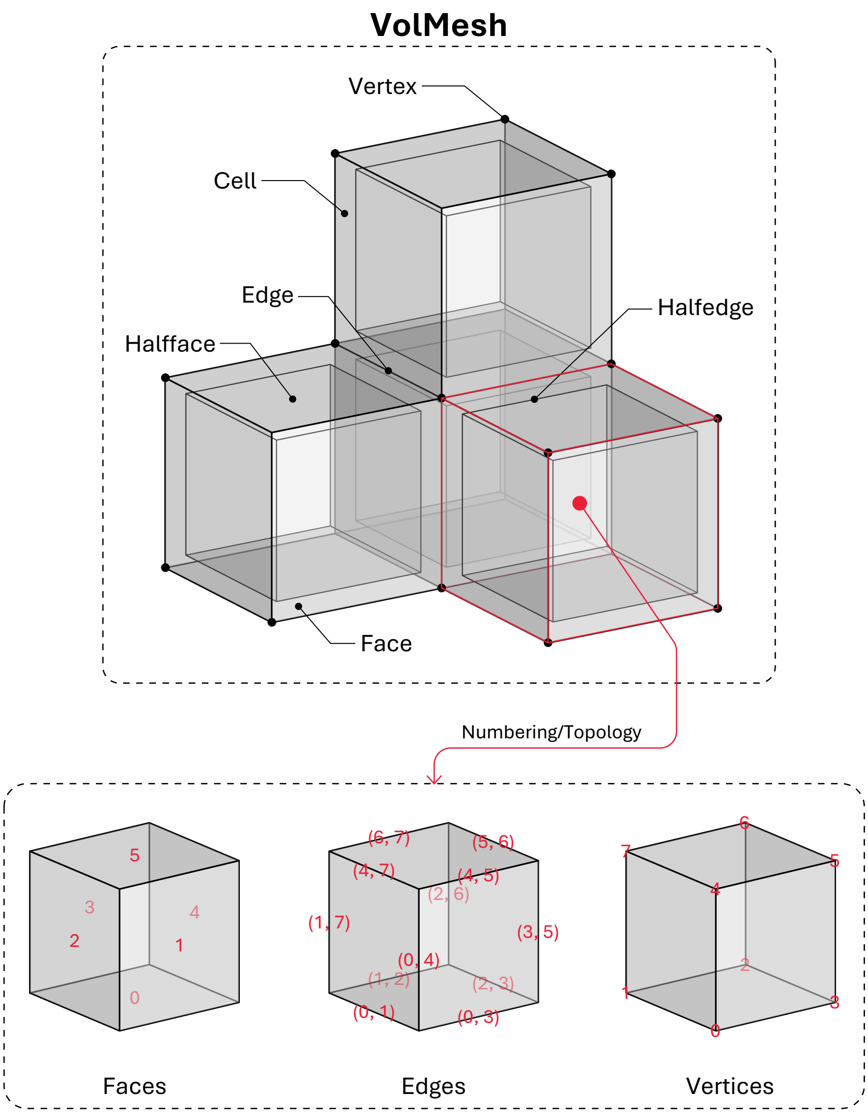


Figure 2.12: Illustration of a volmesh

The VolMesh class includes a variety of built-in methods for both topological and geometrical operations. For example, topology-related methods such as *is_halfface_on_boundary* check whether a given halfface lies on the mesh boundary, while *halfface_halfedges* returns the sequence of halfedges that define a halfface. Geometry-related methods include *cell_points*, which retrieves the 3D coordinates of a cell's vertices and *edge_vector*, which returns the directional vector of an edge. Together, these tools make VolMesh a powerful framework for building and analysing 3D geometry in a structured and scriptable manner.

2.2.3.3 Data handling

Managing and transferring data between applications and workflows can be approached in various ways. For structured and easily maintainable data, Excel is a convenient format that allows for straightforward adjustments and extensions. However, when using such data in Python-based workflows, a conversion step is typically required. Among the many available Python libraries for data processing, Pandas is a widely used and powerful open-source tool for data analysis and manipulation. It enables efficient reading, filtering and transformation of structured data. By handling data programmatically, workflows become more reproducible and less prone to manual error. Through Pandas, Excel files can be converted into JavaScript Object Notation (JSON), a lightweight and human-readable data-interchange format. JSON is particularly well-suited for data storage and transfer in scripting environments, making it a practical choice for integrating data into parametric design tools.

2.2.3.4 Data visualisation

Visualising data effectively is a key aspect of enabling insight and supporting data-driven decision-making, particularly in engineering and design contexts. Graphical representations allow complex relationships and trends to be understood more intuitively than raw numerical data. Among the available tools for data visualisation, the Python library Matplotlib is widely used due to its flexibility and extensive functionality. It provides a well-developed framework for generating various types of plots, such as bar charts, line graphs and scatter plots. These visual formats are commonly used to communicate performance metrics, compare design alternatives, or highlight patterns within datasets, thereby improving the clarity and accessibility of quantitative information.

2.3 Environmental impact

The environmental impact of buildings is a key area of study within sustainable construction, particularly concerning the greenhouse gas (GHG) emissions associated with materials and structural systems. The construction sector contributes significantly to global and national GHG emissions. In Sweden, the industry accounted for approximately 22% of domestic emissions in 2022 (Boverket, 2025). Within a typical building project, the structural system often represents the largest share of these emissions. As described by Malmqvist et al. (2023), structural components can account for up to 60% of GHG emissions during the construction phase. These emissions, commonly referred to as embodied carbon, are determined by choices made during design and material selection, and cannot be modified once the building is completed.

2.3.1 What is environmental impact?

Environmental impact refers to the effects that human activities, natural events, or industrial processes have on the environment. These impacts can be positive or negative, though the term is most commonly used to describe the negative effects on ecosystems, natural resources and human health. In the context of building design and construction, environmental impact assessments are commonly carried out using LCA. LCA is a standardised methodology that quantifies the environmental impacts associated with a product, process, or system across its entire life cycle, from raw material extraction to end-of-life.

2.3.2 Greenhouse gas emissions and global warming potential

Among the many environmental impact categories addressed in LCA, GHG emissions are of particular concern due to their role in driving climate change. These emissions include gases such as carbon dioxide (CO_2) and methane (CH_4). To enable comparison of different products, processes or systems, emissions are expressed in terms of global warming potential (GWP), using a common metric of CO_2-equivalents (CO_2e).

2.3.3 Embodied carbon in structural systems

Embodied carbon refers specifically to the GHG emission originating from the production, transportation and construction of building materials and elements. In the context of LCA, the embodied carbon is corresponding to the stages A1 - A5 as defined in SS-EN 15978:2011 (European Committee for Standardization, 2011), illustrated in Figure 2.13, which include:

- A1 - A3: Product stage. Raw material supply, transport and manufacturing (often referred to as 'cradle to gate').
- A4: Transport to site.
- A5: On-site construction installation process.

Stages A1–A5 are of particular relevance, as environmental impact declarations in Sweden generally include these phases.

SS-EN 15978:2011: Building assessment information																
A1 - A5 Construction stage					B1 - B7 Use stage							C1 - C4 End of life				D Benefits and loads beyondthe system boundary stage
A1 - A3 Product stage			A4 - A5 Construction process stage													
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Construction - installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction/ demolition	Transport	Waste processing	Disposal	Reuse-, recovery- and recycling potential

Figure 2.13: Life cycle stages as defined in the European standard SS-EN 15978:2011, with the stages A1 - A5 highlighted. Illustration adopted from (European Committee for Standardization, 2011) and (Birgisdottir & Rasmussen, 2016).

Because these emissions occur before the building is in service, they are effectively locked in once construction is completed. As noted by Pomponi and Moncaster (Pomponi & Moncaster, 2018), "Once the building has been completed and the 'as built' embodied carbon is assessed there is no room for reducing it" (p.2440). This underscores the importance of addressing embodied carbon during the early phases of design.

2.3.4 Estimating embodied carbon in early design stages

While full life cycle assessments are well suited to detailed design phases, they are often difficult to apply in early-stage decision making. This is due to the lack of precise data on materials, quantities and construction processes. In early design, simplified approaches are more practical. Such a method typically estimate environmental impact by combining preliminary material quantities with embodied carbon coefficients derived from databases or environmental product declarations (EPDs).

EPDs are standardised, third-party verified documents that provide LCA-based environmental information for specific products. They report a range of impact metrics across all life cycle stages and are particularly valuable when product-specific data is available. If the specific product is not known, generic data sources, such as Boverkets Klimatdatabas (Boverket, n.d.-a), can be used for early comparisons and estimations under uncertainty, which includes both conservative- and typical values.

By multiplying material quantities with embodied carbon coefficients (from EPDs or generic databases), it is possible to estimate the embodied GHG emissions of the structural system. This approach enables design teams to assess and compare the environmental performance of different structural options, even at early stages of the project.

To facilitate evaluation, the results are often normalised by the building's gross floor area (GFA), resulting in a performance indicator in units of kg CO_2e/m^2. This metric allows for comparison between design alternatives and supports environmentally informed decision-making within the constraints of early-stage design.

2.3.5 Strategies for reducing embodied carbon

Reducing embodied carbon is essential in addressing the climate impact of the built environment, particularly since structural systems often represent a significant share of a building's total emissions as described in Section 1.1. As design decisions made early in the process greatly influence a building's material use and carbon footprint, it is important to identify and apply strategies that effectively reduce emissions from structural components. Fang et al. (2023) present several such strategies, highlighting their respective advantages and limitations. Two holistic approaches are emphasised: (1) exploring or optimising the parametric design space, and (2) comparing design concepts, case studies and benchmarks.

The parametric design space strategy (1), models structural systems through variable parameters, enabling designers to evaluate and optimise multiple design alternatives based on performance metrics such as embodied carbon. This approach not only facilitates multi-objective optimisation but also supports the identification of near-optimal solutions, offering flexibility in early-stage decision-making. In contrast, the comparison-based strategy (2), focuses on evaluating a limited number of discrete design concepts, often through case studies or benchmarks, allowing for more detailed analysis of each alternative but with a narrower view of the wider design space. The first approach typically offers greater potential for minimizing embodied carbon but may require more time and resources to implement effectively.

It is important to recognise that every structural design problem involves multiple design variables and decision-making possibilities, with each project subject to unique constraints. The impact of these variables on environmental performance can vary significantly depending on the context. By using a parametric model, engineers can systematically explore different design options and identify the most influential variables. This approach helps reveal which design choices have the greatest effect on environmental impact, providing engineers with valuable insights to guide their decisions more effectively.

Gholam (2020) found that minimising embodied carbon is most effective when focusing on the overall structural system rather than individual components. Optimising grid spacing, floor types and foundations has a greater impact on reducing embodied carbon than refining individual structural members.

2.4 User interface

User interface (UI), often referred to as the front-end, is the visual and interactive part of a software application that facilitates communication between the user and the back-end, which handles data management and processing behind the scenes. The front-end includes graphical elements such as buttons, menus and input fields for data entry, as well as the presentation of results, charts and other information. A well-designed UI enhances usability, making the tool accessible to users with varying background and level of expertise. Furthermore, clear and intuitive parameter adjustments, combined with well-presented feedback and results, enable users to perform quick and efficient design iterations.

Säwén et al. (2024) finds that interactivity is essential in design-oriented settings such as internal workshops or meetings with clients. Real-time feedback allows users to immediately observe the consequences of design changes, supporting a more intuitive and iterative workflow. To be effective in such settings, feedback must be presented in a clear and interpretable way, especially for users without a deep background in building science (Säwén et al., 2024).

During the development of an application, the method of User-Centred Design (UCD) can be applied to ensure the solution aligns with user needs (Interaction Design Foundation - IxDF, n.d.). UCD is an iterative process in which users are actively involved throughout development, providing developers with valuable insight into user behaviour and expectations. Each iteration typically consists of four phases, as displayed in Figure 2.14: *Understand context of use*, *Specify user requirements*, *Design solutions* and *Evaluate against requirements*. In the final phase, developers assess the outcomes based on user feedback. If the evaluation reveals shortcomings, the process is repeated in a new iteration.

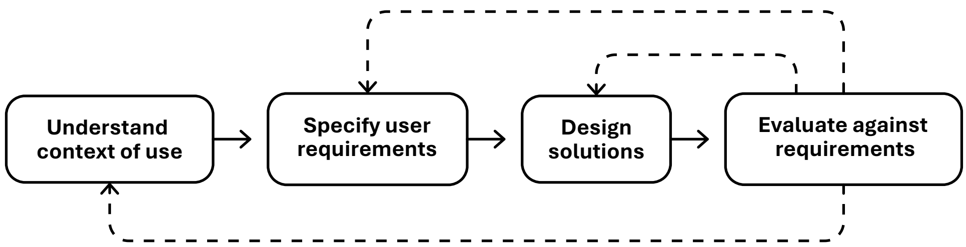


Figure 2.14: The iterative process of user-centred design (UCD), adopted from Interaction Design Foundation - IxDF (n.d.).

It is important to design the user interface with the imagined user in mind and importantly, defining this user's skills and software practice. As Säwén et al. (2024) states it, "Without defining a real or imagined user of the tool, and without defining the aspects covered by "friendliness", it is impossible to find out in such broad terms whether a tool is user-friendly or not" (p.7). As explained by Säwén et al. (2024), the usability of a tool can be evaluated based on its success in meeting user needs, its ease of use and its performance in terms of efficiency and accuracy. The most common usability criterion in the literature is friendliness, which relates to ease of data entry, workflow navigation and the visual appearance of the interface.

When it comes to visualising LCA results, several approaches can be applied. Hollberg et al. (2021) finds that the most commonly used visualisation types in existing LCA tools are bar charts and their variations, as well as pie charts. The study also finds that there is no clear distinction in the choice of visualisation type across different building design phases. Instead, the suitability of a visualisation method largely depends on the intended purpose, such as whether it is used for hotspot identification or for comparing design alternatives. Pie charts and vertical bar charts are generally appropriate for representing a single variable, such as the embodied carbon associated with different building elements. On the other hand, when the goal is to compare design options, bar charts are particularly effective, as they can clearly communicate differences while maintaining a limited and comprehensible amount of information.

3 Methodology

This chapter outlines the methodology used to develop and evaluate the parametric tool. The process was structured in several stages, combining literature review, tool development and case studies to address the research objectives.

The main steps of the workflow were:

1. Literature study of relevant papers.
2. Analyse the previous developed tool, study relevant structural systems.
3. Conceptualise new functionality and define intended workflow.
4. Implement and develop the design tool and improve it with new functionality.
5. Apply the tool in case studies and evaluate the results.

The work began with a literature study to explore strategies for early-stage structural design (Section 1.1.2) and potential implementation methods. A key focus was to identify how the new tool could address gaps in existing functionalities while remaining usable within the project's time frame.

Following this, the conceptualisation phase defined the tool's intended functionality, informed by case-specific needs and discussions with users. This included the formulation of requirements based on real design scenarios and an outline of the tool's structure, specifying its input and output parameters, as well as the calculations it should perform. The applicability of the tool will be evaluated through case studies.

Figure 3.1 illustrates how the iterative process of this work will be carried out. This reflects the process of user-centred design (UCD) (Section 2.4), and is here adopted to the method of this thesis.

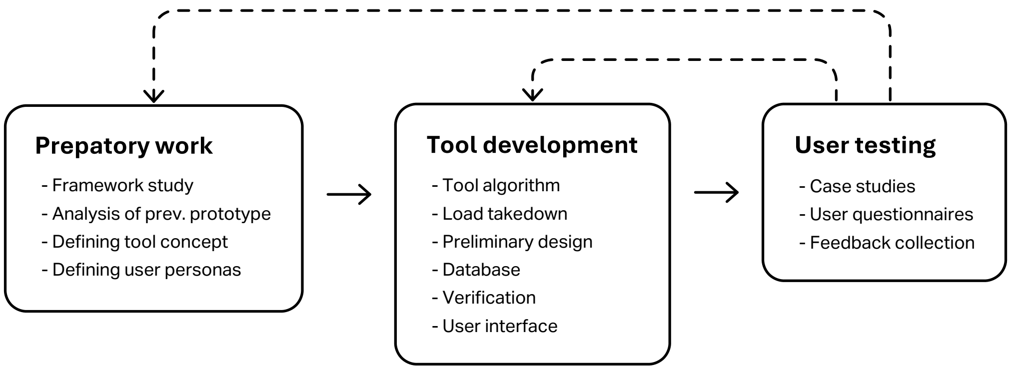


Figure 3.1: Illustration of the iterative method for this thesis.

3.1 Assumptions and simplifications

As described in Section 1.4, the structural system is simplified as an orthogonal grid with one-way, simply supported slabs, as well as simply supported beams and columns. These assumptions were made to enable a modular and computationally efficient load evaluation framework, aligning with the aim of developing a practical and adaptable tool for early-stage design exploration. Cantilevering structural systems are not considered, as the tool is limited to vertical load paths in simply supported configurations.

Snow load is modelled as a uniformly distributed load and does not account for snow pockets that may occur near taller adjacent buildings or in multi-span roof configurations. Consequently, effects on the snow load shape factor (μ) are not considered in such cases.

Environmental impact calculations were based on the primary structural materials. Reinforcement in concrete elements and steel fasteners in timber connections were excluded, as these were not represented in the tool during development.

The tool is intended for users with prior knowledge of the architecture, engineering and construction (AEC) industry and therefore assumes familiarity with basic structural concepts, material properties and design principles.

3.2 Prototyping

Prototyping is an integral part of the tool development methodology, allowing for iterative testing and refinement throughout the development process. During the build of the parametric tool, prototypes will be developed whenever suitable to explore and evaluate new functions, plug-ins, or frameworks. Additionally insights from supervisors will help guide the development of prototypes. This approach ensures that different solutions can be tested in practice, providing knowledge of their feasibility, performance and compatibility with the overall concept. By doing prototyping in parallel to the development, the process remains flexible and adaptive, making the integration of new functions structured. This iterative method also helps identify potential challenges early, allowing for adjustments early on, before too much time is invested.

3.3 User personas

The tool is developed with the intention of being used by individuals from different disciplines and with varying levels of experience in Rhino and Grasshopper. To address this, different user personas were defined. The process was guided by an investigation of potential users and the roles typically involved in early-stage design teams, which informed the categorisation of relevant user types.

3.4 Structural elements

The parametric tool will incorporate an automatic preliminary design process for structural elements, ensuring that each component is sized based on governing loads, user input and material selection. This will be achieved through a tabulated approach, enabling rapid computation and a rather instant feedback to the user. Existing tabulated values from the work by Flyman (2024) will provide a foundation for this process, covering various structural elements. To enhance the tool's applicability, this dataset will be expanded to include a broader range of elements and structural profiles. Through this approach to structural preliminary sizing, the tool will facilitate quick design iterations, allowing architects and engineers to explore different structural solutions efficiently in the early design stages. Additionally, the approach is transparent as the preliminary design relies on tabulated values that an engineer easily can verify, minimising the black-box effect of the tool.

3.5 Verification

During tool development, visual checks and logical consistency were continuously checked to ensure that data were processed correctly. These checks supported debugging and were used to confirm that each function behaved as expected.

A formal verification of the load takedown process and calculation of the global warming potential (GWP) was conducted once the tool reached a functional state. Identical input parameters were used to manually calculate reactions, member loads, initial cross-section sizes and further the GWP of each member. The tool's output was then compared to the hand calculations. Although finite element method (FEM) analysis could have been used for more complex verifications of the preliminary sizing, hand calculations were considered sufficient given the simplicity of a simply supported beam and column system.

3.6 Case studies

To evaluate the performance, usability and potential of the developed tool in early-stage structural design, two case studies were conducted. The first involved users with expertise in structural engineering and familiarity with Rhino and Grasshopper. This initial phase provided detailed and constructive feedback midway through the development process, with a focus on the parametric functionality. The second case study was carried out in collaboration with external architects from Kaminsky Arkitektur AB, placing the tool in a more realistic design context. This required a more refined user interface and enabled an evaluation of the tool's broader applicability.

Insights from the first case study informed further development of the tool prior to the second. Participants were selected to represent all defined user personas, as described in Section 4.3. To collect data, questionnaires were prepared (Section 3.6.1.1), sessions were screen-recorded and written annotations were taken. Before each session, participants were asked about their experience with Rhino and Grasshopper to help classify them into the appropriate user persona.

3.6.1 Case study 1

The first case study was conducted together with academic and industry supervisors. This group was selected not only for their knowledge of structural design and familiarity with the project's goals, but also because they reflect the user types defined in Section 4.3. One participant had limited experience with Rhino and Grasshopper, while the two others were comfortable working with parametric modelling environments. This allowed us to evaluate the tool's usability and workflow from both perspectives.

At this stage of development, the tool was fully controlled through Grasshopper, which made the test setting especially suitable for collecting feedback from users who could navigate the parametric interface, while also identifying potential accessibility issues for less experienced users.

The case study was divided into three individual sessions, each conducted separately and lasting approximately one hour per participant. To ensure a smooth experience and maintain focus on evaluating the tool's functionalities, the setup was prepared in advance on a computer with all necessary installations. Participants were introduced to specific tasks designed to explore different aspects of the tool. The printed version of the task description and questionnaire, given to participants, is available in Appendix A.

Guidance was provided throughout the sessions and participants had the opportunity to ask questions when needed. To support data collection, both screen recordings and written notes were taken. The recordings enabled detailed post-session review of user interactions and helped capture notable observations. Additionally, the material served as a reference for demonstrating the tool to individuals who were not directly involved in the sessions.

The case study consisted of two main tasks:

- **Task A** involved exploring how different design parameters influence the embodied carbon of a predefined building volume. Participants adjusted parameters such as structural grid layout, floor heights, span direction, substructure (e.g., number of basement levels, use of piles), loads and material/profile selections. The impact of these changes was assessed using the tool's output.

- **Task B** focused on user-driven design. Participants were encouraged to create and analyse their own building volumes, test the tool's functionality for geometry import and modification and compare different alternatives based on climate impact. They also tested features for saving and reloading models.

3.6.1.1 User feedback questionnaire

Feedback was collected through a structured questionnaire focusing on usability, clarity, missing features and the perceived usefulness of the tool for early design decision-making. After each user had tested the tool, all three users had a joint discussion of their experience. The following questions were asked to the participants:

1. What worked well in the tool?

2. What was difficult or unclear?

3. Were there any features missing that you expected?

4. Do you think the results can support decision-making processes?

5. Was it easy to generate and compare different design iterations?

6. Was it easy to save and manage your models?

7. Did the results seem reasonable?
8. Could the tool handle variations in geometry effectively?
9. What would you like to improve or add to the tool?

3.6.2 Case study 2

To evaluate the tool in a realistic design environment and assess its overall usefulness, the second case study was carried out in collaboration with structural engineers from VBK and architects from Kaminsky Arkitektur AB. It is divided into two parts, focusing on two separate projects: *Residential Block B in Lerum* and *a new apartment development in Solna*. In both cases, the tool was applied during early-stage design to explore structural alternatives and assess environmental impact.

The architect sought to understand the environmental impact of different structural system choices before the building volume was fixed, with the aim of determining whether a high sustainability standard could be achieved. The results generated by the tool could serve as a basis for their own environmental assessments.

The case study was structured as a collaborative workshop, where the architect and two structural engineers worked together using the tool to explore design options. Assistance was provided only for tool-related questions to ensure that participants engaged with the workflow as independently as possible. The group was selected to represent all three defined user personas, enabling more comprehensive use of the tool and generating richer feedback.

A questionnaire and a brief description of the purpose were provided to the architects before the session to establish expectations for the tool and clarify its intended role.

Purpose of the workshop: The aim was to test the tool in a live, collaborative setting involving both architects and engineers. The workshop format aimed to stimulate discussion among participants and clarify which parameters were most influential in terms of climate impact. The case study also served as a valuable opportunity to gather feedback that would inform further tool development and contribute to the thesis.

Pre-workshop questions for the architect:

- How comfortable are you using tools like Rhino and Grasshopper?
  (Scale 1–5: Not at all – Very comfortable)
- What type of information or feedback from the tool would be most valuable for your work?
  (e.g., climate impact per material/element, comparisons between design alternatives)
- Would you consider adjusting the building design based on the results from the tool at this stage of the project?
  (Scale 1–5: Not at all – Absolutely. If yes, how?)
- Are there any features or types of visualisation you think would be useful to include?

3.6.2.1 User feedback

Feedback was collected at the end of each session through open discussion. Participants were encouraged to share their thoughts freely regarding the tool's usability, functionality and relevance in early-stage structural design. This approach allowed for more spontaneous reflections and helped identify both strengths and potential areas for improvement.

4 Prepatory work

This chapter outlines the foundational work conducted prior to tool development. It includes a study of relevant digital frameworks, an analysis of a previous prototype and a summary of desired improvements. These insights inform the concept for the tool, establishing key functional and usability requirements for early-stage structural and environmental evaluation.

4.1 Framework study

To explore appropriate tools and frameworks for the tool development, a study of existing software environments, plug-ins and frameworks was conducted. The aim was to assess their suitability for geometry generation, user interaction and integration within the Rhino and Grasshopper ecosystem.

Geometry generation can be done directly in Rhino using Grasshopper through its built-in components. It can also be done by scripting custom components, which may allow for a more robust and flexible generation of geometry. There are also possibilities to investigate available frameworks like COMPAS that serves as a complete package of geometry handling and processing. In order to allow for flexibility regarding the input geometry, a robust concept for this have to be found.

User interface (UI) can be built in several ways, where the most simple one is to use Grasshopper itself for interacting with the user. On the other end, a web-based application may allow for the most custom and integrated user interface of the tool. In between there are a number of different approaches to construct a satisfactory UI, some of them are plug-ins to Grasshopper such as Human UI and UI+. Both allows the developer to build custom "windows" for interacting with the user, collecting user-input and displaying outputs and results, while using Rhino as the main software. When designing the UI, inspiration can be taken from software that the intended users already are familiar with. This creates a recognisable effect regarding the visual appearance of the interface, reducing the path to get familiar with the tool.

4.2 Previous prototype

This section covers a description and an analysis of a previous prototype, developed by Flyman (2024). The aim was to identify transferable features, limitations and areas for improvement that inform the current tool development.

4.2.1 Description

The previous prototype was developed with the Rhino-Grasshopper software with Python as programming language. The aims of the tool was to help the decision making in the early design stages and to be user friendly. The tool only needs the user to define the footprint of a building as a surface in the Rhino software as input for the tool to generate a grid and properly work. The grid is restricted as a orthogonal, static grid and cannot have different element spacing along axis. The floor levels are also limited in the sense that all levels have the same height. The script can be broken down into separate sections, as shown in Figure 4.1. The Inputs section is the only section where the user can interact, this becomes the tool's user interface, where the user can change input parameters and choose what results should be visualised and displayed in the Rhino window. Material data is gathered from manufacturers and the environmental data collected from Boverkets climate database. This information is documented as Excel files which is imported and read by the script. Further, a main python component is programmed for calculations of load takedown and embodied carbon. The structural elements are scripted to be object oriented, which means that classes are defined and these objects are assigned with attributes, containing unique information about the object.

An investigation was conducted to add a more user friendly interface for users not at all familiar with the parametric software, Grasshopper, but it was never implemented in the final version of the tool but instead referred as proof of concept (Flyman, 2024), leaving a good option to further investigate and implement. To identify the most optimal solution for a given building footprint, an optimisation solver was employed. The multi-objective optimisation plug-in, Wallacei, was tested for topology optimisation and its results were compared to the case study.

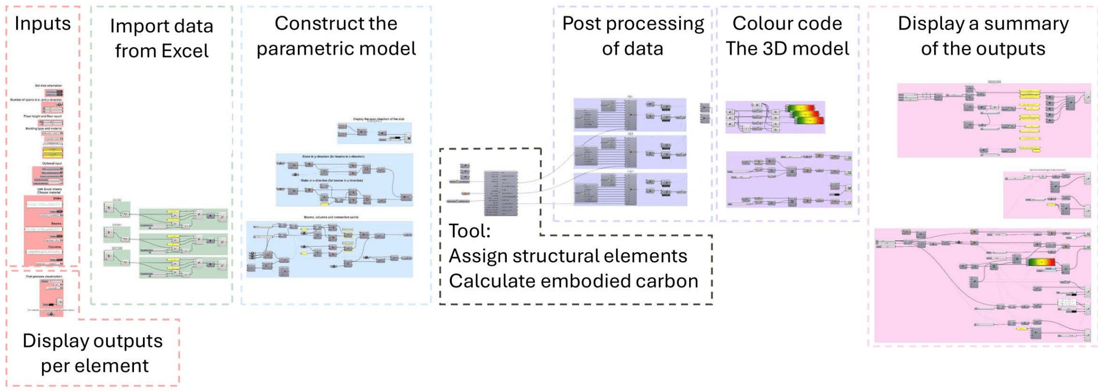


Figure 4.1: Overview of the previous prototype's Grasshopper script (Flyman, 2024).

A case study was conducted where a reference building was selected and analysed. The tool was verified together with hand calculations, for embodied carbon, results was compared with the commercial software OneClickLCA. Choice of elements and properties of the tool was compared against an experienced engineer. The comparisons showed some difference and was explained by a lack of material data and as the tool used pre-calculated elements there could be uncertainties regarding the capacity of the system (Flyman, 2024). To better confirm the confidence of the tool, an FEM analysis could be included in the workflow.

A summary of potential areas for further improvement was given:

- Adding more types of structural systems
- Adding horizontal stability together with core and bracing
- Adding a roof, snow, and wind loads
- Adding foundation

- Adding a FEM analysis to the workflow
- Adding a cost metric to each element

4.2.2 Analysis

This section covers an analysis of previous prototype, focusing on the overall- and data-structure, data collection and user interface.

4.2.2.1 Script structure

The script has a well-structured layout, divided into modules as described in Section 4.1. This organisation makes it possible to extend the script by adding new modules as needed. However, mostly all calculations happen through one custom-built Python component, making it a bit hard to follow the calculation process.

4.2.2.2 Data collection

The approach for preliminary design structural elements, is through tabulated values. This is a quick and good-enough way of sizing the elements. The existing data is structured as Excel-tables where the script read-in data for slabs, beams, columns and piles, based on specified span lengths and loads. Using Excel-tables allows for quick and easy addition of more elements or adjustment of the data. However, regarding performance of the script, use of data dedicated format would make it somewhat quicker but also avoiding the need of plug-ins for reading Excel data as well as avoiding the need of matching the correct Excel-cells in the Grasshopper/Python script. Use of a format such as JavaScript Object Notation (JSON) would eliminate the need of adjusting the script if the list of data change. This is more of a "database" approach. Nevertheless, this approach requires that the list of data need to be either written in JSON or exported from Excel to JSON. There might be a point of having the data somewhat "hard to adjust" as it contain calculated values which shouldn't be quick to change but rather be more controlled.

4.2.2.3 Data structure

The input geometry consists of slabs represented as surfaces, and beams and columns represented as lines. This geometry is organised using data trees, a standard data structure in Grasshopper, where each floor corresponds to a separate branch. When working with data trees, maintaining the correct order of elements is crucial. However, this approach becomes problematic when allowing for more flexible geometry input, particularly in cases where different floors contain varying numbers of structural elements (e.g., differing numbers of slabs, beams, or columns). In such cases, relying solely on element order within data trees proves to be insufficient and error-prone.

For easier data processing and visualisation, it is arguably more convenient to use a flat data structure for the geometry, drawing benefits of object-oriented programming (OOP) by assigning attributes to each element. This approach allows for more straightforward access to specific elements and their properties.

4.2.2.4 UI

The final version of the tool has its interface entirely within the Grasshopper window. For users experienced with Grasshopper, the interface is intuitive and easy to use. However, for new users with no prior experience, the Grasshopper visuals can be confusing or seen as a bit intimidating.

As mentioned in Section 4.1, a study was conducted on implementing a more user-friendly interface using UI+, but it was never implemented. To accommodate a broader range of users, further exploration into this aspect would be beneficial, with potential implementation in the future. Options include developing a custom UI or utilising Grasshopper plug-ins such as Human UI or UI+.

The prototype displays results directly in the Rhino viewports, where both the 3D model and graphs are visible. However, separating the model from the data visualisation could be more effective. Using UI plug-ins would allow parameters, result values and graphs to be displayed within the same window.

Since Flyman's tool only handled one option at a time, direct comparison between different options was difficult. A significant improvement would be enabling multiple models to run simultaneously or saving previous solutions for comparison. This could be achieved by organising options into separate tabs, with one dedicated tab providing a clear comparison of all models.

4.3 User personas

As a basis for the user oriented process, the following user personas have been defined. These represent users with knowledge in the AEC industry.

Persona A: (Structural engineer)
This persona is new to the software and has no prior experience in Rhino or Grasshopper. To use the tool, the user only needs to have or define a geometry in the Rhino viewport as a simple boundary representation (BREP). The interface is presented as a pop-up window where all parameters, material choices and structural definitions can be selected. The goal is to provide a simple and intuitive experience that allows the user to quickly generate results and compare different structural systems without confusion or errors.

Persona B: (Structural engineer + programmer)
This user has prior experience with both Rhino and Grasshopper. They interact with the tool similarly to Persona A, but can also create more complex geometries, such as BREPs with varying heights and irregular footprints. The user is also capable of working within the Grasshopper interface and can change parameters or add custom features to the tool. These additional functionalities can be integrated and applied directly to the user interface.

Persona C: (Architect + programmer)
This user is not a structural engineer and may lack the ability to make informed assumptions about specific structural requirements. However, they possess at least basic

knowledge of Rhino and Grasshopper and are comfortable navigating the interface. The tool is intended to support this user by offering pre-defined assumptions and visual guidance, allowing them to explore structural alternatives without requiring detailed engineering input.

4.4 Tool concept

The initial idea of the concept is to further expand the previous prototype of the tool, to include more functions. Combining conclusions from literature study (Section 1.1.2) and framework study (Section 4.1), as well as recommended features from previous tool developer and supervisors, a prioritised list of main desired inclusions has been established.

It can be summarised as the following:

1. Adding substructure
2. Adding roof element
3. Flexible geometry input
4. User interface (UI)
5. Expanding database of materials and cross-sections
6. Adding load-bearing walls

The goal is to implement these features within a parametric workflow built on a modular structure. This approach enables each component to function independently while supporting a cohesive system logic. Object-oriented elements are used to attach relevant information to each structural component, making it easier to execute specific operations, such as load evaluation or environmental impact calculation.

Building on the analysis of the previous prototype and insights from the literature review, several key requirements have been identified to fulfil the aim of this thesis. These include a fast and intuitive interface, clear visualisation of structural and environmental results, and the ability to easily compare multiple design alternatives.

The final tool is intended to be easily manageable by defined users and to provide results that support the evaluation and validation of different design options during decision-making in early-stage design.

5 Tool Development

This chapter outlines the development of the parametric tool, introduced as WP, from concept to final implementation. The process was guided by an iterative workflow and informed by insights from earlier prototypes, literature and framework studies, with a focus on functionality, usability and performance evaluation.

It covers the tool's algorithm, input structure, structural and environmental logic, and database setup. Output features, including visualisation and export, are presented, followed by verification and a review of the user interface.

5.1 Process

The development of WP has followed the method outlined in Chapter 3. It has been an iterative process, with a focus on implementing functionalities step by step and continuously evaluating their performance. An overview of the main development milestones is presented in the timeline in Figure 5.1.

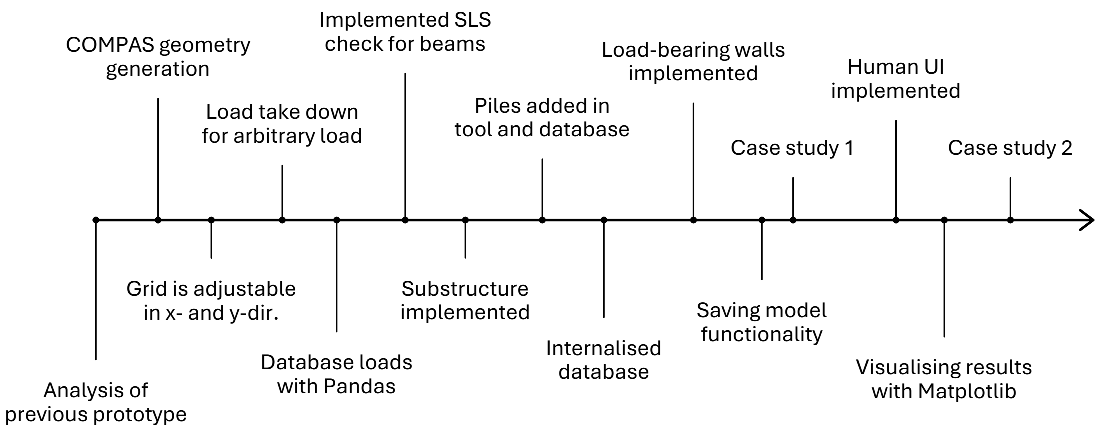


Figure 5.1: Timeline over the development process with important milestones.

5.2 Tool algorithm

The tool algorithm, as illustrated in Figure 5.2, outlines the step-by-step computational process from user input to tool output. It begins with the defined user inputs and the generation of the geometry, followed by a sequential procedure of preliminary design, load transfer and visualisation for each structural element, from slabs and beams to columns, walls and piles. Lastly WP computes the environmental impact as a result from the preliminary sizing of every element. The results are presented in various categorisations making it possible for the user to view what is of interest. The tool algorithm is a part of a larger Grasshopper definition which is presented in Appendix G.

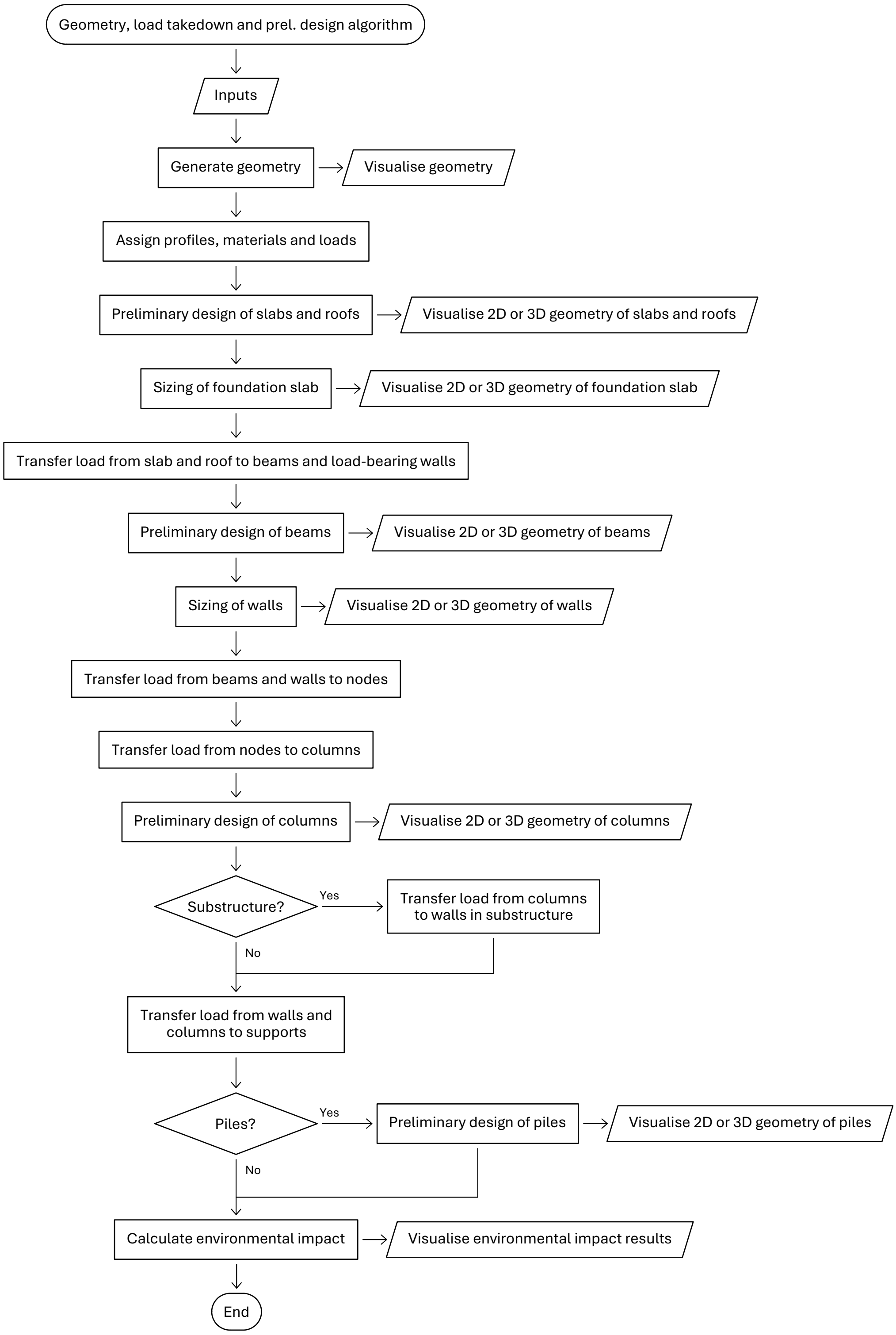


Figure 5.2: Tool algorithm.

5.3 Input

To define the building, the script takes a volume, one or multiple boundary representation (BREP), as a starting point. Together with number of spans in x- and y-direction as well as floor heights, cells are constructed. These cells are representing the bays in the grid, consisting of a slab, beams, columns and possibly walls. The user can input parameters such as number of floors in substructure, inclusion of piles, load categories and material selection. For an overview of all input parameters and their intended use, see Appendix F.

5.3.1 Geometry

The input volume represents the building's outer boundaries, an example is shown in Figure 5.3, and serves as the foundation for generating the structural elements. This can be defined in multiple ways depending on the complexity of the design, the user's preference and skill level. This volume is the starting point for generating the building elements together with the other user inputs. Since the volume can be adjusted during the design process, the tool allows users to explore how changes in building form affect the structural layout and associated environmental impact.

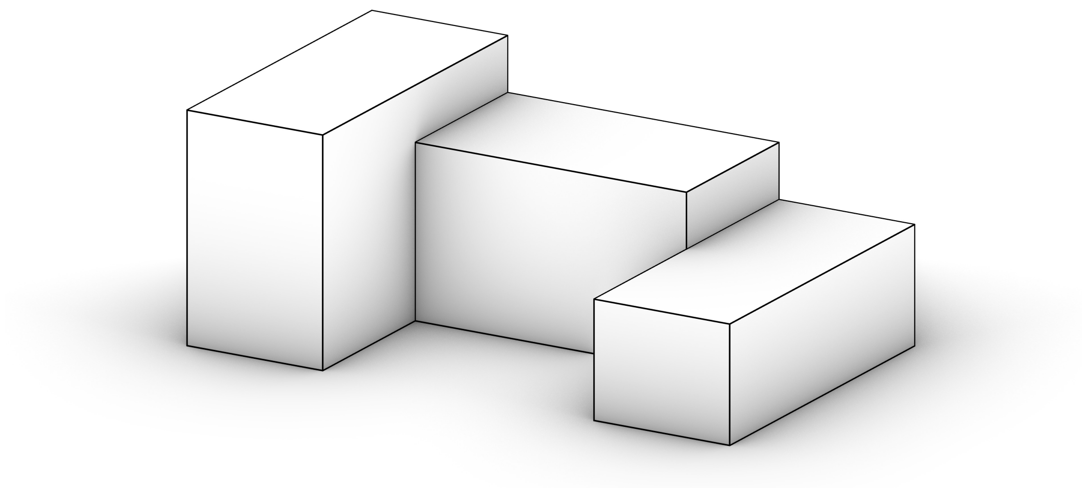


Figure 5.3: An example of a user input volume.

5.3.2 Grid

The structural grid divides the building volume into segments following an orthogonal pattern. It defines the span lengths for slabs and beams, as well as the spacing of columns. The grid is determined by the total footprint of the building and the number of divisions in each direction, both of which are user-defined inputs. By default, the grid is evenly spaced along each edge of the building. However, it can be adjusted interactively through a click-and-drag functionality in Rhino, providing the user with an intuitive way to modify the layout. The grid is continuously updated visually, with span lengths displayed, as illustrated in Figure 5.4, to support informed adjustments during the design process.

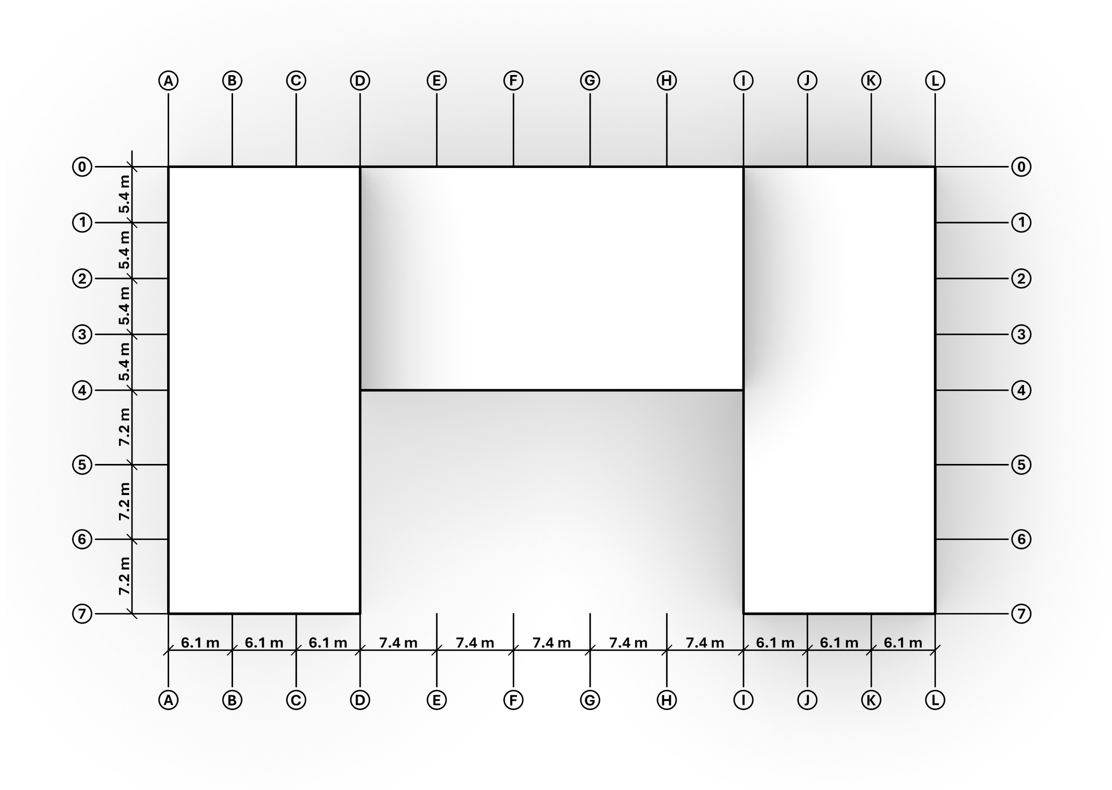


Figure 5.4: An example of a grid for the building volume, shown in Figure 5.3.

Similarly, the building height is divided into segments, defined by each floor's height. The user initially sets a uniform floor height, which can then be individually adjusted to reflect varying storey heights, as shown in Figure 5.5. This vertical division enables the tool to generate structural elements floor by floor and supports early exploration of how height variations influence structural design and material quantities.

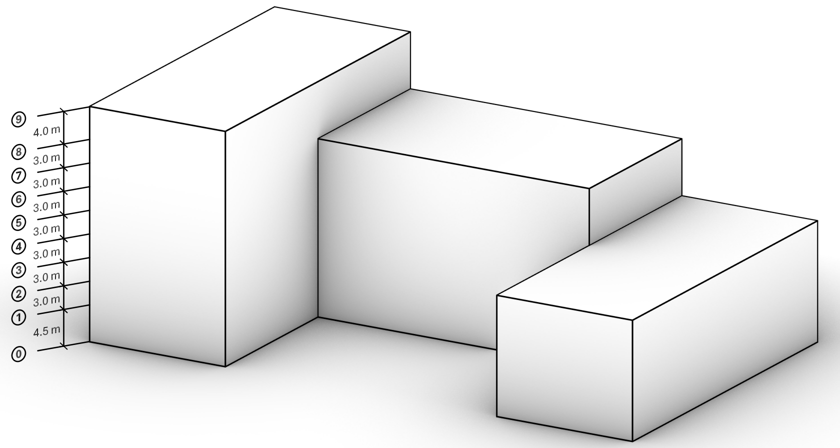


Figure 5.5: An example of a elevation grid for the building volume, shown in Figure 5.3.

5.4 Structural system

WP covers systems in the category of column-beam typology. This means that slabs, beams and columns are represented as simply-supported members. In Figure 5.6, a structural system of the building volume presented in Figure 5.3, is illustrated.

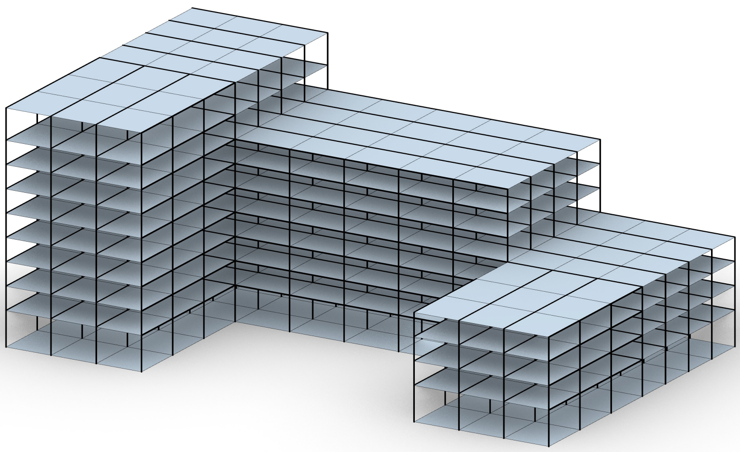


Figure 5.6: A structural system for the building volume, shown in Figure 5.3.

5.4.1 General

Some of structural members appear both in the superstructure and the substructure and those are covered in this subchapter. In Figure 5.7, the interface between super- and substructure is illustrated.

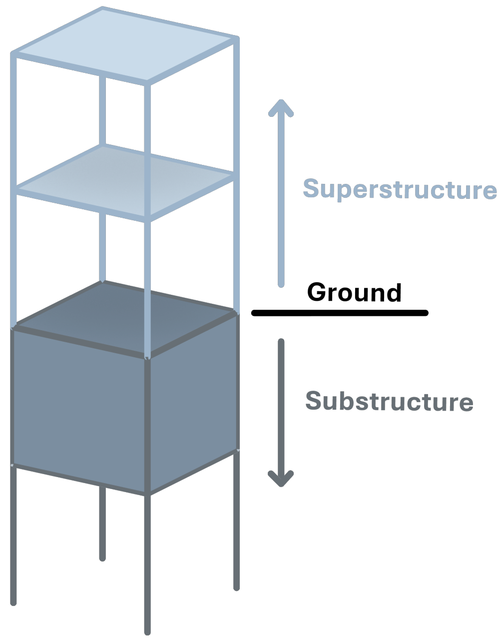


Figure 5.7: Illustration of the interface between super- and substructure in relation to the ground.

5.4.1.1 Slabs

Slabs are modelled as one-way spanning elements supported by beams. The span direction is a user-defined parameter and the span length is determined by the structural grid. WP also offer the option of automatically detecting the shortest span length of a slab and selecting this as span direction. This allows the user to guide the structural layout while the tool automates sizing of the slabs. The slab preliminary design function takes the following input parameters:

- Slab category (e.g. hollow-core)
- Span length
- Superimposed dead load (SDL)
- Variable load (imposed load)

These parameters are used to find a suitable slab from the pre-calculated slabs in the database. The selection process is illustrated in Figure 5.8, and filter out the available slabs by the given inputs. If no slab in the database fulfils any of the checks, an error message is returned and further displayed to the user, providing feedback on what is the problem.

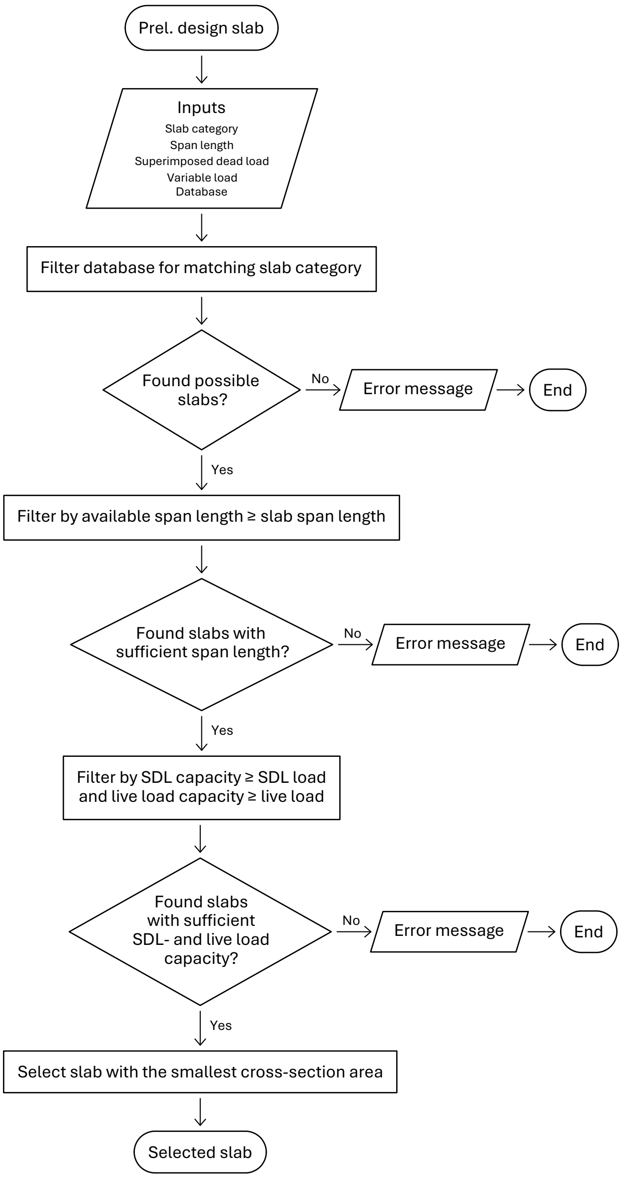


Figure 5.8: Flowchart illustrating the preliminary design logic for slabs and roofs.

5.4.1.2 Beams

Beams are preliminary designed based on these parameters: ULS- and SLS load and span length. Deflection check is included for beams where governing SLS load combination is used, depending on the material. The default deflection limit is span length divided by 300. However, this setting can be adjusted by the user. Figure 5.9 shows the logic for finding a suitable beam.

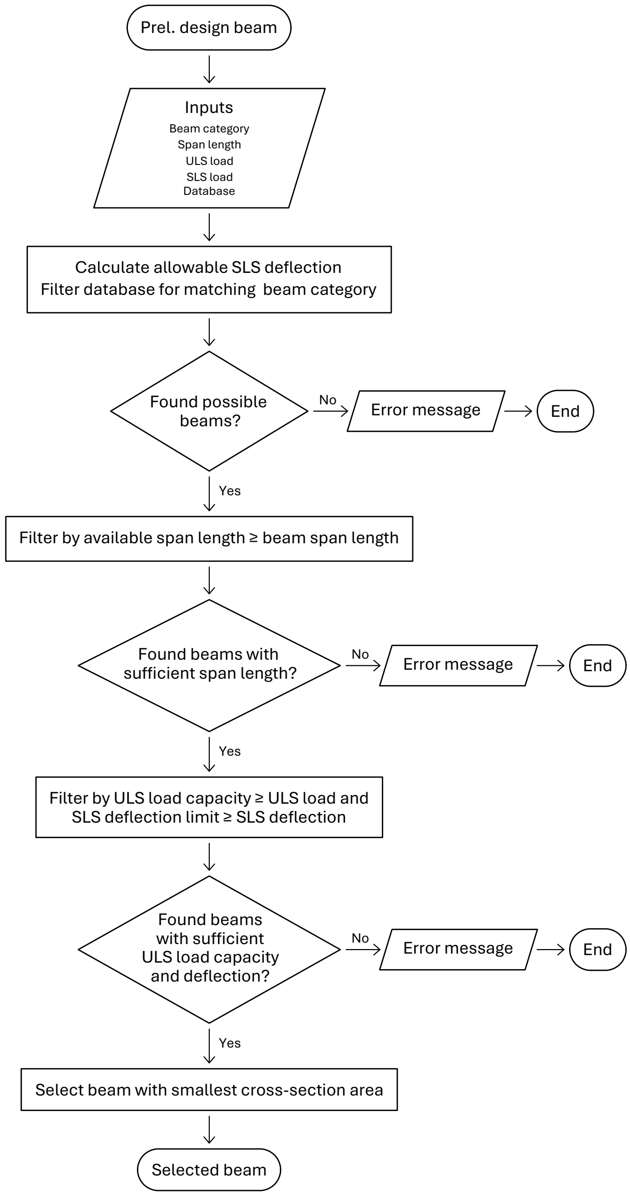


Figure 5.9: Flowchart illustrating the preliminary design logic for beams.

5.4.1.3 Columns

Columns are modelled as simply-supported where the buckling length is equal to the member's length. This means that the axial load and the column length is needed for preliminary design it, other than the selected material and profile. The logic for filtering the available columns in the database and finding a sufficient member is illustrated in Figure 5.10.

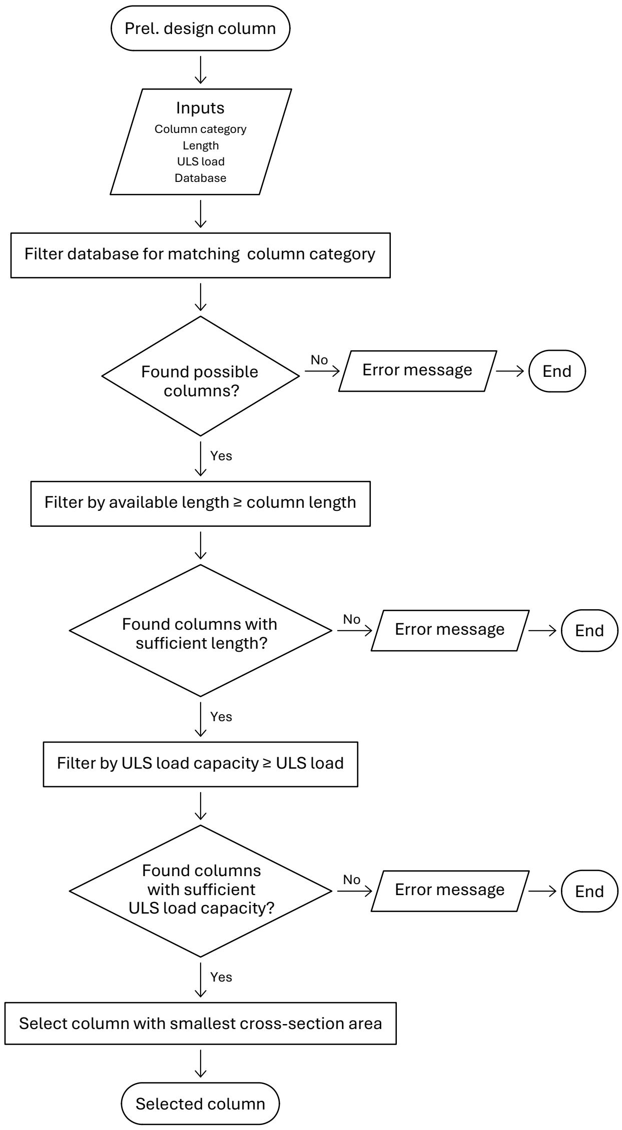


Figure 5.10: Flowchart illustrating the preliminary design logic for columns.

5.4.1.4 Walls

Walls is here referring both to the external walls in basement floors and load-bearing walls. The differ slightly from each other in the tool, where the external walls in the substructure is limited to be out of reinforced concrete while the load-bearing walls can be constructed as reinforced concrete or cross-laminated timber (CLT). The tool does not design the wall according to the loads it is carrying but facilitates an automatic thickness selection where the height of the wall is decisive on its thickness. This is a simplification as the design of walls includes a more complex logic that is not considered in WP.

5.4.2 Superstructure

The roof is constructed in the same manner as the slabs, spanning in one direction and supported by beams. The span length is defined by the structural grid. Preliminary design is based on the SDL of the roof, the snow load and the span length.

The snow load on the ground (s_k) can be selected depending on the geographical location of the building. As the roof is considered a flat roof in the tool, the shape factor μ is set to 0.8.

The SDL of the roof is categorised into three weight classes:

- Light roofs: 0.4 $[\mathrm{kN/m^2}]$
- Medium roofs: 0.8 $[\mathrm{kN/m^2}]$
- Heavy roofs: 1.2 $[\mathrm{kN/m^2}]$

The logic for preliminary design roofs are identical to the one shown in Figure 5.8.

5.4.3 Substructure

5.4.3.1 Piles

Piles are simplified in WP by only considering their structural compressive resistance. The user can choose whether or not to include piles in the structural system. For preliminary design, the axial load and the undrained shear strength is required.

Typically, two piles are placed under each column and one under each wall segment. This is due to practical limitations, piles rarely align perfectly with the ideal load path, which can introduce eccentricities. Piles are assumed to be prefabricated steel or reinforced concrete elements. Controllable parameters include the undrained shear strength of the soil and the pile length.

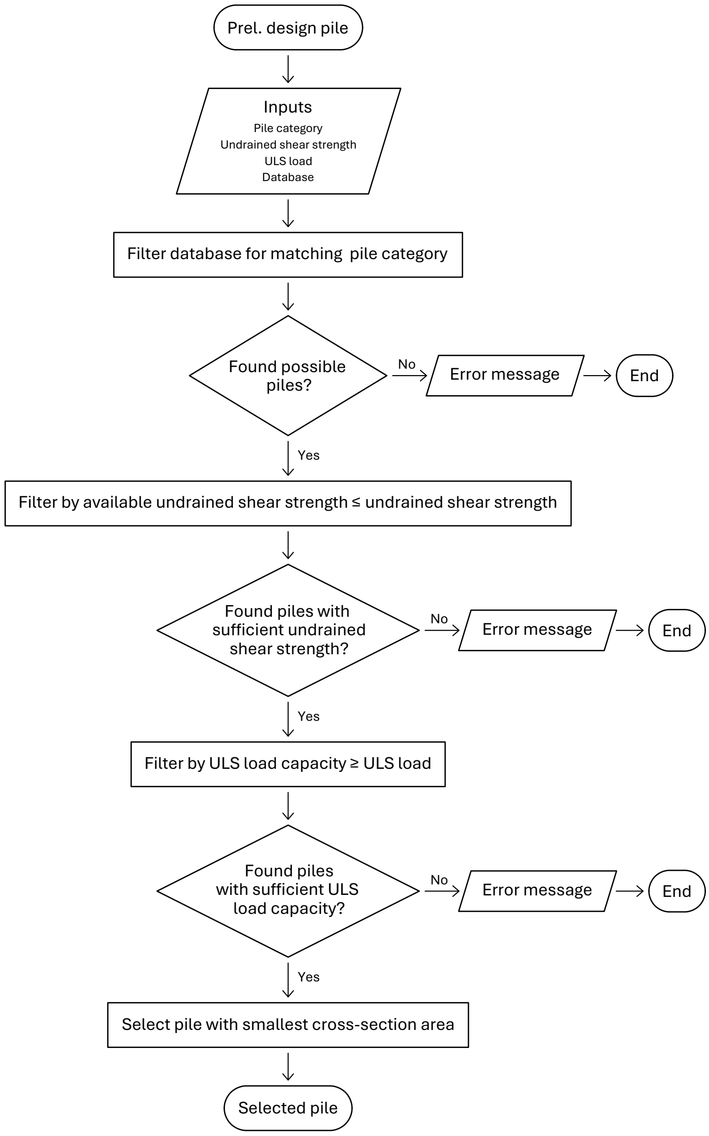


Figure 5.11: Flowchart illustrating the preliminary design logic for piles.

5.4.3.2 Foundation slab

The foundation slab is constrained to be out of concrete and with predefined thickness values for the user to select from. Structurally, as a simplification, the foundation slab is considered as a one-way, simply-spanning member. WP doesn't design the slab according to applied loads but facilitates an auto-option which lets the tool select the thickness of the slab based on its simplified span length. The user also has the option to explicitly select the thickness of the foundation slab.

5.4.4 Stability

The user has the option to add load-bearing walls to their design. This is done by making the grid lines selectable, illustrated in Figure 5.12, and thus creating walls in the selected bays of the grid, illustrated in Figure 5.13. These load-bearing walls is then running through the entire height of the building. The walls are not verified to ensure overall building stability, but are included primarily to account for material quantities and thereby the estimated global warming potential of the walls.

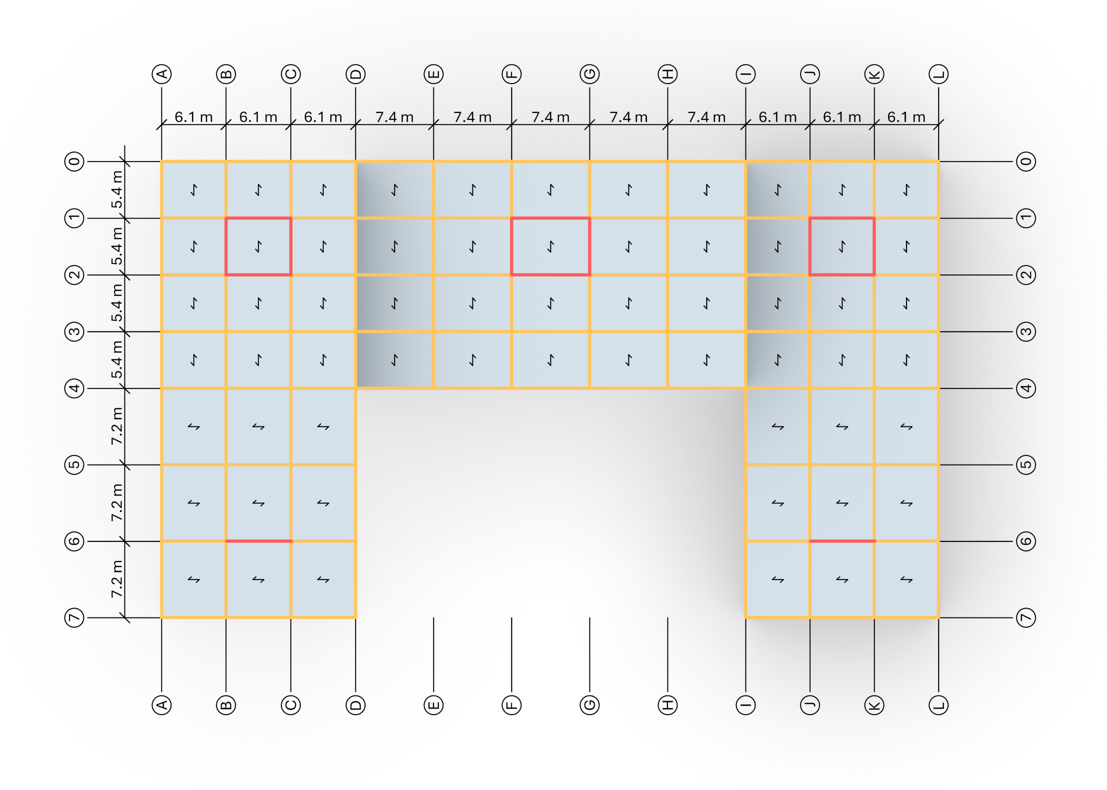


Figure 5.12: Illustration of wall selection in the tool. Orange: selectable lines. Red: selected lines.

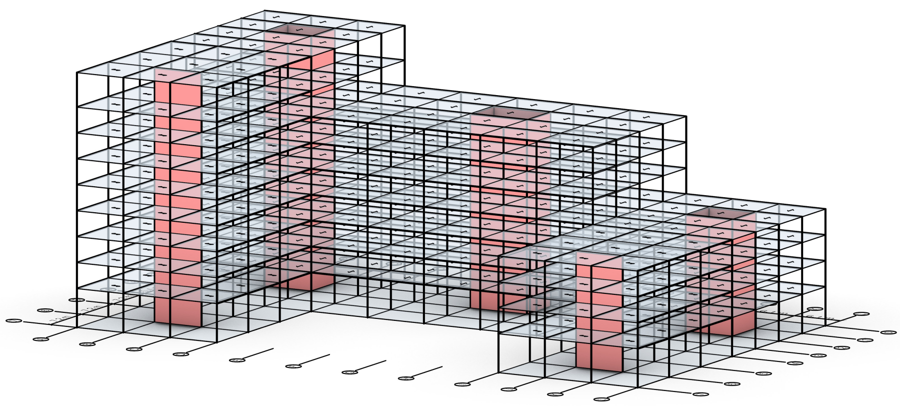


Figure 5.13: Illustration of a structural system with walls generated by the tool, highlighted in red.

5.5 Calculation of environmental impact

The data of environmental impact, regarding global warming potential (GWP), can be declared in either kg CO_2e/kg of material or kg CO_2e/m^3 of material. In the database, both units are found to make a robust collection of data were both inputs are possible and one is converted to the other by the conversion factor, often referred to the density of the material. The tool is generally designed to calculate the environmental impact by multiplying the volume of each material by its impact per volume of material, except from the slabs and roofs, which are calculated by multiplying the weight of the material by its impact per weight of material. This is due to some slab elements are not solid, i.e., hollow-core slabs.

To summarise the environmental impact of a design alternative, the calculated GWP from all members are added up and presented to the user, as well as percentage of the total GWP, categorised by structural member and material. Additionally, the total GWP are divided by the total gross floor area (GFA) to obtain a value that is comparable with other designs.

5.6 Database

The database is essential for the tool's functionality. The database is created and maintained in Excel, with both data for preliminary design of elements and environmental impact. The structure of the Excel-file is through sheets for each structural member, slab, beam, column and pile and environmental data in an additional sheet. Each of these sheets are structured in its own way, a documentation of these can be found in Appendix C. An overview of commonly used structural profiles, along with those included in the database within the scope of this thesis, is presented in Figure 5.14.

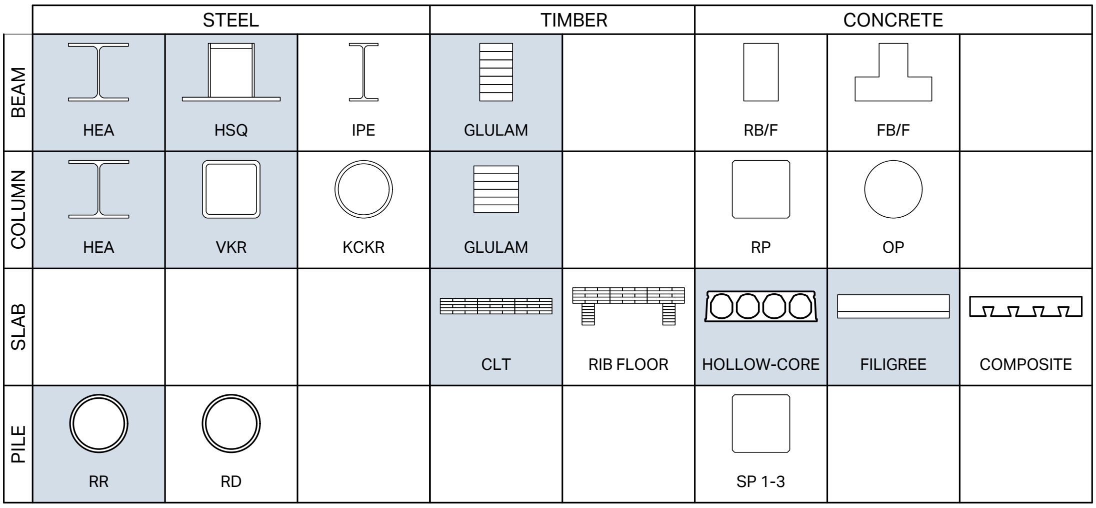


Figure 5.14: Commonly used structural profiles in building construction. Highlighted profiles are included in the database.

The data is structured as a list, where each structural member appears multiple times, once for each span length it can span. This results in some repetition within the dataset. However, this structure enhances clarity and usability from a programming perspective, as it allows the entire dataset to be imported into the tool and treated as a conventional database. This enables efficient filtering of structural members based on lengths and loads, making the selection of suitable elements during the preliminary design process quick.

The database can be extended with additional materials and pre-calculated structural members. However, the data is internalised within the Grasshopper script to improve performance. Referencing the Excel file directly was causing the script to run noticeably slower, especially when the database became larger. By internalising the data, the script becomes more responsive and stable in use. The downside is that any changes made to the Excel file are not automatically reflected. To update the database in the script, a superuser must manually reload the data from Excel and internalise it again. Each sheet of the Excel-file is converted to a separate "database" in the Grasshopper script, making the preliminary design processes only filtering through the governing set of data, i.e., looking through beam-data when designing beams.

The database used for the preliminary design includes structural data for slabs, beams, columns and piles, as well as environmental data for material-related GWP. Slabs and roofs are covered by the Slab-sheet, which contains data originating either from producers or from engineers' own calculations. In some cases, this data includes vibration and fire checks depending on the producer's input. Although these aspects are not explicitly considered in this thesis, WP conservatively incorporates them where available. The beam dataset includes ULS load capacities and deflection values, enabling the tool to assess deflection using the corresponding serviceability load combinations based on material type. Column data is based on simplified assumptions, with the element modelled as simply supported under axial compression and with the buckling length set equal to the column length. Pile data includes only the structural compressive resistance. Environmental data primarily originates from Boverkets Klimatdatabas (Boverket, n.d.-a), which provides both conservative and typical values. The current implementation uses the conservative values for common structural materials, complemented by selected product-specific environmental product declarations (EPDs), such as Setra Trävaror AB (2022) and Tibnor AB (2020). The database is structured to allow for future expansion, including the addition of further EPDs or data from other generic sources.

5.7 Output

The output from WP primarily consists of the generated geometry of structural members, calculated GWP results and visualisations to support analysis and comparison.

The GWP results is shown as a stacked bar chart, making it easy to compare different alternatives. A stacked bar chart categorised as structural members and structural materials is presented where the user can select which design options to compare and present. Each stacked bar contains data about how much each member or material is accounting for, as a portion of the total. This makes it easy to evaluate how the structural members or materials is distributed in relation to each other. The visualisation of the results is plotted in a Python script, using Matplotlib, saving an image in a pre-defined directory as a .jpg file. This image is accessible to be forwarded to the architect or other member in the design team.

The tool facilitates a functionality that lets the user save their designs. This is in practical implemented as a *bake geometry*-function that converts the Grasshopper geometry to Rhino geometry. When this is done, all structural members along with the structural grid and a defined name of the design is baked into Rhino. Additionally, each member gets their profile names and GWP-data baked as object attributes, allowing the user to select a member in Rhino and inspecting its information.

5.8 Scripting

The development of WP was carried out in the Grasshopper environment, where essential parts of the calculation process are performed through custom-built Python components integrated within Grasshopper.

5.8.1 Grasshopper

The tool is built in the Grasshopper environment, where user inputs are retrieved either from Rhino or through the user interface. The script follows a logical layout, with inputs placed on the left side of the canvas and results appearing to the right. Between these, data flows through a combination of custom Python components and native Grasshopper components. The native components are primarily used for geometry preview and visual feedback in the Rhino viewport, while the Python components handle the main computational tasks.

5.8.2 Python

To achieve a structured, scalable and robust application, object-oriented programming (OOP) is used. By the use of the COMPAS framework and its datastructure module, it makes it feasible to create geometric objects, corresponding to each structural member, where all the needed attributes can be attached. At this point, the class structure is kept to a single level, with one main class and several associated classes beneath it, illustrated in Figure 5.15. Using COMPAS datastructure VolMesh, enables a structured topology where the building is being discretised into cells, where the the framework facilitates a organised topology, where with its methods is possible to efficiently perform computations and filtering. In practice this means, for example, that horizontal faces may be slabs, horizontal edges may be beams and vertical edges may be columns. To each of these classes, attributes such as lengths, coordinates, materials and functions can be attached to them.

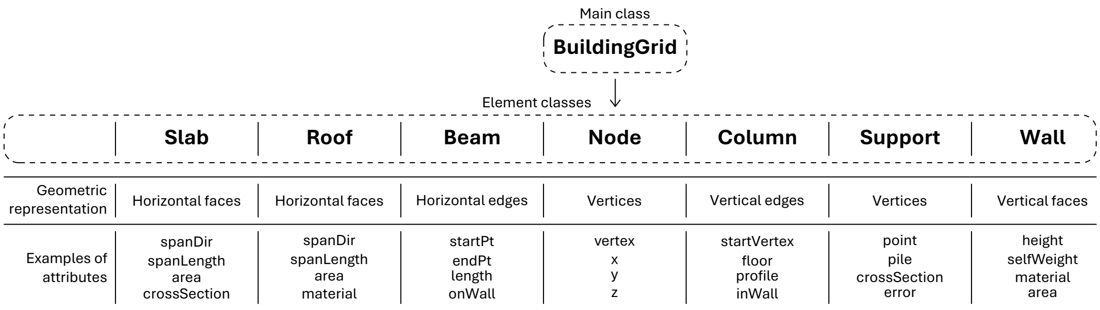


Figure 5.15: Hierarchy of the classes used in Python.

The database is written and maintained in Excel and also saved as a .xlsx-format which is further read by the script using the Python library Pandas. This library enables the script to convert the Excel-data to a JavaScript object notation (JSON)-format which can be used as a list-like database where applicable in the tool.

5.9 Verification

To check the tool's reliability, simple hand calculations of load takedown, preliminary design of members and calculation of GWP has been conducted and compared to the result from WP. This showed good alignment of the results, for a more detailed overview, see Appendix E.

The test case was based on an example geometry, with a regular grid of 9 × 4 spans, with a floor height of 3.0 m and applied loads. The model includes two storeys and a basement level, with foundation piles. This configuration was chosen to represent a reasonable level of complexity while remaining manageable for manual verification. The same step by step procedure applies to systems with more floor levels or more flexible layouts.

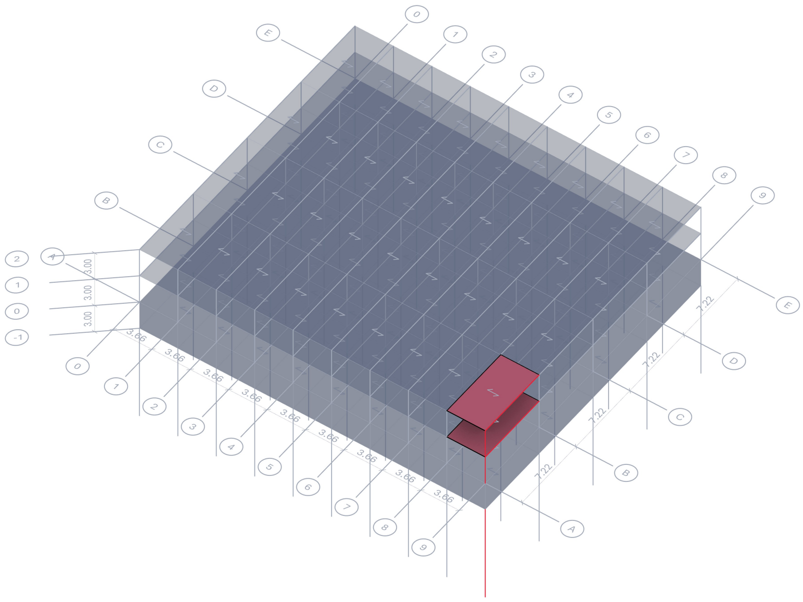


Figure 5.16: Verification model. Members highlighted in red are selected for the load takedown and preliminary design verification.

5.9.1 Load takedown verification

To verify the tool's load evaluation, a hand calculation was carried out using the same input parameters. The verification focused on a corner of the structure, highlighted red in Figure 5.16, where the resulting loads on beams, columns and support reactions were calculated by hand.

The process involved calculating the total load on each structural member, estimating appropriate cross-sections and selecting profiles from the available database. The selected profiles were also assessed for deflection against L/300 criterion, which was satisfied in for both cases. For slabs, the ULS load combination was not conducted because the dead- and imposed loads provided by the manufacturer were directly compared to the chosen design values.

As shown in Table 5.1, the results from WP closely match the hand calculations for all main load paths along the selected section of the structure. For example, the calculated reaction force at level 1 beam differs by less than 0.6% between methods and column loads and self-weights show negligible deviation. Minor differences are mainly due to numerical rounding in the Grasshopper environment.

These results confirm the structural logic of the tool and indicate that its load takedown functionality aligns well with conventional engineering calculations. The complete hand calculation and the corresponding results from WP are presented in Figure E1.

	Tool ULS	**Hand calculation** ULS	**Difference**	**Difference** [%]
Beam lvl.2	5.789 [kN/m]	5.758 [kN/m]	-0.032 [kN/m]	-0.54
Column lvl.1	42.148 [kN]	42.147 [kN]	-0.001 [kN]	-0.00
Beam lvl.1	5.953 [kN/m]	5.920 [kN/m]	-0.033 [kN/m]	-0.56
Column lvl.0	43.323 [kN]	43.222 [kN]	-0.101 [kN]	-0.23
Piles	303.157 [kN]	303.651 [kN]	0.494 [kN]	0.16

Table 5.1: Load takedown verification between tool and hand calculation.

5.9.2 Global warming potential verification

To verify the GWP calculations performed by WP, a comparison was made with a manual calculation conducted in Excel. The same structural model, as presented in Figure 5.16, was used for both the tool and the manual calculation, where all structural members were included in the analysis. Table 5.2 illustrates the differences between the results obtained from the tool and the hand calculation. The comparison demonstrates a strong agreement between the two approaches, indicating that the tool provides reliable estimates of GWP. The small differences are probably due to rounding-effects from the tool. The complete hand calculation and the corresponding results from WP are presented in Figure E3, in Appendix E.

	Tool [kg CO_2e]	**Hand calculation** [kg CO_2e]	**Difference** [kg CO_2e]	**Difference** [%]
Pile	19632	19634	2	0.010
Foundation slab	102560	102559	-1	-0.001
Wall	23692	23693	1	0.004
Slab	72799	72799	0	0.000
Beam	40958	40963	5	0.012
Column	10097	10096	-1	-0.010
Roof	36399	36399	0	0.000

Table 5.2: GWP calculation verification.

5.10 User interface

A custom interface was developed to improve usability and better support non-expert users, as the native Grasshopper sliders and panels were found to be limiting in terms of layout control, clarity and workflow separation. The primary goals were to separate parameter inputs from the Grasshopper canvas, support more intuitive user interaction and create a user experience more aligned with conventional design software.

5.10.1 Analysis of interface options

Several interface options were considered during the development of WP, each with varying degrees of complexity, flexibility and compatibility with Grasshopper and Rhino. The purpose of this comparison is to evaluate their suitability for integration into a parametric design tool within the scope and time frame of the thesis. Table 5.3 presents a qualitative comparison of four different approaches: Human UI, UI+, a web-based interface and the native Grasshopper UI. The assessment is based on technical characteristics and practical implementation experience.

Criteria	**Human UI**	**UI+**	**Web-based UI**	**Grasshopper**
Layout flexibility	High	Medium	Very high	Low
Developer learnability	Easy	Moderate	Difficult	Easy
Widget variety	Yes	No	Yes	No
Platform support	Windows only	Windows only	Cross-platform	Cross-platform
Community/ tool support	Strong	Limited	Varies	Native only
Maintenance status	Not maintained	Maintained	Varies	Active
Integration with tool logic	Direct	Direct	Requires API	Native

Table 5.3: Comparison of UI options based on suitability for integration in the tool within the thesis time frame.

As shown in Table 5.3, each solution has its strengths and limitations depending on the intended use. Human UI was selected as the most suitable interface for this tool, offering a strong balance between layout flexibility, visual clarity and ease of integration with Grasshopper. While it is no longer actively maintained and limited to Windows platforms, it proved to be stable and effective within the scope of this thesis. It was also easier to implement and offered a broader set of configurable components than UI+.

Compared to web-based interfaces, it required significantly less development time and allowed for direct interaction with the parametric model within the Rhino environment.

Although the main version of WP uses Human UI for this purpose, a parallel version is also maintained with all inputs defined directly within the Grasshopper environment. This version is intended for more experienced users and facilitates further development by allowing easier integration of new features.

5.10.2 Implementation

As the interface components, such as sliders, buttons and value lists were added to Grasshopper throughout the tool's development, the user interface was gradually structured using a column-based layout. This layout grouped components by function: input, material, selection, visualisation, model saving and settings.

Once the core functionality of WP was defined, a more pedagogical interface was implemented using Human UI. The layout was based on the same logical grouping as the Grasshopper version, but now divided into separate tabs to improve clarity and user experience.

Following case study 1 (Section 6.1), several interface improvements were made based on user recommendations. These included making key controls and information always visible, such as:

- A status message box providing guidance and error alerts.
- Visual output of the geometry and environmental impact results.
- Accessible view controls and interaction buttons.

The Human UI window contains all the familiar interface components required for user interaction, such as sliders, buttons, toggles and drop-down lists. To further assist users, especially when structural terms or values might be unfamiliar, help buttons were integrated throughout the interface to provide explanatory text or guidance when needed.

Figure 5.17 presents a schematic overview of the data flow and interaction between the main components of the tool: the user, Rhino, Human UI and Grasshopper. The diagram illustrates how data is exchanged throughout the workflow, with a particular emphasis on how user inputs and outputs are handled.

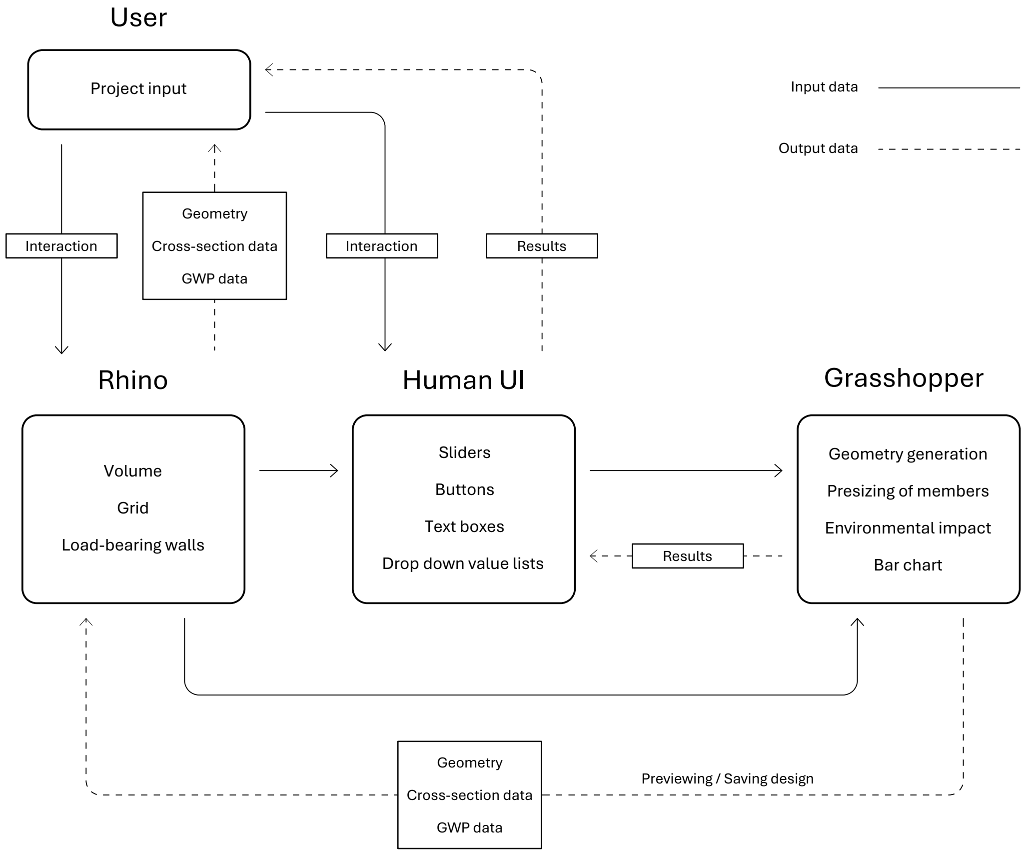


Figure 5.17: Schematic of data flow and interaction between the user, Rhino, Human UI and Grasshopper in the tool workflow.

The user only has to interact with Rhino and Human UI, defining the initial project input (e.g., building volume, grid layout and load-bearing walls) in Rhino and controlling all parameter settings via the Human UI window. Inputs in Human UI are provided through standard interface components such as sliders, dropdown lists, toggles and buttons. These are directly connected to the Grasshopper script, where geometry generation, member sizing and environmental impact calculations take place.

The results, including visualised geometry and GWP are then fed back through Human UI and previewed in Rhino. Key outputs, such as status messages, structural system dimensions and comparative environmental indicators, are made continuously visible to the user within the Human UI window. This structure allows for real-time interaction, rapid iteration and intuitive feedback throughout the early-stage design process.

5.10.3 Result interpretation

This section presents the resulting user interface of the developed tool, highlighting how key functionalities are made accessible to users through both the Grasshopper definition and the Human UI-based window. The interface was designed to enable intuitive interaction with parameters, while clearly visualising results relevant to early-stage decision-making.

Figure 5.18 shows the internal structure of the interface developed in Grasshopper. It served as the foundation during prototyping and reflects the logical grouping of parameters by category, such as geometry input, material selection and result visualisation. These were later mirrored in the Human UI layout for improved usability and clarity.

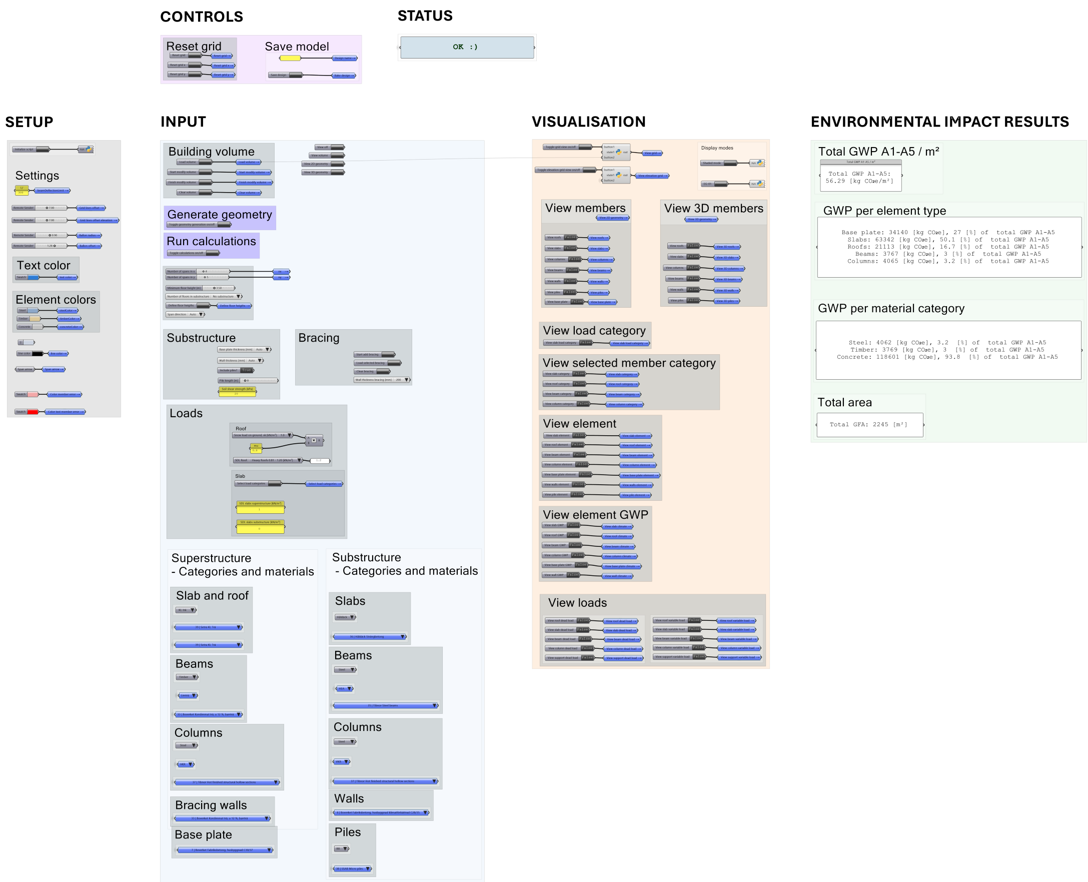


Figure 5.18: Grasshopper user interface.

Figure 5.19 illustrates the Human UI window, where users interact with WP's input parameters. Tabs are used to separate functionality, improving the clarity and usability of the interface. The input tab includes geometry setup (volume, grid, storey height), substructure and load parameters. A full overview of the tabs can be viewed in Appendix D.

As a result of the feedback from case study 1 (Section 6.1), several adjustments were made to the interface. The status message box was generally appreciated, but users noted that it could better indicate the specific cause of an error when one occurred, for example, whether a slab design failed due to excessive span length or a load that exceeded capacity. Additionally, commonly used controls were made more easily accessible in the final version of the UI. The interface window consistently displays visual feedback, including the status message box, essential control buttons and visibility toggles.

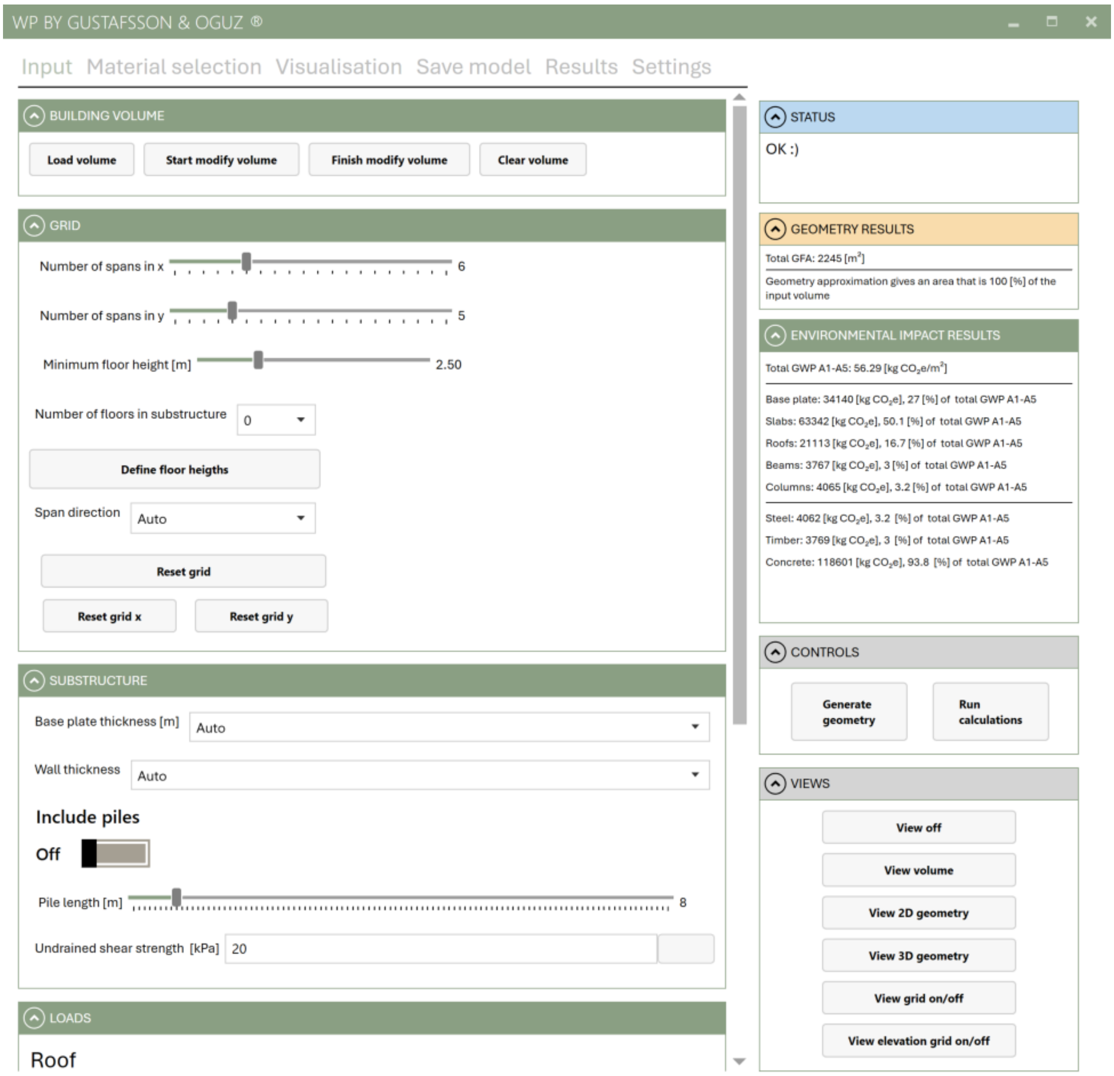


Figure 5.19: Human UI user interface - Input tab

The results tab, shown in Figure 5.20, presents a summary of both geometric and environmental performance indicators. These include GFA, total and per-element GWP (A1–A5) and comparative visualisations. A bar chart compares structural members and materials across model variants, allowing users to assess the impact of design alternatives.

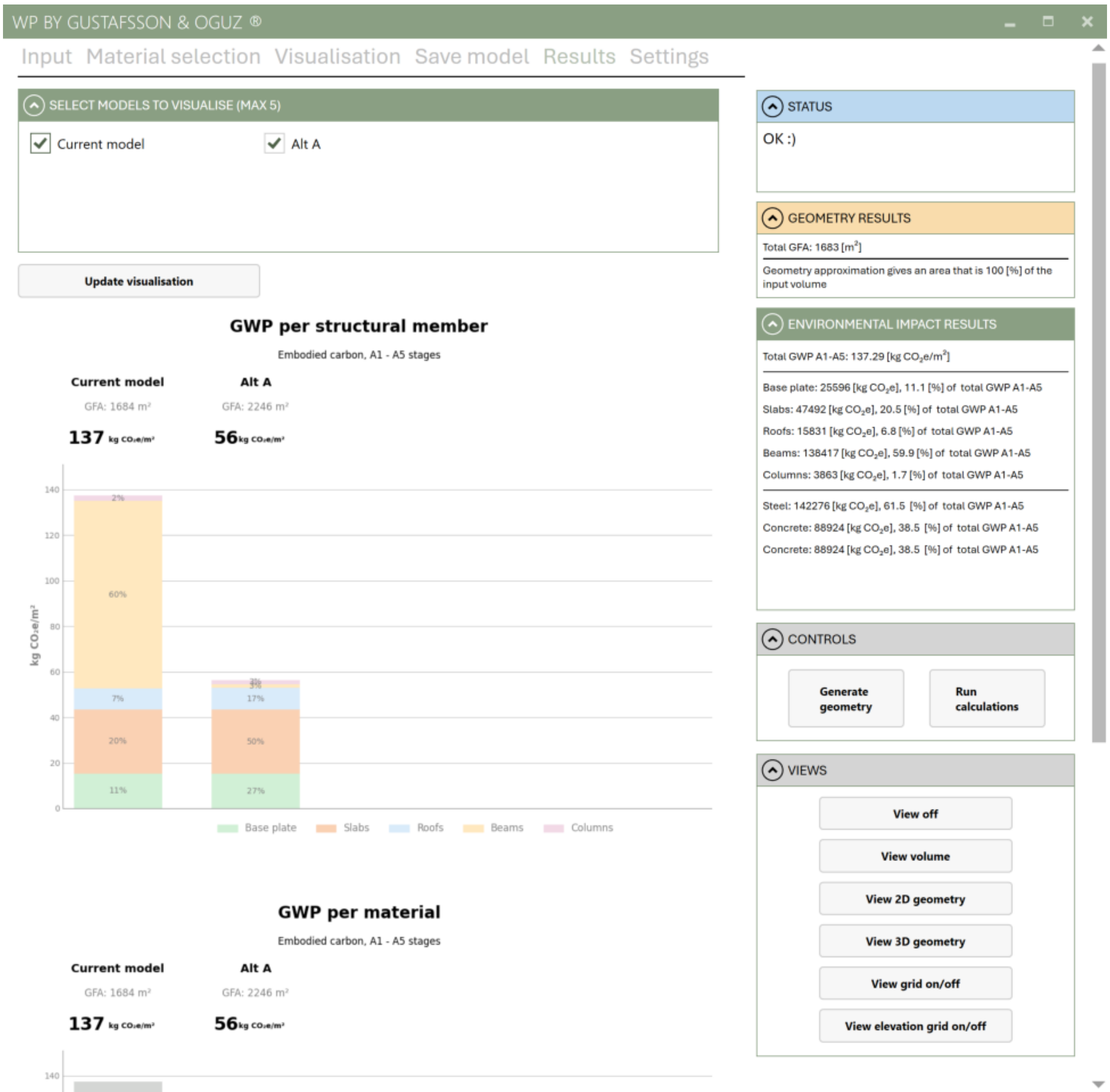
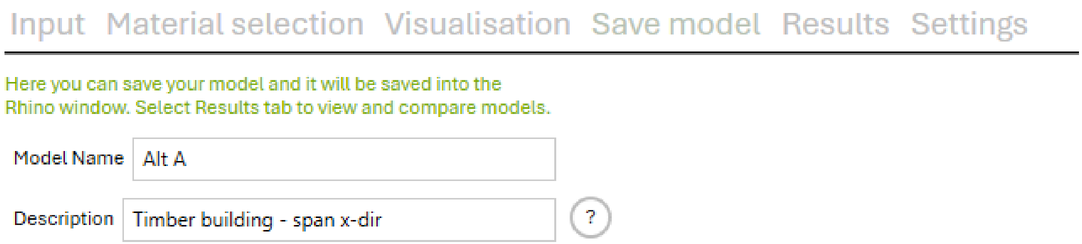


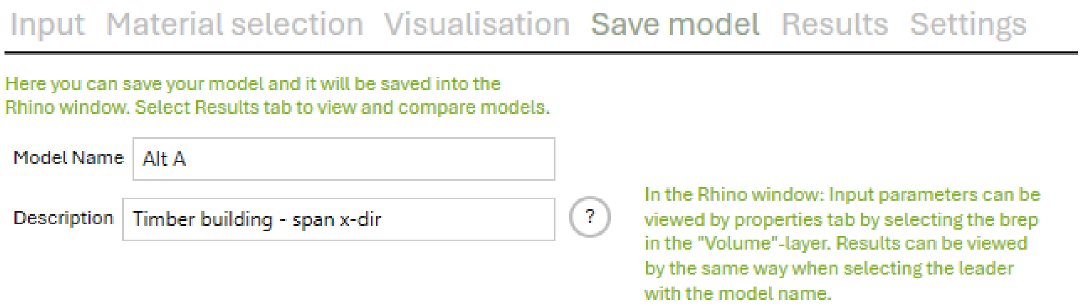
Figure 5.20: Human UI user interface - Results tab

The interface allowed users to control inputs and interpret outputs within a single, cohesive environment. Its visual clarity and tab-based structure were noted in the case studies as supportive to collaborative exploration between architects and structural engineers.

To support users during input, help buttons in the form of question mark icons have been added next to selected parameters. These are intended to either clarify specific structural input fields, particularly those that may be unfamiliar to non-structural engineers or to explain general tool functions. Figure 5.21 shows an example, where the help button provides guidance on how to view saved results in the Rhino window, more such prompts were requested by users in the case studies. This feature enhances usability and can be extended to additional inputs in future versions of the tool.



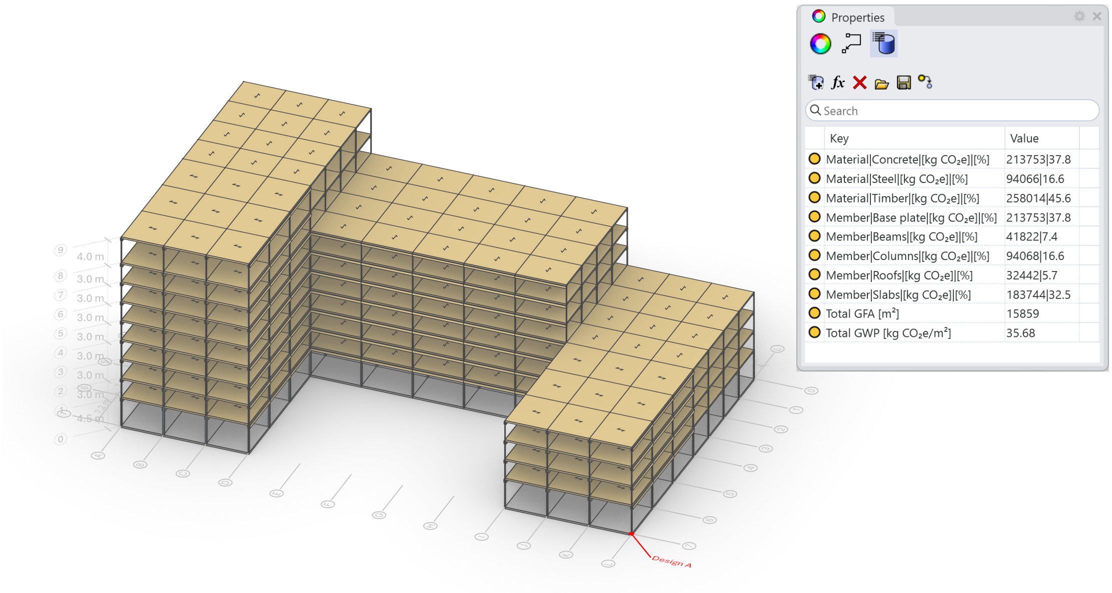
(a) Help button collapsed



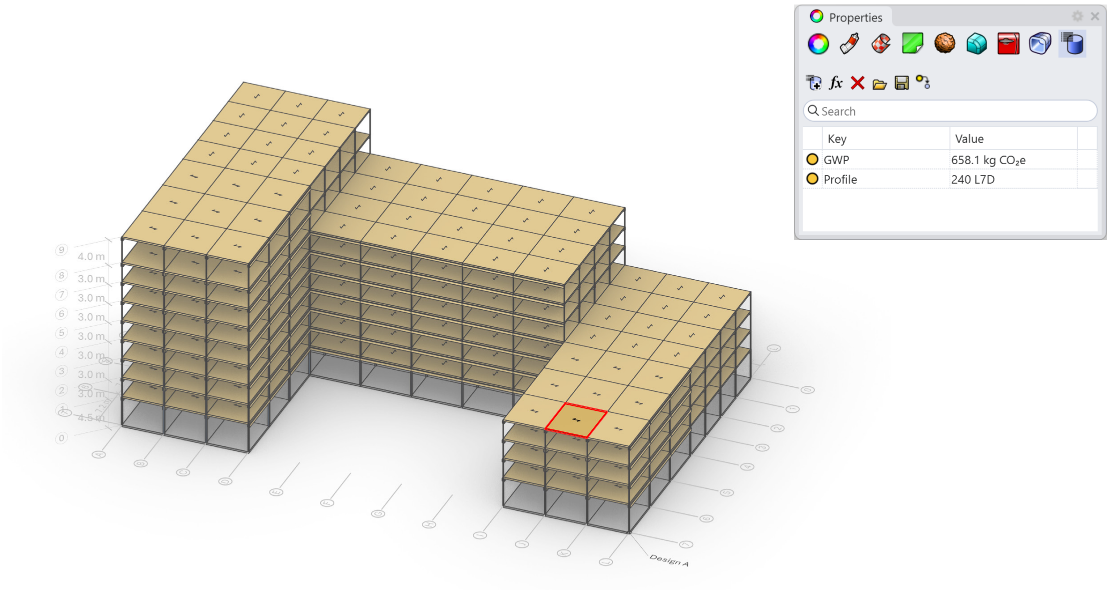
(b) Help button expanded

Figure 5.21: Toggle effect of a help button in the user interface.

When a design model is saved in the Human UI window, it is generated as 3D geometry within the Rhino environment. The user can then interact directly with the model in Rhino to view detailed results. By selecting the model leader (labelled by name), a summary of key result values, such as GWP for each member category is shown. Alternatively, selecting an individual structural member reveals specific information about its cross-section profile and corresponding GWP. This data is accessed through the Properties panel in Rhino. The generated model can also be exported to other formats, making it possible to use the geometry as a base for further design development or external analysis. An example of this interaction is shown in Figure 5.22, where (a) displays the summary results retrieved by selecting the leader, and (b) shows detailed data obtained by selecting an individual member.



(a) Summary of design results by selecting leader.



(b) GWP and profile data by selecting a member.

Figure 5.22: Accessing results of a saved design in Rhino.

6 User testing

This chapter presents the outcomes of two case studies conducted to evaluate the tool's (WP's) usability, accuracy and potential value in early-stage design. Case study 1 focused on individual users with varying backgrounds, while case study 2 was conducted in collaboration with practising architects and engineers on real development projects. Together, they provide qualitative insights into tool functionality, user behaviour and interdisciplinary collaboration.

6.1 Case study 1

This section presents the main findings from case study 1, based on observations made during the testing sessions as well as the answers given in the user feedback questionnaire. The observations are structured around each test person to highlight differences in user experience depending on their background and familiarity with parametric tools. A summarised feedback is presented below.

Tool state

At the time of case study 1, WP had the following functionality:

- **User interface:** Fully implemented within Grasshopper.
- **Available elements:** Slabs, beams, columns, substructure walls and piles.
- **Database contents:**
  - *Slabs:* Hollow-core and CLT
  - *Beams:* HEA, HSQ and Glulam
  - *Columns:* VKR and HEA
  - *Piles:* RR piles
- **Model output:** Saved models were previewed in the Rhino viewport only and were not generated as geometries for export or further processing.

6.1.1 Observations

Test person 1 (User persona A)
With our guidance, the user was able to navigate both the Rhino and Grasshopper interfaces. Since a predefined geometry was provided for Task A, the user encountered no difficulties. The concept of parameters, understanding what they are and how to manipulate them, was handled without issues. Interpreting results was also clear and the user actively attempted to minimise environmental impact by changing specific parameters and values, such as grid span lengths, span direction and material choices.

When the user was assigned the task of creating their own geometry, they did not immediately try to generate a simple box by freely clicking and dragging. Instead, the user requested support to input exact dimensions by assigning specific values. Afterwards, the user had no problem experimenting with different variations and saving models. This persona is a structural engineer.

Test person 2 (User persona B)
This user had no difficulties navigating the Grasshopper script or understanding the interface and parameters. With prior knowledge of the software, the user created more complex geometries and explored the tool's limitations, for example, by attempting to create spheres. In doing so, a problem within the script was discovered: the substructure levelling was constrained to Rhino's global z-level of 0. As a result, having any part of the geometry below $z = 0$ caused an error. This feedback enabled a correction in the script. This persona is a structural engineer.

Test person 3 (User persona C)
Similar to person 2, this user had no difficulty using the software or navigating the interface. However, unlike the previous personas, this user is not a structural engineer and lacked familiarity with specific building terminology, norms and reasonable load assumptions. As a result, choices related to substructure inputs were made without contextual understanding.

While exploring the grid layout and interactivity, such as dragging grid lines, the user also tested what would happen if a grid line was deleted. The outcome was that nothing occurred, which may require further attention or feedback from the tool.

6.1.2 Tool result

Test participant 3 explored a non-orthogonal, irregularly shaped volume, as illustrated in Figure 6.1. This highlighted a key limitation of the current tool setup: the structural system generation is based on an orthogonal grid and a modular-cell approximation. As a result, the tool approximates the geometry to fit the orthogonal grid and does not represent the input volume completely.

This case prompted the suggestion to implement a feature that quantifies and visualises the percentage difference in gross floor area between the original user-defined volume and the structural volume generated by WP. Such a metric would help users understand the extent of approximation and inform further refinement of the structural system.

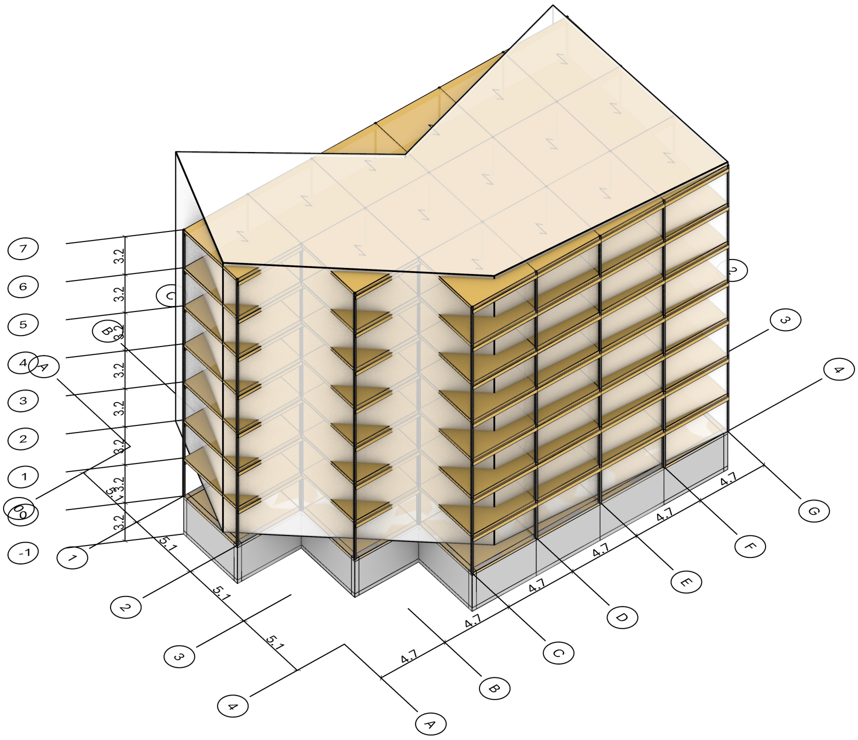


Figure 6.1: Visualisation of the structural system approximation, by test person 3.

6.1.3 Summary of user feedback answers

1. **What worked well in the tool?**
   The tool was fast and intuitive. It was easy to experiment with materials and profiles. The interface had a systematic structure and was agile. Geometry presentation was clear and effective. The inclusion of status feedback was helpful for understanding the next steps and for recognising errors.

2. **What was difficult or unclear?**
   Some error messages were difficult to interpret, making it unclear what exactly caused the error and which parameter should be changed to resolve it.

3. **Was there any feature missing that you expected?**
   The tool lacked visualisation of loads and environmental impact. A colour-coded display showing which elements contribute most would be helpful. Descriptions of functions and parameters were also requested. Buttons and components used frequently should be easily accessible.

4. **Do you think the results can support decision-making processes?**
   Yes, the output data, such as climate impact was considered informative and could help support real design decisions.

5. **Was it easy to generate and compare different design variants?**
   Yes, this function was appreciated and worked well at this stage of tool development.

6. **Was it easy to save and manage your models?**
   Some issues were observed. Returning to a saved model sometimes led to unintentional overwriting or erasing when interacting with buttons. A locking feature to prevent changes to saved models would be beneficial. It would also be helpful to load a saved model and continue modifying it.

7. **Did the results seem reasonable?**
   The reported environmental impact in kg CO_2e/m^2 seemed lower than expected.

8. **Could the tool handle variations in geometry effectively?**
   When models extended below the global z = 0 coordinate, problems occurred during substructure generation. A suggestion was made to use a local coordinate system for such cases.

9. **What would you like to improve or add to the tool?**
   - Ability to view material quantities used.
   - Optimisation by selecting two or three parameters to control.
   - Divide LCA stages from A1–A5 into A1–A3, A4 and A5.
   - Implement core/walls for stability, making the tool more complete.

6.2 Case study 2

This section presents the main findings from case study 2, which was conducted in collaboration with architects and engineers. It consisted of two separate projects: *Residential Block B in the Dergården area* in Lerum, Sweden and *A new apartment development* in Solna, Sweden. The results are based on observations made during the testing sessions, as well as comments gathered through discussion and feedback from participating architects and engineers. Observations and feedback are summarised collectively, as both projects were explored in parallel and raised similar themes.

Tool state:

At the time of case study 2, WP had the following added functionality:

- **User interface:** Implemented using Human UI.
- **Added elements:** Load-bearing walls
- **Added database contents:**
  - *Slabs:* Filigree slab
  - *Columns:* Glulam
- **Model output:** Saved models were generated in the Rhino viewport as geometries with information of environmental impact and dimensions in each member. Enabling further export of geometries.

6.2.1 Pre-questionnaire – Architect

Prior to testing the tool, a short questionnaire was given to the participating architect to gather background information and expectations. Below is a summary of the response:

- **How comfortable are you using tools like Rhino and Grasshopper?** (Scale 1–5: Not at all – Very comfortable)
  "5 for me personally, but it varies greatly across the office. Most people are not comfortable with Grasshopper, it is considered a specialist skill."
- **What type of information or feedback from the tool would be most valuable to your work?** (e.g., climate impact per material/structural component, comparisons between design alternatives)
  "Climate impact per structural component. Span lengths (affects floor plan layouts), amount of structure in façades (affects appearance), floor thickness/storey height/total height (timber structures often get ruled out in favour of slimmer concrete systems that allow for one extra storey)."
- **Would you consider adjusting the building design based on the tool's results (at this stage of the project)?** (Scale 1–5: Not at all – Absolutely. If yes, how?)
  "We don't make the final decisions, the client does, but I personally think the analysis the tool provides is extremely relevant and should be a basis for decision-making at this stage. The tool would definitely influence the proposals we present to the client."
- **Are there any functions or types of visualizations you spontaneously think would be useful?**
  "Clear illustrations describing the structural system concept, plan and section

showing heights and span lengths. A graph comparing proposals, both totals and per structural component, possibly also including span lengths and heights. It's also important that the data can be exported (e.g., to comma separated values (CSV) or Excel) so that project specific graphs can be created and the information can easily be integrated into a larger LCA analysis."

6.2.2 Project A: Residential Block B in the Dergården area

The project is a early-stage residential building located in the Dergårdsområdet area of Lerum. The tested building, referred as Residential Block B, is part of a larger urban development initiative aiming to create a vibrant and attractive town centre in Lerum. The zoning proposal includes approximately 300 new homes, a new upper secondary school for 2,000 students, a cultural centre with a theatre, library and arts education facilities, as well as commercial spaces and parking structures.

Residential Block B is designed to fit into the local cultural and architectural context. The architectural vision emphasises low eaves height, varied roofscapes and detailed façades (Lerums kommun, 2024). As the project is part of an ongoing zoning process, it provided a realistic and relevant setting for testing the tool's functionality and value during early-stage design.

Figure 6.2 shows a section of the tested building, while Figure 6.3 illustrates the plan view, highlighting the specific area of the building evaluated with the tool.

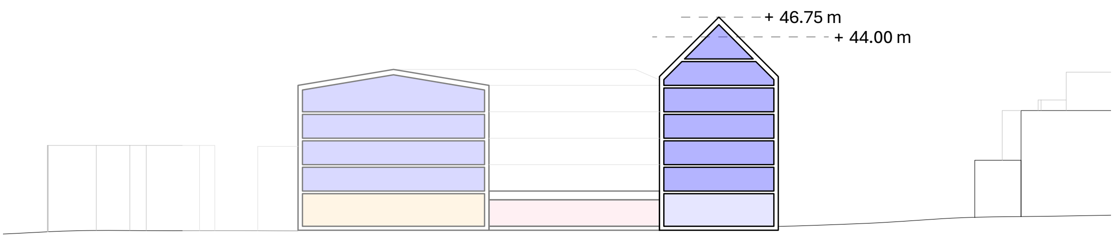


Figure 6.2: Section drawing of Residential Block B, abstracted from Kaminsky Arkitektur AB. The highlighted part served as the basis for the case study.

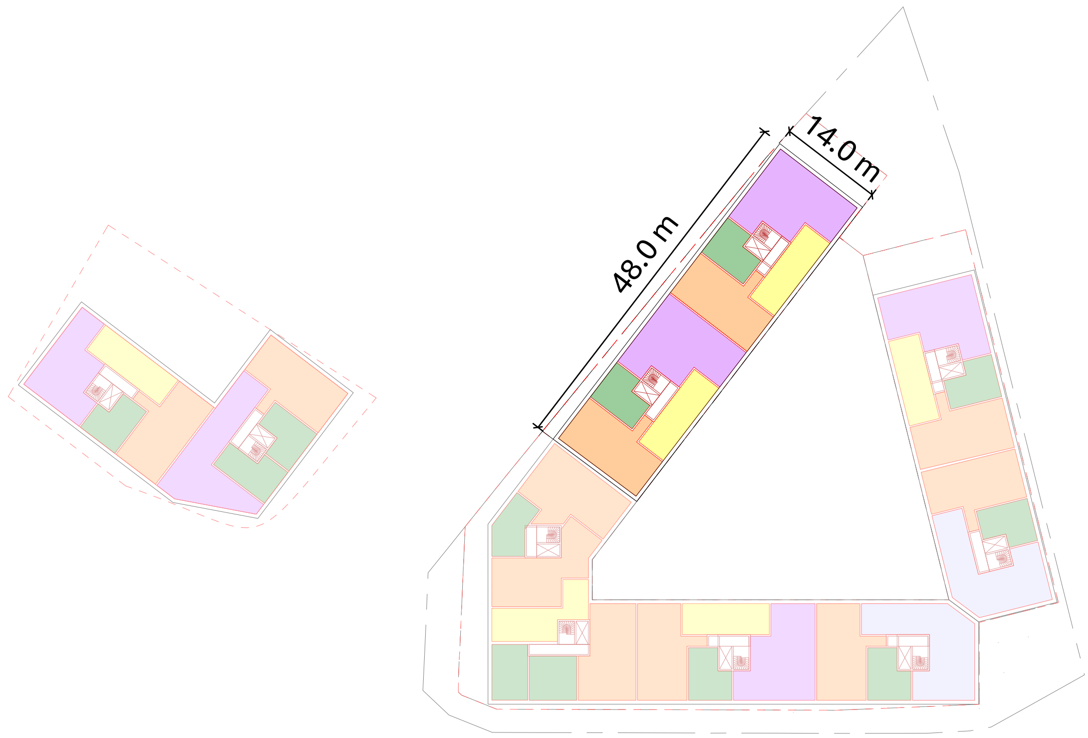


Figure 6.3: Plan view of Residential Block B, abstracted from Kaminsky Arkitektur AB. The highlighted part served as the basis for the case study.

6.2.2.1 Tool results

To explore different structural strategies for the project, two alternative design models were developed, each representing distinct combinations of materials and structural systems. These variations, outlined in Table 6.1, allowed for comparative evaluation in terms of environmental performance. The analysis focused on a selected part of the project, marked in Figures 6.2 and 6.3, with the resulting structural configurations visualised in Figure 6.4. GWP results by element and by material are shown in Figure 6.5 and Figure 6.6, respectively.

	Slabs	**Beams**	**Columns**	**Load-bearing walls**
Design 2	CLT	Glulam	VKR	CLT
Design 4	Hollow-core	HEA	VKR	Concrete

Table 6.1: Overview of structural model variants used in Project A.

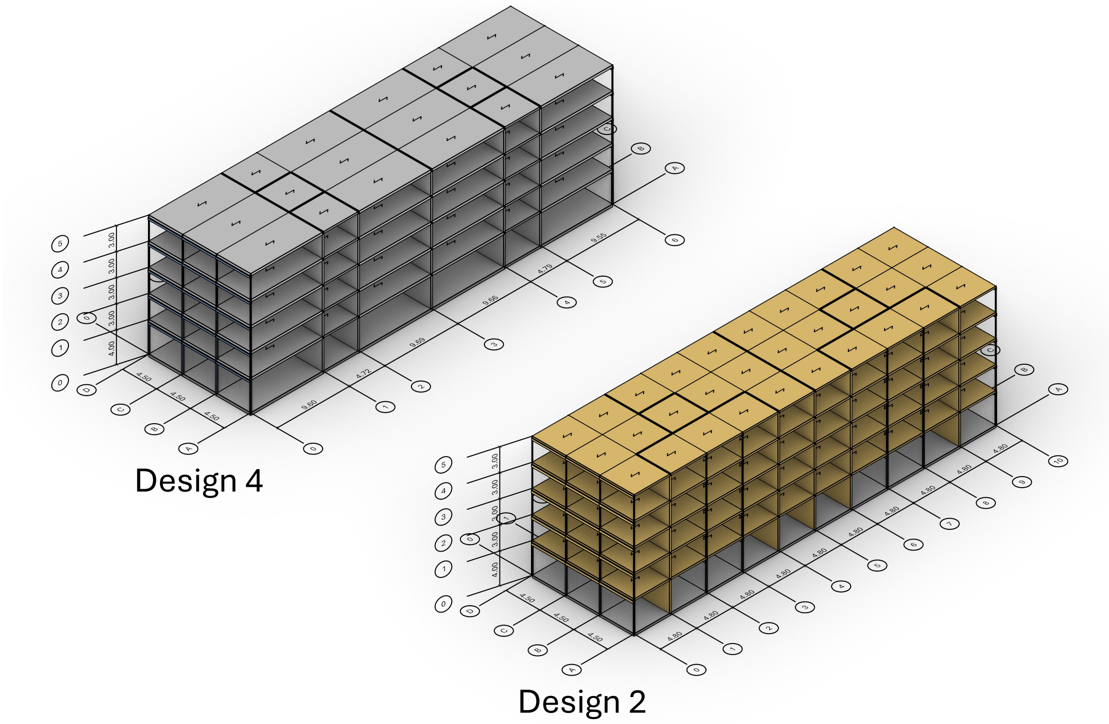


Figure 6.4: 3D visualisation of the two structural systems generated by WP.

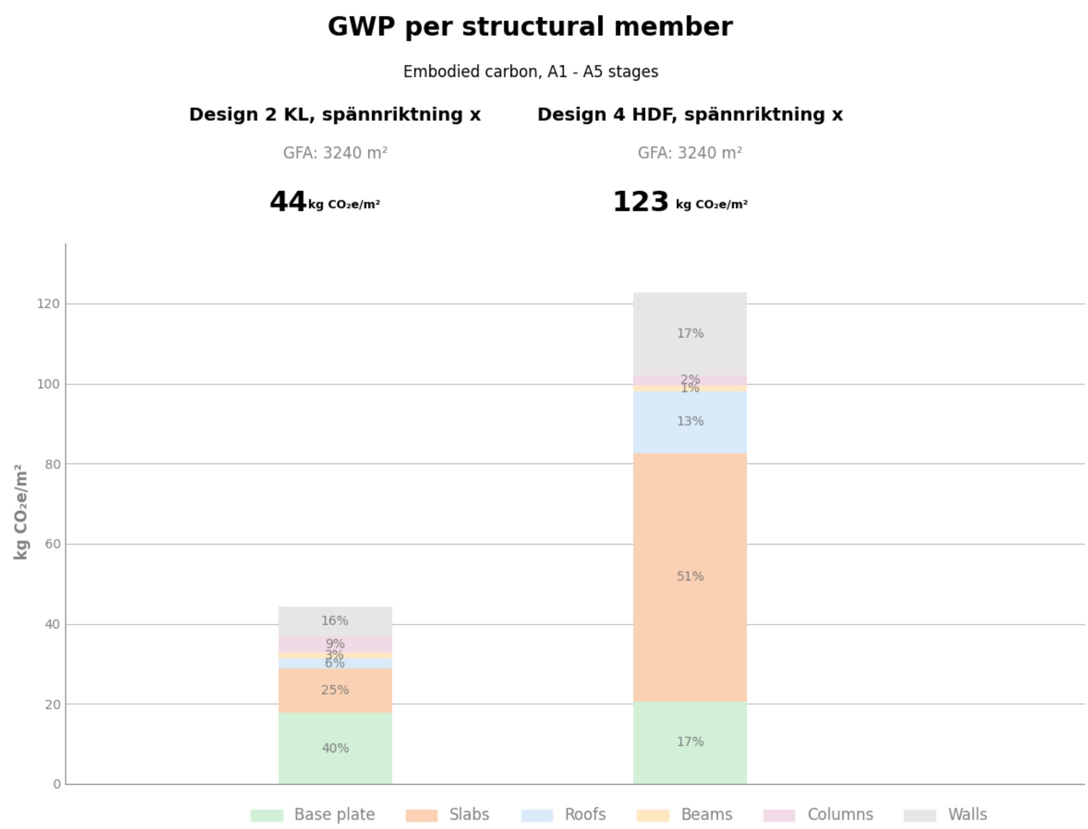


Figure 6.5: Visualisation of GWP for the two designs, categorised by structural member. An output from WP.

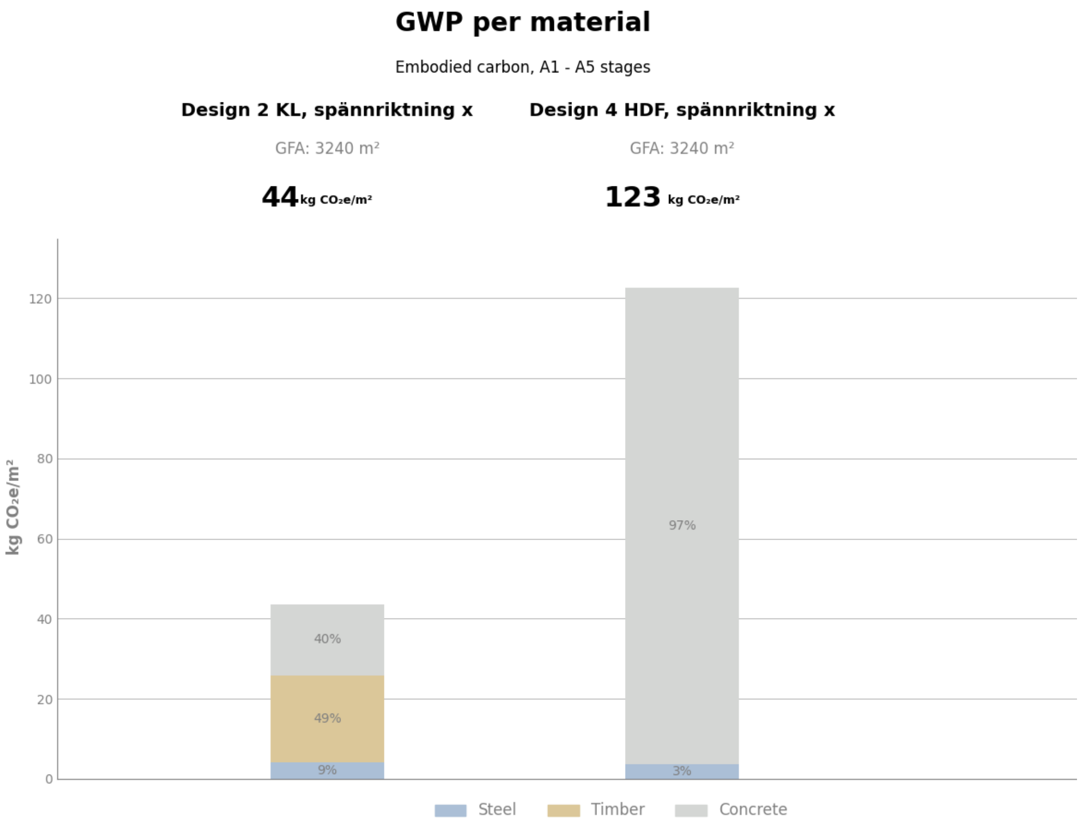


Figure 6.6: Visualisation of GWP for the two designs, categorised by structural material. An output from WP.

6.2.3 Project B: A new apartment development in Solna

The second part of case study 2 focused on a new residential development in Solna, currently in the early planning phase. The project is part of a zoning process and aims to ensure that the design meets the client's climate targets. Specifically, the goal is to stay below 160–170 kg CO_2e/m^2 gross floor area (GFA), in accordance with the Swedish climate declaration requirements (excluding the basement level and courtyard slab). The climate assessment is to follow the Lokal Färdplan Malmö 2030 (LFM30) methodology, a local climate roadmap for Malmö, developed to achieve climate-neutral construction by 2030 (LFM30, 2024), which requires separate accounting of dark GFA areas.

The study includes an exploration of Building 1, one of the three proposed volumes visible in the 3D site overview shown in Figure 6.7. For this tower block, two structural system alternatives were initially proposed by the architect:

- **Alternative A – CLT-based system**
  Cross-laminated timber floors and interior load-bearing walls, glulam columns in the façade and light timber-framed external walls.
- **Alternative B – Climate-improved concrete**
  Filigree slabs, steel beams (e.g., HSQ), concrete core walls and partitions, steel columns in the façade and infill walls.

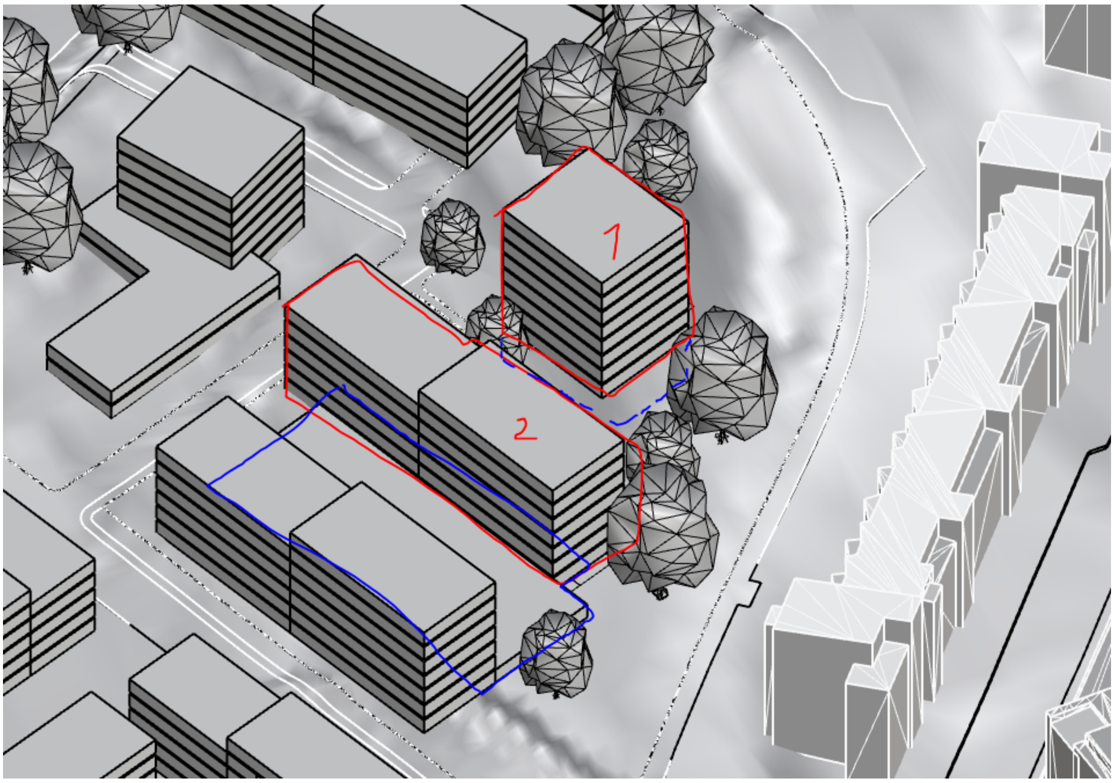


Figure 6.7: Site overview, from Kaminsky Arkitektur AB.

The intent was to evaluate and eventually combine these alternatives into a hybrid structure optimised for climate performance and constructibility. The architect also requested preliminary sizing of structural members.

Figure 6.8 and Figure 6.9 illustrates the section- and plan view of the site with Building 1 highlighted.

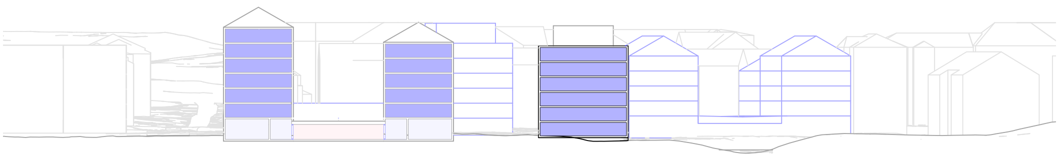


Figure 6.8: Section A-A, abstracted from Kaminsky Arkitektur AB.

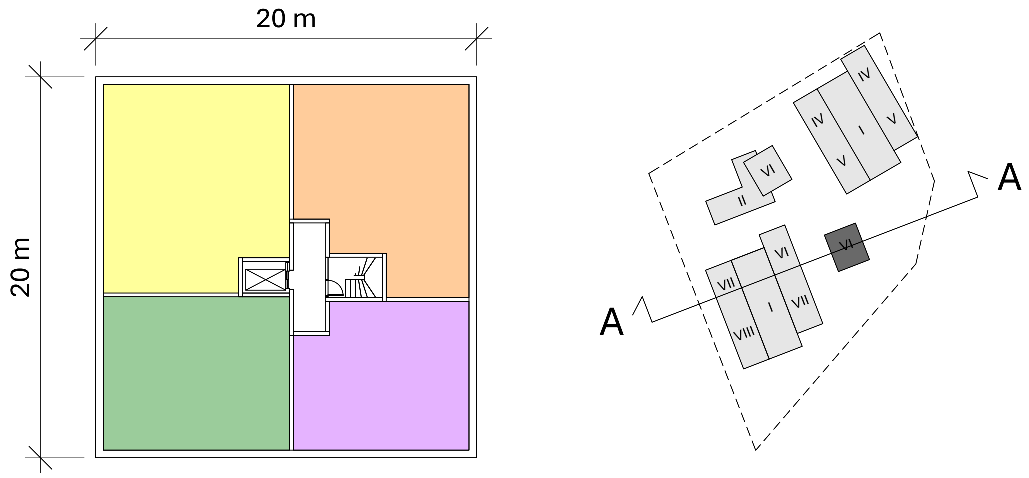


Figure 6.9: Plan drawing, abstracted from Kaminsky Arkitektur AB.

6.2.3.1 Tool results

After exploring the two alternatives A and B, further possible options were studied and four different designs were made. They are described in Table 6.2 and illustrated in Figure 6.10. Environmental impact results are shown in Figures 6.11 and 6.12.

	Slabs	**Beams**	**Columns**	**Load-bearing walls**
Alt. A	CLT	Glulam	Glulam	CLT
Alt. B	Hollow-core	HEA	VKR	Concrete
Alt. C	Hollow-core	Glulam	Glulam	Concrete
Alt. D	Hollow-core	Glulam	Glulam	CLT

Table 6.2: Overview of structural system variants.

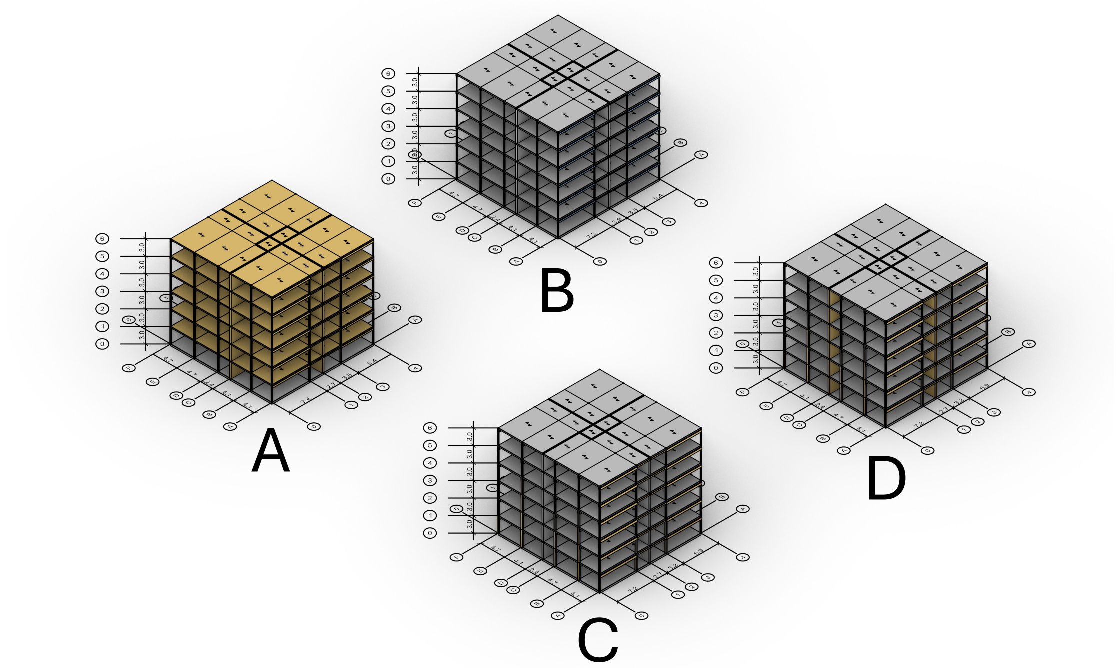


Figure 6.10: 3D visualisation of structural systems of Buildin 1, generated by WP

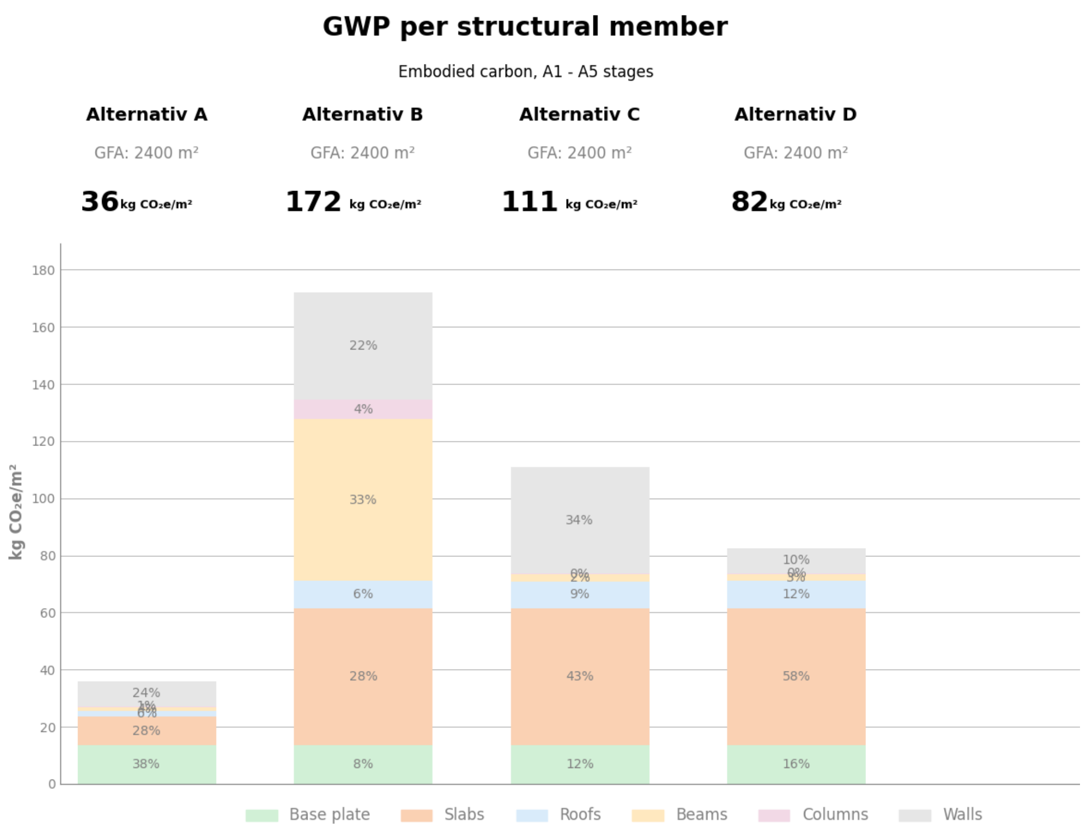


Figure 6.11: Visualisation of member environmental impact, an output from WP.

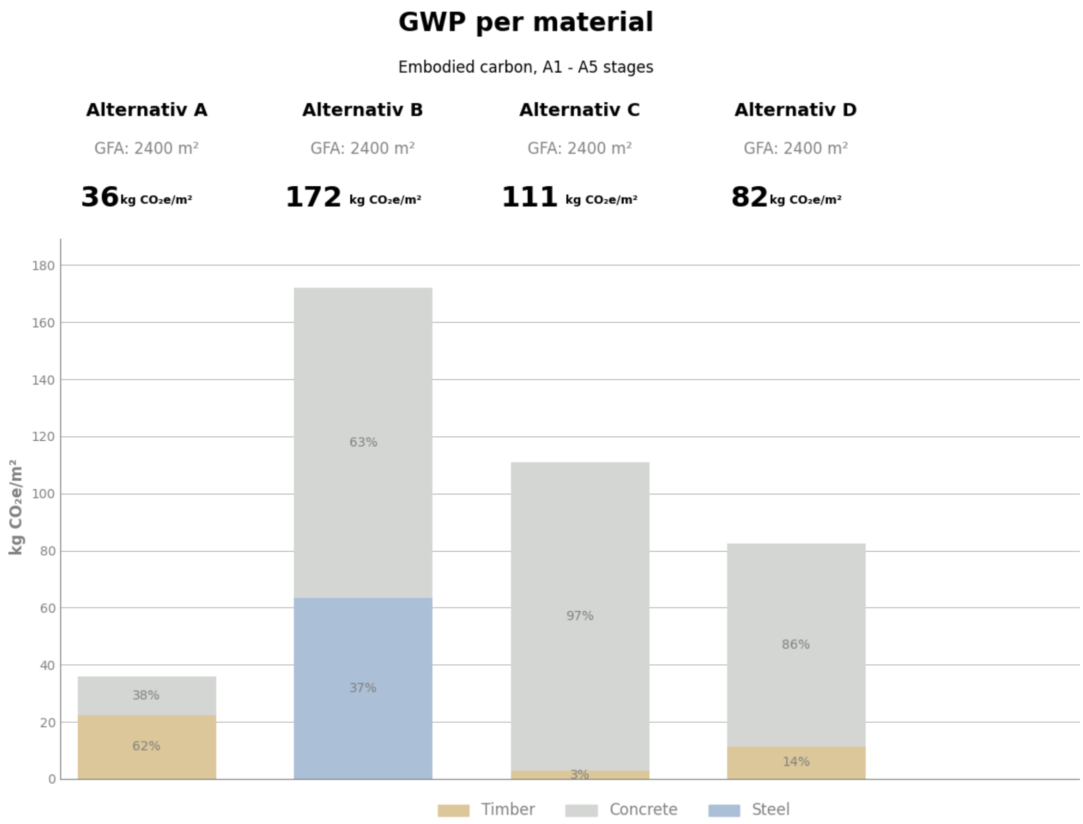


Figure 6.12: Visualisation of material environmental impact, an output from WP.

6.2.4 Observations

During the case study sessions, direct observations were made while architects and structural engineers interacted with WP. These observations highlight technical issues, user behaviour and discussion themes that emerged during the workshops.

Tool functionality

- For project A, Dergården, certain pop-up windows did not render properly due to a display bug, which occasionally affected the user experience.
- The visualisation of material legends of the bar chart was not always accurate, leading to potential confusion about the assigned material types.

Design discussions and user behaviour

- Although not part of the tool's current scope, fire safety considerations were brought up, particularly regarding the placement of fire-rated walls and how they relate to selected wall types.
- Users expressed a desire for more integrated discussions like the ones sparked during the workshop, noting that such dialogue is a valuable part of their collaborative design process.
- It was emphasised that the tool should not replace design evaluation, instead, it supports architects and structural engineers in making informed judgments.

Applicability and structural modelling assumptions

- The tool currently models structural systems with a one-way load-bearing assumption, which aligns well with hollow-core slab systems commonly used in office buildings.
- However, for systems such as CLT plates or filigree slabs (which distribute loads in two directions), this assumption leads to overestimated quantities and environmental impact values, as number of supporting members could be reduced in practice.
- This limitation was noted to reduce the reliability of environmental impact comparisons between certain structural systems and should be addressed in future tool development.

6.2.5 User feedback

Following the second case study, detailed feedback was gathered from the participating architect and engineers. The responses reflect both the immediate impressions during the workshop and additional reflections after tool usage. The following summary presents the feedback in a structured format, grouped by discipline.

Architects

- **Functionality and assumptions:**
  - Include a default value or template for reinforcement quantities.
  - Provide the option to export a PDF or summary sheet outlining key assumptions, such as:
    - Conservative values based on Boverket guidelines.
    - No consideration of fire or acoustic design requirements.
    - Exclusion of steel connections in timber systems.
  - Allow separate definitions for interior wall types (e.g., concrete for stair cores and CLT for partition walls).
- **Material selection:**
  - The selection process for materials, particularly concrete strength class, was unclear.
  - Suggested improvement: highlight common or recommended values, or mark them as "favorites" to guide users unfamiliar with material classifications.
- **Visual output and clarity:**
  - Result bar charts should include benchmark limits (e.g., from Boverket's climate declaration) for easier comparison across design options and better client communication.
  - Include clear visualisations of total building height and free floor height.
  - Visualisation quality was praised as aesthetically appealing and easy to interpret.

- **Flexibility in layout and grids:**
  - Architects requested the ability to draw custom grid lines to accommodate offset wall layouts.
  - Current auto-placement of columns along fixed grid lines was seen as limiting for architectural flexibility.
- **Usability and collaboration:**
  - The interface was described as intuitive and pedagogical.
  - The tool was considered a valuable dialogue aid between architects and engineers, helping clarify the structural consequences of design decisions at an early stage.
- **Data handling:**
  - Support for exporting project data to CSV or Excel was requested, to allow custom analysis or integration into larger LCA tools.

Structural engineers

- **Profile and design settings:**
  - Requested inclusion of additional profile types, such as KKR profiles for columns. Additionally, reinforcement amounts for walls and foundation slabs could be included to improve comparability.
  - Desire to manually define utilisation ratios for structural members.
  - Functionality for limiting unique profile types per floor or globally.
- **Optimisation logic:**
  - The existing automatic beam optimisation, which selects profiles based on the smallest cross-section area, was generally appreciated. However, engineers suggested incorporating additional criteria, such as structural depth minimisation, to enable more flexible and diverse optimisation strategies.

General reflections

- **Workflow efficiency:**
  - The tool was described as fast and responsive, allowing users to efficiently explore both material-driven and layout-driven design approaches.
- **Interdisciplinary usefulness:**
  - The tool was considered a valuable platform for collaboration, enabling shared understanding and iterative exploration between architects and structural engineers. It supports a shift away from the traditional workflow, where architects develop a proposal independently before handing it over to the engineer for structural assessment, towards a more integrated design process.
  - This collaborative approach is particularly effective with a small team, such as one architect and one engineer. For improved efficiency, the architect could prepare a base geometry prior to a working session, allowing structural alternatives and calculations to be explored together in real time.

6.3 Summary of findings and requirements for future development

This section summarises key findings from both case studies and brings together user observations and feedback into a set of future requirements. These are intended to inform future iterations of the tool and align with the overall aim of supporting early-stage structural and environmental decision-making through intuitive, transparent and flexible design feedback.

- **Usability:** Include default presets for common assumptions to support less experienced users.
- **Structural modelling:** Extend logic to include two-way spanning elements and improve representation of stability systems. Expand the structural system library (e.g., foundation types, wall systems). Include approximation of reinforcement amounts.
- **Geometry flexibility:** Enable custom grid layouts and span spacing. Allow better handling of non-orthogonal geometries and visualise approximation differences.
- **Visualisation and output:** Include benchmarks (e.g., from Boverket) in result charts. Provide export options for LCA integration (CSV, Excel, PDF) and allow filtering/grouping of outputs.
- **Workflow support:** Enhance the tool's function as a collaboration platform between architects and engineers during early design iterations.

These requirements define a clear roadmap for further development of the tool, focused on expanding functionality, improving interaction and supporting interdisciplinary workflows.

7 Discussion

This chapter presents a discussion of the methods, results and development choices made throughout the project. It reflects on the theoretical background, software environment and structural simplifications, as well as the insights gained through case studies. The chapter concludes by identifying current limitations and outlining potential directions for future research and development.

7.1 Literature study

The literature study in Section 1.1.2 outlines various strategies and tool developments aimed at reducing embodied carbon in early-stage structural design. Fang et al. (2023) emphasise the need for user-friendly, accessible and data-driven tools to support informed decision-making at the early stages, highlighting the practical gap between sustainability ambitions and implementation. Fusari et al. (2024) address this through the development of the Smart Massing Tool (SMT), an in-house Grasshopper plug-in developed by a UK-based engineering firm. The tool enables users to explore structural typologies, input custom materials and compare embodied carbon performance through a user-friendly interface.

The tool (WP) developed in this thesis shares many of the same ambitions as SMT, including rapid generation of design alternatives, integration with Rhino/Grasshopper, and a focus on accessibility for users without deep parametric modelling skills. The detailed functionality of SMT is difficult to assess, as it is an in-house developed tool that is not publicly accessible. However, based on the available publication about SMT (Fusari et al., 2024), some differences can be identified. WP includes the option to model the substructure, allowing it to be incorporated into the GWP calculation. Moreover, WP is tailored to the Swedish construction industry, incorporating commonly used structural members and materials as well as environmental data from Boverket.

Both tools support iteration and comparison across multiple design options. SMT allows users to flip through previously saved typologies and assemble matrices of alternatives. The present tool takes a similar approach but enhances it by embedding GWP data into the Rhino model, allowing users to query members directly and access cross-section and material impact information. It also incorporates a broader range of structural types, such as piles and load-bearing walls, and uses localised environmental data from Boverket's climate database.

Despite these differences, several common challenges remain. Fusari et al. (2024) note limitations in SMT related to stability systems, cantilevers and transfer structures, components also not fully addressed in this thesis. Likewise, issues of interoperability and generalisation are still open areas for development. Both tools demonstrate that while rapid early-stage analysis is valuable, it must be balanced with structural credibility and transparency regarding assumptions.

In conclusion, the work presented here builds on the principles articulated in the literature by integrating early-stage usability with deeper structural and environmental logic.

It reinforces the shared view that tools of this kind should not replace expert judgement but rather serve as a means to facilitate interdisciplinary dialogue and support informed design decisions from the outset.

7.2 Tool development and implementation

WP was developed as a parametric system, where user-defined parameters serve as inputs to generate and evaluate structural systems. Rhino and Grasshopper were considered suitable environments for the implementation, particularly due to their visual and interactive capabilities. This setup supports intuitive workflows, enabling users to define geometry, adjust structural grids and manipulate inputs through direct, visual interactions. Grasshopper manages the parametric logic and interface, while the underlying calculations are primarily performed in Python. This separation of interface and computation not only keeps the tool responsive but also allows the core functionality to be adapted to other environments. However, the use of Rhino may enhance the user experience, especially in early design stages where graphical feedback is important. While Rhino and Grasshopper offer a powerful platform for early-stage exploration, they also limit accessibility to users unfamiliar with these tools. Therefore, future development could explore the possibility of creating a stand-alone version to reach a broader user group.

The implementation was based on object-oriented programming (OOP) in Python, which allowed for a modular and extensible structure. This approach supports flexible logic and efficient geometry generation. Together with a tabulated method for preliminary sizing of structural members, this keeps WP's runtime low and allows for rapid feedback, an important feature in early design stages. The simple syntax of Python further facilitated development and debugging.

The simplification of the structural system to only include simply supported elements allowed for a systematic and modular load take-down procedure. This made it possible to analyse and size each element independently. However, in practical cases, structural elements may be designed as continuous members over multiple spans, which often leads to more material-efficient solutions. Their exclusion in the tool may lead to somewhat skewed comparisons, where certain systems appear less efficient than they might be in a real-world design. Additionally, the tool currently does not account for the reinforcement content in foundation slabs and walls, which may further contribute to skewed comparisons. Including an approximation of reinforcement quantities in these members could be a valuable future improvement.

A central component of WP is the structural member database, which contains data on spans, cross-sections, materials and load-bearing capacities. The ability to modify or extend the database makes it adaptable to different contexts. However, the resolution of this data might have a significant impact on the results. A coarse dataset, for example, with values only at every third meter, may lead to less differentiated outcomes, where alternative designs appear equivalent. A more detailed dataset could allow for finer distinctions and potentially support a more optimised design outcome, within the limits of the simplified assumptions.

Currently, the selection of structural members is based on those that satisfy strength criteria and minimise cross-sectional area. While this approach supports material efficiency, it may not always align with specific project goals, such as minimizing structural depth or total embodied carbon. Allowing users to define their own selection criteria could improve flexibility and user control in future versions of the tool.

7.3 Case studies

The two conducted case studies were highly valuable for the development and refinement of WP's functionalities, particularly the second one, which involved two practising architects. The first case study was based on an imagined real-world scenario, designed to cover as many aspects of the tool as possible. This setup allowed for controlled testing of specific features and helped identify areas for technical improvement.

In contrast, the second case study was more naturally embedded in ongoing practice. The projects explored were based on the actual work being carried out by the participating architects at the time. These happened to be two residential buildings, which provided meaningful insights into the tool's applicability in a real-world design context. The case study showed that the functionality of adding load-bearing walls is useful when designing residential buildings, as these walls naturally align with the separations between residential units. In early-stage design, architects may already have an idea of where such separations will be placed, allowing them to be incorporated directly into the design using WP. While the projects, covered by the second case study, served the purpose well, it would have been beneficial if one of them had represented a different building typology, such as an office building, in order to further test the tool's flexibility across a broader range of use cases. This variation could have provided a more comprehensive understanding of the tool's strengths and limitations across different structural and building requirements.

Beyond the scenarios themselves, the study's methodological setup also introduced certain limitations. In addition to technical assumptions, the data collection methods present some constraints. The number of participants in the case studies was relatively small, and the selection was based on availability rather than a systematic sampling process. As a result, the feedback gathered, while rich in detail, may not fully represent the diversity of project contexts, user experiences or expectations within the broader design community.

Based on the insights gained, future development would benefit from a dual approach: continuing with idealised case studies to enable controlled testing of specific functionalities, while placing greater emphasis on practice-embedded studies to evaluate usability and decision-making support in real design settings. This combination would strengthen both the technical foundation of WP and its practical applicability. Including a broader range of project types and user profiles will also be important to ensure the tool's adaptability and relevance across different contexts. The case studies also indicated that the tool can support structural engineers in illustrating and communicating the implications of structural system choices to architects, enabling more informed and collaborative decision-making in early-stage design.

7.4 Structural system results

The simplification of using only single-span slabs influences how structural systems are compared in WP. For example, a filigree slab may be designed as a continuous, multi-span element in practice. While the cross-section may remain largely unchanged, additional reinforcement is introduced to handle negative moments over supports. This can reduce the number of beams required, leading to a more efficient structural layout and potentially lower overall embodied carbon. In the current version of WP, such system-level effects are not captured, which may result in an overestimation of the GWP for certain slab types, such as filigree slabs. However, given the purpose of early-stage design, the simplified representation may still offer a sufficiently reliable basis for comparing alternative systems. It provides an initial indication of relative performance, acknowledging that more refined assessments would be needed in later design phases.

The simplification of using orthogonal grids is generally sufficient when a building has an overall topology that is close to orthogonal in both plan and elevation. However, for buildings with more complex footprints, WP approximates the geometry by fitting an orthogonal grid pattern. This simplification affects the results, both when evaluating the GWP of a specific design and when comparing it to one with a more orthogonal form. Still, when comparing several complex designs, the approximation may still be sufficient to indicate which alternative performs better relative to the others. It should also be noted that constructibility aspects are not considered in the tool, neither for complex nor orthogonal geometries, even though structural systems based on orthogonal grids may be more economical to construct.

Design alternatives are compared in WP through bar chart plots, where the calculated values for GWP are presented explicitly. While this format is effective for visual comparison and for illustrating the relative contributions of different materials or structural members, it may also lead to misinterpretation. Users who are not familiar with the underlying assumptions and simplifications might interpret the results as exact, absolute values. This could give a misleading impression of precision, particularly in early-stage design where uncertainties are high and several aspects, such as construction method, detailing and multi-span behaviour, are not accounted for.

The rationale for using bar charts is their clarity and ability to communicate comparative performance efficiently. However, there may be value in complementing the results with ranges or uncertainty bands that reflect potential variation in environmental impact. This would better align the output with the level of precision that can reasonably be expected in early-stage assessments and support more informed decision-making.

7.5 User interface

The iterative process of user-centred design (UCD) was particularly useful because of its natural workflow of developing a tool. This work covered two case studies, which essentially corresponds to two iterations of the UCD process. In the second iteration, user requirements was modified as well as design of new solutions in WP. New user requirements was defined, such as the need of improved error messages and description of functions and parameters. The major new solution in the tool in the second iteration was to build a dedicated user interface window. Moreover, the development process of

WP ended after the evaluation of requirements in the second iteration.

The decision to implement the user interface using Human UI was made to improve accessibility for users with limited experience in Grasshopper. This approach allowed users to interact with the tool through a tab-based window, rather than navigating the underlying visual script. Based on the case studies, this design choice appears to have been effective, participants from all defined user personas were able to complete tasks without requiring access to the Grasshopper interface.

Compared to early prototyping directly within Grasshopper, Human UI offered a more structured and pedagogical interface, which seems to have contributed to more confident user interaction and lowered the threshold for use. The status message box and visual feedback were particularly appreciated. The iterative process of refining the interface based on case study input played an important role in improving usability.

However, the interface is still dependent on having Grasshopper running in the background, which may limit its applicability in more stand-alone or practice oriented environments. Future development could explore decoupling the interface from Grasshopper to improve flexibility and broaden potential use cases. While Human UI enabled sufficient functionality for the purposes of this study, its limitations in terms of layout customisation and performance could constrain future expansion of the tool.

7.6 Usability and decision-making support

The case studies showed that WP has good usability and an intuitive workflow. In particular, the second case study highlighted the effectiveness of the tool in a context where architects and structural engineers explore possible design options collaboratively. As users confirmed that WP enabled a new workflow that had not been feasible during the early design phase. This highlights the need for a tool of this kind, and further development could strengthen and formalise this collaborative design process even further.

Importantly, participants emphasised that the tool is not intended to replace professional judgement or detailed design evaluation. Instead, it should be viewed as a decision-support tool that empowers architects and structural engineers to make more informed choices during the early design phase. By offering immediate, visual feedback on structural and environmental implications, WP can enhance the quality of dialogue and encourage earlier engagement with performance-oriented considerations. This reinforces the tool's role as a facilitator of informed design discussions, rather than a substitute for expert analysis.

In addition, the need for clearer benchmarking and contextualisation of results was highlighted. Users suggested that result bar charts should include reference values, such as Boverket's climate declaration limits, to enable clearer comparisons across design options. Incorporating such comparative standards would also support more inclusive design dialogues, helping clients and other stakeholders understand how a design performs in relation to regulatory or industry expectations, without requiring deep technical knowledge.

7.7 Reflection on the research question

The research question guiding this thesis was:

How can a parametric tool with an intuitive user interface and rapid feedback support more informed decision-making and improve understanding of the structural system's environmental impact in early-stage design?

The results from the tool development and the two case studies indicate that this objective was largely achieved. The developed tool (WP) enables rapid generation of structural design alternatives, accompanied by immediate feedback on global warming potential (GWP). Through the integrated user interface, even users with limited experience in parametric modelling environments were able to engage with the tool and perform meaningful design iterations.

In both case studies, users reported that the tool supported their decision-making by clarifying the structural and environmental consequences of different early-stage design choices. The ability to quickly compare design alternatives and understand how parameters such as span direction, material choice, or grid layout affect environmental impact was frequently highlighted. The tool also encouraged interdisciplinary collaboration by making structural aspects more accessible and transparent in the design dialogue between architects and engineers.

A particularly notable outcome from the user testing was the tool's potential to enable structural engineers to participate earlier in the design process than what is traditionally the case. This early involvement fosters a more integrated and holistic design process, where structural and environmental considerations are addressed all together rather than sequentially. As a result, the tool has the potential to contribute to design processes that lead to lower environmental impact from buildings, not only by quantifying impact, but by enabling such assessments to be made already in the early stages, when important design decisions may be made.

This shift is illustrated in Figure 7.1, where the traditional and tool-enabled workflows are compared in terms of disciplinary involvement.

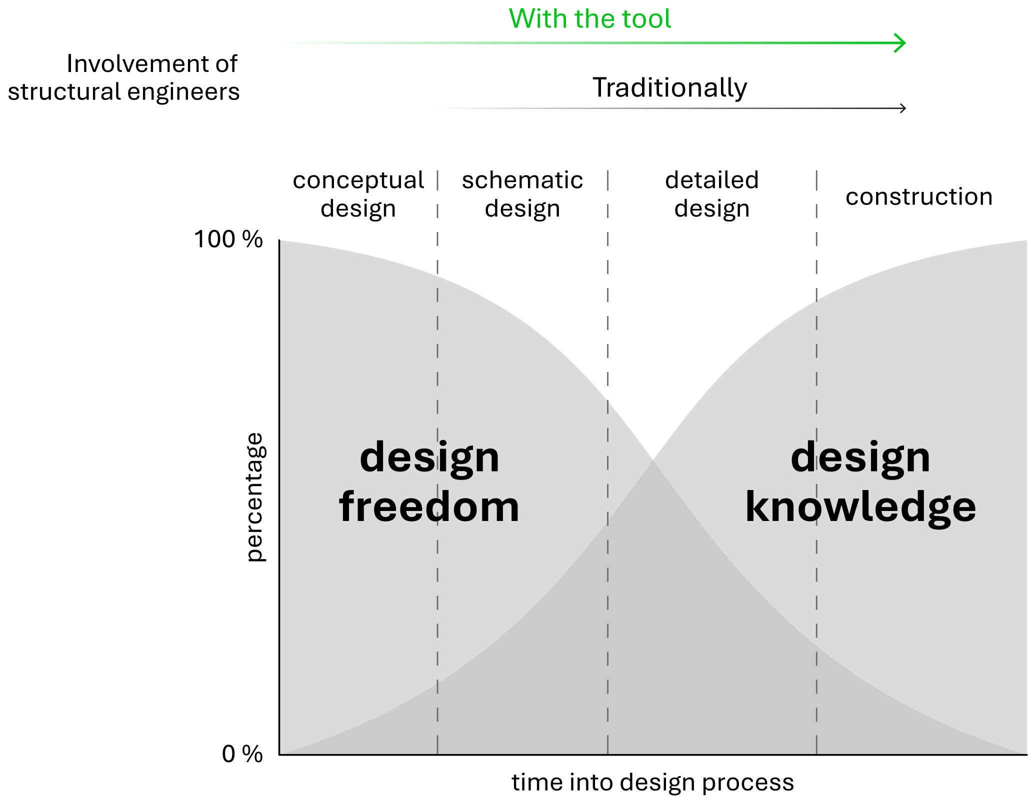


Figure 7.1: Illustration highlighting the traditional design process as shown in Figure 1.1 and the tool supported process, demonstrating the earlier involvement of structural engineering.

However, the study also revealed limitations in how the research question could be addressed within the scope of this thesis. The simplifications introduced, such as the assumption of simply supported elements, orthogonal grids and the exclusion of reinforcement in certain members, contribute to faster computations and greater usability but affect the precision of the environmental estimates. These simplifications should be clearly communicated to users to avoid misinterpretation of results as fully detailed or final.

In conclusion, the findings suggest that a parametric tool such as WP can effectively support informed decision-making and contribute to a better understanding of structural systems' environmental impact in early design phases. Additionally, the tool has the potential to influence design processes in a way that promotes more sustainable outcomes, by making structural knowledge and feedback available earlier and more interactively.

7.8 Future work

One promising area for future research is to explore how computational tools like the one developed in this thesis can take a more active role in the design process, by not only evaluating user-defined alternatives, but also proposing suitable design options based on project-specific inputs. Such functionality could shift the tool's role from being a passive evaluator to an interactive design partner, offering input to the design team rather than simply responding to theirs. Investigating how such a feature influences decision-making and how it is perceived by architects and engineers, could provide valuable insights into the evolving role of computational tools in interdisciplinary design workflows. This includes exploring questions such as: Does the tool stimulate creativity? Does it build trust? Does it help users think differently about structural systems and environmental performance?

Further research could also investigate the tool's applicability in other project contexts, such as office buildings, and assess how it can be adapted to support different workflows among design professionals. Testing the tool in practice and evaluating its usability and impact across project stages would help establish its potential as a decision-support system. Such studies could also provide insights into how the tool actually contributes to achieving lower-impact buildings. This would likely require following the design process over time, comparing decisions that would have been taken without the tool to those enabled by it, and evaluating the resulting outcomes in terms of environmental impact

From a technical development perspective, several enhancements could be explored. One is the integration of optimisation features to allow systematic evaluation of alternatives based on defined criteria, such as minimising embodied carbon or structural depth. Another is to incorporate utilisation checks for structural members, with adjustable safety margins. This would enable users to estimate how conservative their design is at an early stage and better anticipate how the structure will evolve through further detailing.

Other possible improvements include incorporating façade loads, enabling user-defined slab span directions, reinforcement inclusion and expanding the grid functionality to allow users to sketch custom grids rather than adjusting a predefined one. These changes would offer greater flexibility and realism in the structural layout.

Additionally, extending the structural database with additional structural members would improve WP's applicability and flexibility. A richer dataset would allow the tool to capture a wider variety of design scenarios and better reflect available products and construction techniques.

Finally, the implementation of a design exploration feature remains a key future opportunity. By automatically generating and comparing feasible design options, such a feature could support early-stage creativity while still providing rigorous performance feedback. Acting as a "design explorer," WP could offer a new way of engaging with structural design, blending intuition, automation and environmental awareness.

8 Conclusion

In this Master's thesis the development of a parametric computational tool to support the exploration and comparison of structural systems in early-stage building design, with a particular focus on estimating environmental impact in terms of greenhouse gas emissions was accomplished. The work was guided by the question of how such a tool, through an intuitive user interface and rapid feedback, can support more informed decision-making and improve understanding of structural systems environmental impact.

Based on insights from the literature and interviews with practitioners, several key requirements were identified for tools supporting early-stage structural design: Fast performance, intuitive interaction and immediate feedback. In response to these findings, the developed tool provides a workflow that enables rapid evaluation of design alternatives while estimating environmental impact in terms of greenhouse gas emissions.

The tool is tested in two case studies, both of which demonstrate its practical relevance in early-stage design. Feedback from users indicates that the tool offers an intuitive workflow and user-friendly interface, and that it serves as a valuable basis for discussion between architects and structural engineers. Its ability to clearly present and compare the embodied carbon of different design options was positively received. In addition, its usefulness in communicating structural aspects, such as beam depth and column placement, was particularly appreciated by architects.

The developed tool includes several simplifications, such as only considering simply supported members, excluding accidental load scenarios, not accounting for acoustic demands and limiting configurations to orthogonal grids. These assumptions are appropriate for evaluating structural systems in an early design context, where speed and clarity are prioritised. Additionally, the small testing group in the study also limits the generalisability of the findings, and broader validation would be needed to confirm usability across more diverse project types and user profiles.

Future research can further investigate collaborative workflows between architects and structural engineers, identifying opportunities for enhanced functionality and integration. From a development perspective, the tool can be extended with features such as optimisation algorithm, horizontal stability check and a design exploration functionality. Integration into real design environments or commercial workflows may also serve as an important step toward bridging early-stage design decisions with sustainable structural outcomes.

The tool developed in this thesis demonstrates potential to enhance early-stage structural design and support interdisciplinary collaboration. Key requirements for achieving this were a responsive interface, visual clarity, and ease of parameter control. These features enabled design alternatives to be explored and discussed in real time. Users confirmed that the tool allowed workflows and conversations that would otherwise have been difficult to initiate at such an early stage.

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Appendix

A Case study 1 - Task and questionnaire

Case study 2025-04-03

Deltagare:

Daniel Jonsson

Jonathan Söderqvist

Toivo Säwén

Uppgift A

Fokus: Utforska olika parametrar och utvärdera arbetsflödet

Använd fördefinierad geometri i Rhino. Utifrån denna volym utvärdera hur klimatpåverkan förändras utifrån följande parametrar:

- Grid (stomlinjer). Gridlinjer blir synliga i Rhino och kan användas för att manuellt ändra specifika linjer genom att klicka och dra i respektive riktning.
- Våningshöjder.
- Spännriktning.
- Substructure. Antal källarvåningar. Pålar eller ej.
- Laster.
- Materialval och profiler.

Uppgift B

Fokus: Testa skapa egna volymer med varierande former. Testa spara modeller

Använd verktyget och skapa olika alternativ. Jämför deras klimatpåverkan med hjälp av verktyget. Testa ladda din egen geometri och använd funktionen för att modifiera den. Testa olika varierande volymer. Testa spara modeller och ladda in dem.

Figure A1: Task description of case study 1.

Feedbackfrågor

1. Vad fungerade bra i verktyget?
2. Vad var svårt eller otydligt?
3. Saknades någon funktion du förväntade dig?
4. Tror du resultaten kan vara till hjälp i beslutsfattande processer?
5. Var det enkelt att skapa olika varianter?
6. Var det enkelt att spara modeller?
7. Kändes resultaten rimliga?
8. Kunde verktyget hantera variationen av geometri?
9. Vad skulle du vilja förbättra i verktyget?

Figure A2: User questionnaire of case study 1.

B Classification of loads

This appendix presents general load types that a building typically is designed for.

B.1 Permanent loads

Permanent loads, commonly denoted as point loads G [kN] or distributed loads g [kN/m] or [kN/m^2], refer to actions that remain essentially constant throughout the entire lifespan of a structure. These include the self-weight of structural elements, such as beams, slabs, columns and walls, which is calculated by multiplying the material density by gravitational acceleration and the volume of the member.

In addition to the self-weight, permanent loads also include non-structural components such as floor finishes, screeds, façades, partitions and fixed services (e.g., HVAC ducts). These are commonly referred to as superimposed dead loads (SDLs). In structural design, all permanent loads are typically combined and treated as a single load in load combinations.

B.2 Variable loads

Variable loads are actions that can change in magnitude, position, or frequency over time, commonly denoted for a point load as Q [kN] or for a distributed load q [kN/m] or [kN/m^2]. They include imposed loads, traffic loads on bridges or slabs, snow loads, wind loads and thermal actions. These loads are not constant over time and must be considered as varying depending on usage, weather, or environmental conditions.

B.2.1 Imposed loads

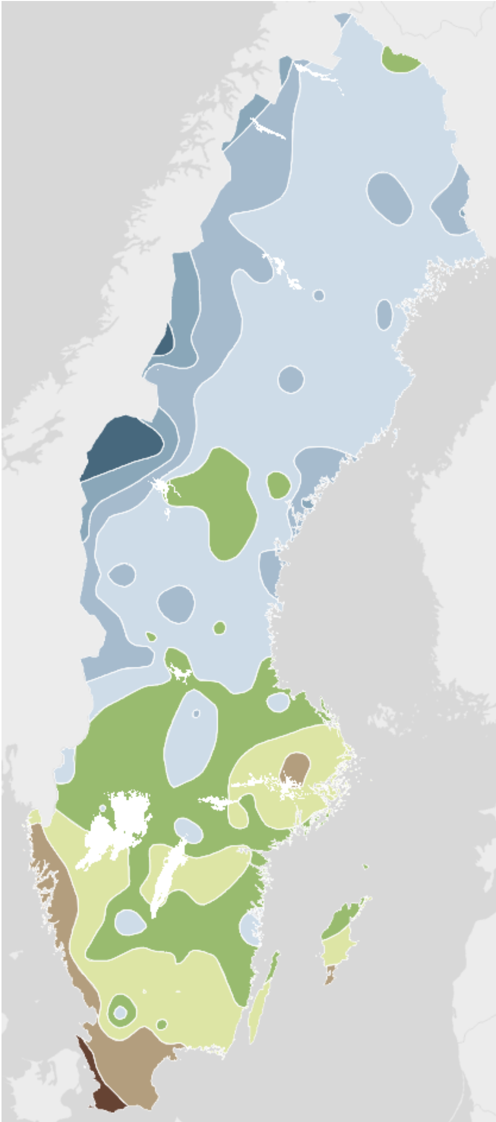
Imposed loads are a category of variable actions. They represent loads arising from the intended use of a building, such as people, furniture, movable equipment and vehicles. The magnitudes of these loads vary depending on the type of occupancy and function of each space. Table B1 presents the imposed loads for slabs, stairs and balconies, covering categories A - H, as regulated by SS-EN 1991-1-1 (European Committee for Standardization, 2002) and the existing national annex in Sweden, EKS 12 (Boverket, 2022).

Category	q_k [kN/m^2]	$Q_k[kN]$
A: Rooms and spaces in residential buildings		
– Slabs	2.0	2.0
– Stairs	2.0	2.0
– Balconies	2.5	2.0
– Attic floor I	1.0	1.5
– Attic floor II	0.5	0.5
B: Office spaces	2.5	3.0
C: Assembly areas		
C1 – Spaces with tables, e.g. classrooms, cafés, restaurants, dining halls, lobbies	2.5	3.0
C2 – Spaces with fixed seating, e.g. churches, theatres, cinemas, auditoriums, waiting areas at railway stations	3.0	3.0
C3 – Spaces with unrestricted movement, e.g. museums, exhibitions, communication zones in public buildings, hotels, hospitals, etc.	3.0	4.0
C4 – Spaces for physical activities, e.g. gyms, stages	4.0	5.0
C5 – Large assembly areas (e.g. arenas, terraces)	5.0	7.0
D: Retail areas		
D1 – Retail spaces	4.0	4.0
D2 – Shopping malls	5.0	4.5
E: Storage areas		
E1 – Stored goods	5.0	7.0
E2 – Industrial areas	5.0	7.5
F: Areas for traffic with vehicles $\leq$ 30 kN	2.5	20
G: Areas for traffic with vehicles 30 kN $<$ axle load $\leq$ 160 kN	5.0	90
H: Roof areas	0.4	1.0

Table B1: Imposed characteristic loads on slabs, stairs, balconies, etc., in buildings according to EKS 12 (Boverket, n.d.-b), and SS-EN 1991-1-1.

B.2.2 Snow load

The magnitude of the characteristic snow load depends on the geographical location and the probability of that location experiencing such snowfall. Sweden is divided into eight different snow zones and is based on meteorological data. Figure B1 shows the distribution of the snow zones and their corresponding characteristic snow load.



Snow load s_k [kN/m^2]	
1.0	
1.5	
2.0	
2.5	
3.0	
3.5	
4.5	
5.5	

Figure B1: Snow zones in Sweden and the corresponding characteristic snow load values s_k for each zone in accordance with EKS 12 (Boverket, n.d.-b).

The snow load on a roof under a persistent or transient design situation is determined as

$$s = \mu_i \cdot C_e \cdot C_t \cdot s_k, \tag{B1}$$

where:

- μ_i is the shape coefficient for snow load
- C_e is the exposure coefficient
- C_t is the thermal coefficient
- s_k is the characteristic value of the snow load on the ground

The snow load s is assumed to act vertically on the horizontal projection of the roof surface. This equation applies to the normal design situation, without considering exceptional conditions (accidental snow events or snow drifts).

In cases where snow accumulates due to obstructions such as higher adjacent buildings or multi-span roof, snow pockets may form. These local accumulations are treated using specific form factors and defined snow pocket lengths. The value of the shape factor μ_1 depends on the roof slope, as shown in Table B2. A simple sloped roof with angle α is illustrated in Figure B2.

Roof slope α	$0° \leq \alpha \leq 30°$	$30° < \alpha < 60°$	$\alpha \geq 60°$
μ_1	0,8	$0{,}8 \cdot (60 - \alpha)30$	0,0

Table B2: Values of μ_1 depending on roof slope α, SS-EN 1991-1-3 (European Committee for Standardization, 2003).

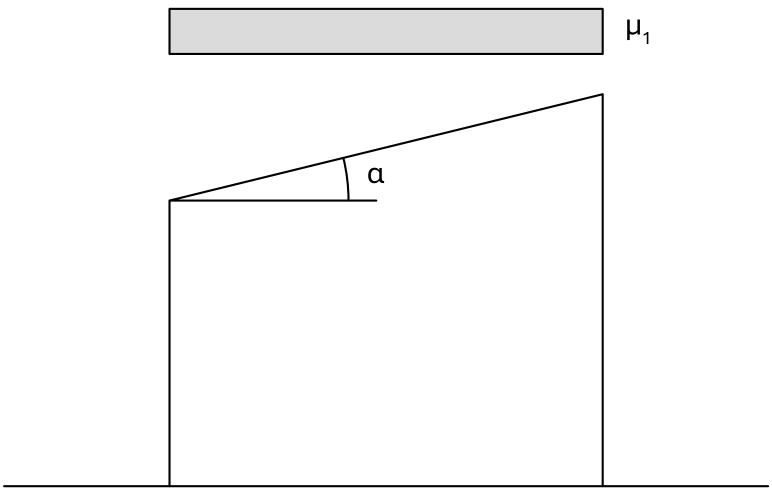


Figure B2: Shape factor for snow load on roof.

B.3 Load combinations

Design of structural members is generally done through verifications in two different limit states, the ultimate and serviceability limit state. These are evaluated through defined load combinations that incorporate partial safety factors, load reduction factors, and reliability classifications. The following subsections describe how these are applied in accordance with SS-EN 1990 (European Committee for Standardization, 2023) and EKS 12 (Boverket, 2022).

B.3.1 Load reduction factors

Load reduction factors (ψ-factors) are used to account for the low probability that all variable loads acting on the structure will reach their maximum values simultaneously. They also reflect the influence of load duration and variability over time. The values depend on the type of load and usage category, as summarised in Table B3, based on EKS 12 (Boverket, 2022).

The different ψ-factors are used in various design contexts:

- ψ_0: Combination factor used in ultimate limit state (ULS) combinations to reduce non-dominant variable actions,
- ψ_1: Frequent value factor used in serviceability limit state (SLS) checks for short-term effects (e.g., deflection or vibration),
- ψ_2: Quasi-permanent value factor used for long-term effects such as creep or sustained deformation.

Load category	ψ_0	ψ_1	ψ_2
Category A: Residential rooms and spaces	0.7	0.5	0.3
Category B: Office areas	0.7	0.5	0.3
Category C: Meeting rooms	0.7	0.7	0.6
Category D: Retail areas	0.7	0.7	0.6
Category E: Storage areas	1.0	0.9	0.8
Category F: Areas for traffic with vehicles $\leq$ 30 kN	0.7	0.7	0.6
Category G: Areas for traffic with vehicles 30 kN $<$ axle load $\leq$ 160 kN	0.7	0.5	0.3
Category H: Roof areas	0.5	0.2	0.0
Snow load, $3.0 \leq s_k \leq 3.2$ kN/m^2	0.8	0.6	0.2
Snow load, $2.0 \leq s_k < 3.0$ kN/m^2	0.7	0.4	0.2
Snow load, $1.5 \leq s_k < 2.0$ kN/m^2	0.6	0.3	0.1

Table B3: Load reduction factors for different load categories, adapted from EKS 12 (Boverket, 2022).

B.3.2 Reliability class

Reliability classes are defined to reflect the consequences of structural failure, particularly regarding personal injury. According to EKS 12 (Boverket, 2022), each class is associated with a partial safety factor γ_d, increasing with the level of risk.

An overview of the reliability classes and their associated γ_d values is presented in Table B4.

Reliability class	γ_d	**Description**
1	0.83	Low risk of serious personal casualties
2	0.91	Some risk of serious personal casualties
3	1.00	High risk of serious personal casualties

Table B4: Reliability classes adapted from EKS 12 (Boverket, 2022).

B.3.3 Ultimate limit state

The ultimate limit state (ULS) ensures that structural components have sufficient capacity to withstand critical loading scenarios that may lead to failure. ULS primarily addresses safety by evaluating the structure's performance under the most demanding load combinations, accounting for both permanent load, variable- and accidental actions. These actions include environmental loads, live loads, and other imposed effects, which can interact in either favourable or unfavourable ways.

To ensure structural reliability, partial safety factors are applied to each load component. These factors are based on the nature of the load and the reliability class of the structure. The governing load combination is selected by evaluating different load cases, ensuring that the most critical one governs the design.

The load combinations used in ULS assessments are defined in SS-EN 1990 (European Committee for Standardization, 2023) and may be modified by national codes. In EKS 12 (Boverket, 2022), the ULS load combination is referred to as (6.10b) and is expressed as

$$Q_d = \gamma_d \cdot (0.89 \cdot 1.35 \cdot G_{k,j} + 1.5 \cdot Q_{k,1} + 1.5 \cdot \psi_{0,i} \cdot Q_{k,i}), \tag{B2}$$

where:

- Q_d is the design load
- $G_{k,j}$ is the characteristic value of permanent actions
- $Q_{k,1}$ is the main variable action (characteristic value)
- $Q_{k,i}$ are accompanying variable actions (characteristic values)
- γ_d is the partial factor accounting for reliability class
- $\psi_{0,i}$ is the combination factor for accompanying variable actions

The applied partial factors and combination factors depend on whether the load case is considered favourable or unfavourable.

B.3.4 Serviceability limit state

The Serviceability Limit State (SLS) addresses the structural system's ability to meet performance criteria related to comfort, usability, and appearance throughout the building's service life (European Committee for Standardization, 2023). While the Ultimate Limit State (ULS) ensures structural safety against collapse, SLS primarily limits deformations, deflections, and vibrations that could impair functionality or user comfort.

Depending on how often a given load is expected to act during the building's lifespan, different load combinations are used for serviceability checks. These are categorized as characteristic, frequent and quasi-permanent combinations. The equations are formulated according to SS-EN 1990 (European Committee for Standardization, 2023), and are expressed as the Equations (B3) to (B5).

Characteristic load combination, (6.14) in EKS 12

$$Q_d = G_{k,j} + Q_{k,1} + \psi_{0,j} \cdot Q_{k,j} \tag{B3}$$

Frequent load combination, (6.15) in EKS 12

$$Q_d = G_{k,j} + \psi_{1,1} \cdot Q_{k,1} + \psi_{2,j} \cdot Q_{k,j} \tag{B4}$$

Quasi-permanent load combination, (6.16) in EKS 12

$$Q_d = G_{k,j} + \psi_{2,j} \cdot Q_{k,j} \tag{B5}$$

Constants in the Equations (B3) to (B5) are described as:

- Q_d is the design load for serviceability verification.
- $G_{k,j}$ is the characteristic value of permanent actions.
- $Q_{k,1}$ is the leading variable action (characteristic).
- $Q_{k,j}$ are accompanying variable actions (characteristic).
- $\psi_{0,j}, \psi_{1,1}, \psi_{2,j}$ are reduction factors for variable actions, defined in SS-EN 1990 (European Committee for Standardization, 2023) and EKS 12 (Boverket, 2022).

Each combination type corresponds to different service scenarios:

- The *characteristic* combination assumes a rare but possible worst-case during regular use.
- The *frequent* combination reflects more commonly occurring conditions during the building's service life.
- The *quasi-permanent* combination represents the long-term average effect of variable actions.

These combinations are used in various serviceability assessments, such as evaluating deflections, vibrations, and crack control, to ensure that the structure remains functional and comfortable over time. In the case of deformations, the allowable limits vary depending on the type of structural member, its connection to adjacent building elements, and its location within the building. Common criteria used in building construction are based on limiting deflections to the member's span length divided by typically 300 or 500.

C Overview of database

C.1 Structure of slab data

Field/Header	Unit	Type	Description	Example
Category	[-]	String	What type of slab	KL-trä
Name	[-]	String	The exact name	230 L7D
Thickness	[m]	Float	Total thickness	0.230
Cross-sectional area	[m^2]	Float	The area of the cross-section	0.230
Self-weight	[kN/m^2]	Float	Self-weight per m^2 of slab	0.9825
SDL	[kN/m^2]	Float	Superimposed dead load	1.5
Live load	[kN/m^2]	Float	Live load	2.5
Span length	[m]	Float	The length this slab can span with the specified loads	6.0
Material IDs	[-]	String	Linked materials in the environmental data sheet	39, 33
Reference	[-]	String	Where the preliminary design values originate from	www.setra-group.com/...

Table C1: Data schema for slab elements in the database.

Element	Category	Name	Thickness [m]	Cross-sectional area [m^2]	Self-weight [kN/m^2]	SDL [kN/m^2]	Live load [kN/m^2]	Span length [m]	Material IDs	Reference
Slab	KL-trä	180 L5S	0,180	0,180	0,7689	1,0	2,0	5,0	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	180 L5S	0,180	0,180	0,7689	1,0	2,5	5,0	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	180 L5S	0,180	0,180	0,7689	1,0	3,0	5,0	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	180 L5S	0,180	0,180	0,7689	1,5	2,0	5,0	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	180 L5S	0,180	0,180	0,7689	1,5	2,5	5,0	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	200 L5S	0,200	0,200	0,8543	1,0	2,0	5,5	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	200 L5S	0,200	0,200	0,8543	1,0	2,5	5,5	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	200 L5S	0,200	0,200	0,8543	1,0	3,0	5,5	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	200 L7D	0,200	0,200	0,8543	1,5	3,0	5,0	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	200 L7D	0,200	0,200	0,8543	2,0	2,0	5,0	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	200 L7D	0,200	0,200	0,8543	2,0	2,5	5,0	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	200 L7D	0,200	0,200	0,8543	2,0	3,0	5,0	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	200 L7D	0,200	0,200	0,8543	2,5	2,0	5,0	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	200 L7D	0,200	0,200	0,8543	2,5	2,5	5,0	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	200 L7D	0,200	0,200	0,8543	2,5	3,0	5,0	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	200 L7D	0,200	0,200	0,8543	1,5	2,0	5,5	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	200 L7D	0,200	0,200	0,8543	1,5	2,5	5,5	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	200 L7D	0,200	0,200	0,8543	1,5	3,0	5,5	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	210 L7D	0,200	0,200	0,8543	2,0	2,0	5,5	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	210 L7D	0,200	0,200	0,8543	2,0	2,5	5,5	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	210 L7D	0,200	0,200	0,8543	2,0	3,0	5,5	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	220 L7D	0,200	0,200	0,8543	3,5	2,0	5,0	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	220 L7D	0,200	0,200	0,8543	3,5	2,5	5,0	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	220 L7D	0,200	0,200	0,8543	3,5	3,0	5,0	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	230 L7D	0,230	0,230	0,9825	2,5	2,0	5,5	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	230 L7D	0,230	0,230	0,9825	2,5	2,5	5,5	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	230 L7D	0,230	0,230	0,9825	2,5	3,0	5,5	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	240 L7D	0,230	0,230	0,9825	3,5	2,0	5,5	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	240 L7D	0,230	0,230	0,9825	3,5	2,5	5,5	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	KL-trä	240 L7D	0,230	0,230	0,9825	3,5	3,0	5,5	39, 33	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/kl-tra-setragroup-bjalklag-i-ii-inner-yttervagg-w-okt-2021.pdf
Slab	Plattbärlag	PL 220	0,220	0,220	5,5000	0,0	2,5	5,3	7, 8, 9, 10, 1	https://www.svenskbetong.se/om-betong/prefab/statik/plattbarlag-pl/dimensionering
Slab	Plattbärlag	PL 250	0,250	0,250	6,2500	0,0	2,0	5,8	7, 8, 9, 10, 1	https://www.svenskbetong.se/om-betong/prefab/statik/plattbarlag-pl/dimensionering
Slab	Plattbärlag	PL 250	0,250	0,250	6,2500	0,0	2,5	5,7	7, 8, 9, 10, 1	https://www.svenskbetong.se/om-betong/prefab/statik/plattbarlag-pl/dimensionering
Slab	Plattbärlag	PL 250	0,250	0,250	6,2500	0,0	6,0	5,1	7, 8, 9, 10, 1	https://www.svenskbetong.se/om-betong/prefab/statik/plattbarlag-pl/dimensionering
Slab	Plattbärlag	PL 300	0,300	0,300	7,5000	0,0	6,0	5,9	7, 8, 9, 10, 1	https://www.svenskbetong.se/om-betong/prefab/statik/plattbarlag-pl/dimensionering

Figure C1: An excerpt from the database, presenting the structure of slab data.

C.2 Structure of beam data

Field	Unit	Type	Description	Example
Category	[-]	String	What kind of beam	HEA
Name	[-]	String	The exact name	HEA 360
Material	[-]	String	Material of the beam	Steel
Depth	[m]	Float	Depth of the beam	0.350
Width	[m]	Float	Width of the beam	0.300
Cross-sectional area	[m^2]	Float	The area of the cross-section	0.01428
Self-weight	[kN/m]	Float	Self-weight	1.11284
Span length	[m]	Float	The span length of the beam	7.2
ULS load capacity	[kN/m]	Float	The ULS load that this beam can carry	110
Deflection at ULS load	[mm]	Float	Deflection of the beam when ULS load is applied	55
Material IDs	[-]	String	Linked materials in the environmental data sheet	35, 29, 30
Reference	[-]	String	Where the preliminary design values originate from	www.tibnor.se/...

Table C2: Data schema for beam elements in the database.

Element	Category	Name	Material	Depth [m]	Width [m]	Cross-sectional area [m2]	Self-weight [kN/m]	Span length [m]	ULS load capacity [kN/m]	Deflection at ULS load [mm]	Material IDs	Reference
Beam	HEA	HEA 260	Steel	0,250	0,260	0,008682	0,67720	6,0	65,1	50,0	35, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller
Beam	HEA	HEA 280	Steel	0,270	0,280	0,009726	0,75863	6,0	78,9	46,0	35, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller
Beam	HEA	HEA 300	Steel	0,290	0,300	0,011250	0,87750	6,0	98,2	43,0	35, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller
Beam	HSQ	HSQ-240:200x440 12/10-5	Steel	0,250	0,440	0,009080	0,70824	6,0	45,1	35,9	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	HSQ	HSQ-240:200x440 15/10-5	Steel	0,250	0,440	0,009650	0,75270	6,0	52,6	38,1	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	HSQ	HSQ-240:200x440 20/10-5	Steel	0,250	0,440	0,010600	0,82680	6,0	62,4	40,1	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	HSQ	HSQ-240:200x440 15/12-5	Steel	0,252	0,440	0,010530	0,82134	6,0	61,7	41,3	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	HSQ	HSQ-240:200x440 20/12-5	Steel	0,252	0,440	0,011480	0,89544	6,0	72,6	42,9	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	HSQ	HSQ-240:200x440 25/12-5	Steel	0,252	0,440	0,012430	0,96954	6,0	83,3	44,9	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	HSQ	HSQ-240:200x440 20/15-5	Steel	0,255	0,440	0,012800	0,99840	6,0	83,1	44,2	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	HSQ	HSQ-240:200x440 25/15-5	Steel	0,255	0,440	0,013750	1,07250	6,0	97,1	47,0	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	HSQ	HSQ-240:200x440 30/15-5	Steel	0,255	0,440	0,014700	1,14660	6,0	107,7	48,6	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	HSQ	HSQ-240:200x440 25/20-5	Steel	0,260	0,440	0,015950	1,24410	6,0	96,8	40,7	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	HSQ	HSQ-240:200x440 30/20-5	Steel	0,260	0,440	0,016900	1,31820	6,0	114,6	44,7	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	HSQ	HSQ-240:200x440 40/20-5	Steel	0,260	0,440	0,018800	1,46640	6,0	140,2	49,0	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	HSQ	HSQ-240:250x490 12/10-5	Steel	0,250	0,490	0,010180	0,79404	6,0	54,2	36,9	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	HSQ	HSQ-240:250x490 15/10-5	Steel	0,250	0,490	0,010900	0,85020	6,0	63,5	39,3	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	HSQ	HSQ-240:250x490 20/10-5	Steel	0,250	0,490	0,012100	0,94380	6,0	76,0	41,8	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	HSQ	HSQ-240:250x490 15/12-5	Steel	0,252	0,490	0,011880	0,92664	6,0	73,7	42,0	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	HSQ	HSQ-240:250x490 20/12-5	Steel	0,252	0,490	0,013080	1,02024	6,0	87,3	43,8	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	HSQ	HSQ-240:250x490 25/12-5	Steel	0,252	0,490	0,014280	1,11384	6,0	99,7	46,0	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	HSQ	HSQ-240:250x490 20/15-5	Steel	0,255	0,490	0,014550	1,13490	6,0	99,5	44,9	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	HSQ	HSQ-240:250x490 25/15-5	Steel	0,255	0,490	0,015750	1,22850	6,0	115,7	47,7	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	HSQ	HSQ-240:250x490 30/15-5	Steel	0,255	0,490	0,016950	1,32210	6,0	126,8	48,8	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	HSQ	HSQ-240:250x490 25/20-5	Steel	0,260	0,490	0,018200	1,41960	6,0	118,6	42,4	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	HSQ	HSQ-240:250x490 30/20-5	Steel	0,260	0,490	0,019400	1,51320	6,0	139,7	46,0	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	HSQ	HSQ-240:250x490 40/20-5	Steel	0,260	0,490	0,021800	1,70040	6,0	144,0	42,9	29, 30	https://www.stalforbund.no/wp-content/uploads/2021/10/HSQ-balken.pdf
Beam	Limträ	Limträ 140x270	Timber	0,270	0,140	0,037800	0,15961	6,0	5,9		34	
Beam	Limträ	Limträ 140x270	Timber	0,270	0,140	0,037800	0,15961	6,5	5,0		34	
Beam	Limträ	Limträ 165x270	Timber	0,270	0,165	0,044550	0,18812	6,0	6,9		34	
Beam	Limträ	Limträ 165x270	Timber	0,270	0,165	0,044550	0,18812	6,5	5,9		34	
Beam	Limträ	Limträ 190x225	Timber	0,225	0,190	0,042750	0,18052	6,0	5,6		34	
Beam	Limträ	Limträ 190x270	Timber	0,270	0,190	0,051300	0,21662	6,0	8,0		34	
Beam	Limträ	Limträ 190x270	Timber	0,270	0,190	0,051300	0,21662	6,5	6,8		34	
Beam	Limträ	Limträ 215x225	Timber	0,225	0,215	0,048375	0,20427	6,0	6,4		34	
Beam	Limträ	Limträ 215x225	Timber	0,225	0,215	0,048375	0,20427	6,5	5,4		34	
Beam	Limträ	Limträ 215x270	Timber	0,270	0,215	0,058050	0,24512	6,0	9,1		34	
Beam	Limträ	Limträ 215x270	Timber	0,270	0,215	0,058050	0,24512	6,5	7,7		34	
Beam	Limträ	Limträ 230x270	Timber	0,270	0,230	0,062100	0,26222	6,0	9,7		34	
Beam	Limträ	Limträ 230x270	Timber	0,270	0,230	0,062100	0,26222	6,5	8,3		34	

Figure C2: An excerpt from the database, presenting the structure of beam data.

C.3 Structure of column data

Field	**Unit**	**Type**	**Description**	**Example**
Category	[-]	String	What kind of column	VKR
Name	[-]	String	The exact name	200x200x12,5
Material	[-]	String	Material of the column	Steel
Depth	[m]	Float	Depth of the column	0.200
Width	[m]	Float	Width of the column	0.200
Cross-sectional area	[m^2]	Float	The area of the cross-section	0.00921
Self-weight	[kN/m]	Float	Self-weight	0.71838
Buckling length	[m]	Float	The buckling length of the column	4.5
ULS load capacity	[kN]	Float	The ultimate limit state (ULS) load that this column can carry	2650
Material IDs	[-]	String	Linked materials in the environmental data sheet	37, 29, 30
Reference	[-]	String	Where the preliminary design values originate from	www.tibnor.se/...

Table C3: Data schema for column elements in the database.

Element	Category	Name	Material	Depth [m]	Width [m]	Cross-sectional area [m^2]	Self-weight [kN/m]	Buckling length [m]	ULS load capacity [kN]	Material IDs	Reference	Comment
Column	HEA	HEA 220	Steel	0,210	0,220	0,00643	0,50185	3,0	1640	35, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	Buckling around weak axis
Column	HEA	HEA 220	Steel	0,210	0,220	0,00643	0,50185	3,3	1540	35, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	Buckling around weak axis
Column	HEA	HEA 220	Steel	0,210	0,220	0,00643	0,50185	3,6	1430	35, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	Buckling around weak axis
Column	HEA	HEA 240	Steel	0,230	0,240	0,00768	0,59935	3,0	2050	35, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	Buckling around weak axis
Column	HEA	HEA 240	Steel	0,230	0,240	0,00768	0,59935	3,3	1940	35, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	Buckling around weak axis
Column	HEA	HEA 240	Steel	0,230	0,240	0,00768	0,59935	3,6	1830	35, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	Buckling around weak axis
Column	HEA	HEA 260	Steel	0,250	0,260	0,00868	0,67720	3,0	2410	35, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	Buckling around weak axis
Column	HEA	HEA 260	Steel	0,250	0,260	0,00868	0,67720	3,3	2300	35, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	Buckling around weak axis
Column	HEA	HEA 260	Steel	0,250	0,260	0,00868	0,67720	3,6	2190	35, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	Buckling around weak axis
Column	HEA	HEA 280	Steel	0,270	0,280	0,00973	0,75863	3,0	2790	35, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	Buckling around weak axis
Column	HEA	HEA 280	Steel	0,270	0,280	0,00973	0,75863	3,3	2680	35, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	Buckling around weak axis
Column	HEA	HEA 280	Steel	0,270	0,280	0,00973	0,75863	3,6	2560	35, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	Buckling around weak axis
Column	HEA	HEA 300	Steel	0,290	0,300	0,01125	0,87750	3,0	3310	35, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	Buckling around weak axis
Column	HEA	HEA 300	Steel	0,290	0,300	0,01125	0,87750	3,3	3190	35, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	Buckling around weak axis
Column	HEA	HEA 300	Steel	0,290	0,300	0,01125	0,87750	3,6	3070	35, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	Buckling around weak axis
Column	VKR	VKR 200x200x10	Steel	0,200	0,200	0,00749	0,58422	3,0	2450	37, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	
Column	VKR	VKR 200x200x10	Steel	0,200	0,200	0,00749	0,58422	3,3	2410	37, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	
Column	VKR	VKR 200x200x10	Steel	0,200	0,200	0,00749	0,58422	3,6	2360	37, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	
Column	VKR	VKR 200x200x12,5	Steel	0,200	0,200	0,00921	0,71838	3,0	3000	37, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	
Column	VKR	VKR 200x200x12,5	Steel	0,200	0,200	0,00921	0,71838	3,3	2950	37, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	
Column	VKR	VKR 200x200x12,5	Steel	0,200	0,200	0,00921	0,71838	3,6	2890	37, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	
Column	VKR	VKR 200x200x16	Steel	0,200	0,200	0,01150	0,89700	3,0	3740	37, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	
Column	VKR	VKR 200x200x16	Steel	0,200	0,200	0,01150	0,89700	3,3	3670	37, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	
Column	VKR	VKR 200x200x16	Steel	0,200	0,200	0,01150	0,89700	3,6	3580	37, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	
Column	VKR	VKR 200x200x6,3	Steel	0,200	0,200	0,00484	0,37752	3,0	1590	37, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	
Column	VKR	VKR 200x200x6,3	Steel	0,200	0,200	0,00484	0,37752	3,3	1560	37, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	
Column	VKR	VKR 200x200x6,3	Steel	0,200	0,200	0,00484	0,37752	3,6	1530	37, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	
Column	VKR	VKR 200x200x8	Steel	0,200	0,200	0,00608	0,47424	3,0	1990	37, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	
Column	VKR	VKR 200x200x8	Steel	0,200	0,200	0,00608	0,47424	3,3	1960	37, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	
Column	VKR	VKR 200x200x8	Steel	0,200	0,200	0,00608	0,47424	3,6	1920	37, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	
Column	VKR	VKR 220x220x10	Steel	0,220	0,220	0,00829	0,64662	3,0	2760	37, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	
Column	VKR	VKR 220x220x10	Steel	0,220	0,220	0,00829	0,64662	3,3	2720	37, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	
Column	VKR	VKR 220x220x10	Steel	0,220	0,220	0,00829	0,64662	3,6	2670	37, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	
Column	VKR	VKR 220x220x6,3	Steel	0,220	0,220	0,00534	0,41652	3,0	1760	37, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	
Column	VKR	VKR 220x220x6,3	Steel	0,220	0,220	0,00534	0,41652	3,3	1730	37, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	
Column	VKR	VKR 220x220x6,3	Steel	0,220	0,220	0,00534	0,41652	3,6	1710	37, 29, 30	https://www.tibnor.se/inspiration/downloads/konstruktionstabeller	
Column	Limträ	Limträ 215x225	Timber	0,215	0,225	0,04838	0,20463	3,0	699	34		Buckling around weak axis
Column	Limträ	Limträ 215x270	Timber	0,215	0,270	0,05805	0,24555	3,0	838	34		Buckling around weak axis
Column	Limträ	Limträ 215x315	Timber	0,215	0,315	0,06773	0,28648	3,0	978	34		Buckling around weak axis
Column	Limträ	Limträ 215x360	Timber	0,215	0,360	0,07740	0,32740	3,0	1118	34		Buckling around weak axis
Column	Limträ	Limträ 215x405	Timber	0,215	0,405	0,08708	0,36833	3,0	1258	34		Buckling around weak axis

Figure C3: An excerpt from the database, presenting the structure of column data.

C.4 Structure of pile data

Field	Unit	Type	Description	Example
Category	[-]	String	What type of pile	RR
Name	[-]	String	The exact name	RR140/10
Material	[-]	String	Material of the pile	Steel
Depth	[m]	Float	Depth of the pile	0.140
Width	[m]	Float	Width of the pile	0.140
Cross-sectional area	[m^2]	Float	The area of the cross-section	0.004075
Self-weight	[kN/m]	Float	Self-weight	0.32
Undrained shear strength	[kPa]	Float	The soil conditions at the site	20.0
Structural compression resistance	[kN]	Float	The structural load that this pile can carry	1645
Material IDs	[-]	String	Linked materials in the environmental datasheet	38
Reference	[-]	String	Where the preliminary design values originate from	www.ssab.com/...

Table C4: Data schema for pile elements in the database.

Element	Category	Name	Material	Depth [m]	Width [m]	Cross-sectional area [m2]	Self-weight [kN/m]	Undrained shear strength [kPa]	Structural compression resistance [kN]	Material IDs	Reference
Pile	RR	RR75	Steel	0,0761	0,0761	0,001381	0,108	5	339	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR75	Steel	0,0761	0,0761	0,001381	0,108	10	481	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR75	Steel	0,0761	0,0761	0,001381	0,108	20	548	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR75	Steel	0,0761	0,0761	0,001381	0,108	30	568	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR75	Steel	0,0761	0,0761	0,001381	0,108	40	579	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR90	Steel	0,0889	0,0889	0,001635	0,128	5	440	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR90	Steel	0,0889	0,0889	0,001635	0,128	10	595	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR90	Steel	0,0889	0,0889	0,001635	0,128	20	660	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR90	Steel	0,0889	0,0889	0,001635	0,128	30	681	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR90	Steel	0,0889	0,0889	0,001635	0,128	40	692	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR115/6,3	Steel	0,1143	0,1143	0,002138	0,168	5	667	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR115/6,3	Steel	0,1143	0,1143	0,002138	0,168	10	819	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR115/6,3	Steel	0,1143	0,1143	0,002138	0,168	20	883	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR115/6,3	Steel	0,1143	0,1143	0,002138	0,168	30	906	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR115/6,3	Steel	0,1143	0,1143	0,002138	0,168	40	919	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR115/8	Steel	0,1143	0,1143	0,002672	0,21	5	725	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR115/8	Steel	0,1143	0,1143	0,002672	0,21	10	975	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR115/8	Steel	0,1143	0,1143	0,002672	0,21	20	1080	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR115/8	Steel	0,1143	0,1143	0,002672	0,21	30	1114	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR115/8	Steel	0,1143	0,1143	0,002672	0,21	40	1133	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RRs115/8	Steel	0,1143	0,1143	0,002672	0,21	5	725	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RRs115/8	Steel	0,1143	0,1143	0,002672	0,21	10	1066	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RRs115/8	Steel	0,1143	0,1143	0,002672	0,21	20	1251	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RRs115/8	Steel	0,1143	0,1143	0,002672	0,21	30	1306	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RRs115/8	Steel	0,1143	0,1143	0,002672	0,21	40	1333	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR140/8	Steel	0,1397	0,1397	0,00331	0,26	5	1012	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR140/8	Steel	0,1397	0,1397	0,00331	0,26	10	1260	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR140/8	Steel	0,1397	0,1397	0,00331	0,26	20	1363	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR140/8	Steel	0,1397	0,1397	0,00331	0,26	30	1399	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RR140/8	Steel	0,1397	0,1397	0,00331	0,26	40	1420	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RRs140/8	Steel	0,1397	0,1397	0,00331	0,26	5	1014	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RRs140/8	Steel	0,1397	0,1397	0,00331	0,26	10	1414	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RRs140/8	Steel	0,1397	0,1397	0,00331	0,26	20	1589	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RRs140/8	Steel	0,1397	0,1397	0,00331	0,26	30	1645	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf
Pile	RR	RRs140/8	Steel	0,1397	0,1397	0,00331	0,26	40	1673	38	https://www.ssab.com/api/download?file=/-/media/files/se/infra/ssab_rr_and_rd_palar_anvisningar_for_projekting_och_installation.pdf

Figure C4: An excerpt from the database, presenting the structure of pile data.

C.5 Structure of environmental impact data

Field	Unit	Type	Description	Example
ID	[-]	Integer	Identification number	33
Material	[-]	String	The name of the material	Boverket Korslimmat trä, u 12%, barrträ
Category	[-]	String	What type of material	Timber
Member category	[-]	String	What type of members this material is associated with	Slab, wall
A1-A3 impact (per kg)	[kg CO_2e /kg]	Float	A1–A3 impact per kg of material	0.12
A4 impact (per kg)	[kg CO_2e /kg]	Float	A4 impact per kg of material	0.0348
A5 impact (per kg)	[kg CO_2e /kg]	Float	A5 impact per kg of material	0.0077
A1-A5 total impact (per kg)	[kg CO_2e /kg]	Float	Sum of A1–A5 impact per kg of material	0.1625
Conversion factor	[kg/m^3]	Float	Factor for converting impact per kg to impact per m^3 of material	465
A1-A3 impact (per m^3)	[kg CO_2e /m^3]	Float	A1–A3 impact per m^3 of material	55.80
A4 impact (per m^3)	[kg CO_2e /m^3]	Float	A4 impact per m^3 of material	16.18
A5 impact (per m^3)	[kg CO_2e /m^3]	Float	A5 impact per m^3 of material	3.60
A1-A5 total impact (per m^3)	[kg CO_2e /m^3]	Float	Sum of A1–A5 impact per m^3 of material	75.58
Updated	[-]	String	The date when this data was updated in the database	2025-03-17
Reference	[-]	String	Where the data originates from	https://klimatdatabasen.boverket.se/

Table C5: Schema for GWP data per material in the database.

Element	ID	Material	Category	Member category	A1-A3 impact [kg CO_2e/kg]	A4 impact [kg CO_2e/kg]	A5 impact [kg CO_2e/kg]	A1-A5 impact [kg CO_2e/kg]	Conversion factor [kg/m^3]	A1-A3 impact [kg CO_2e/m^3]	A4 impact [kg CO_2e/m^3]	[kg CO_2e/m^3]	impact [kg CO_2e/m^3]	Updated	Reference
Climate	1	Boverket Fabriksbetong, husbyggnad C20/25	Concrete	Beam, column, slab, wall, base plate	0,1220	0,0036	0,0038	0,1294	2350	286,70	8,46	8,86	304,02	#########	https://klimatdatabasen.boverket.se/
Climate	2	Boverket Fabriksbetong, husbyggnad klimatförbättrad C20/25	Concrete	Beam, column, slab, wall, base plate	0,0913	0,0036	0,0029	0,0978	2350	214,56	8,46	6,70	229,71	#########	https://klimatdatabasen.boverket.se/
Climate	3	Boverket Fabriksbetong, husbyggnad klimatförbättrad C25/30	Concrete	Beam, column, slab, wall, base plate	0,0963	0,0036	0,0030	0,1029	2350	226,31	8,46	7,05	241,82	#########	https://klimatdatabasen.boverket.se/
Climate	4	Boverket Fabriksbetong, husbyggnad C25/30	Concrete	Beam, column, slab, wall, base plate	0,1290	0,0036	0,0040	0,1366	2350	303,15	8,46	9,33	320,94	#########	https://klimatdatabasen.boverket.se/
Climate	5	Boverket Fabriksbetong, husbyggnad C28/35	Concrete	Beam, column, slab, wall, base plate	0,1360	0,0036	0,0042	0,1438	2350	319,60	8,46	9,87	337,93	#########	https://klimatdatabasen.boverket.se/
Climate	6	Boverket Fabriksbetong, husbyggnad klimatförbättrad C28/35	Concrete	Beam, column, slab, wall, base plate	0,1020	0,0036	0,0032	0,1088	2350	239,70	8,46	7,47	255,63	#########	https://klimatdatabasen.boverket.se/
Climate	7	Boverket Fabriksbetong, husbyggnad C30/37	Concrete	Beam, column, slab, wall, base plate	0,1450	0,0036	0,0045	0,1531	2350	340,75	8,46	10,48	359,69	#########	https://klimatdatabasen.boverket.se/
Climate	8	Boverket Fabriksbetong, husbyggnad klimatförbättrad C30/37	Concrete	Beam, column, slab, wall, base plate	0,1080	0,0036	0,0034	0,1150	2350	253,80	8,46	7,90	270,16	#########	https://klimatdatabasen.boverket.se/
Climate	9	Boverket Fabriksbetong, husbyggnad klimatförbättrad C32/40	Concrete	Beam, column, slab, wall, base plate	0,1110	0,0036	0,0034	0,1180	2350	260,85	8,46	8,06	277,37	#########	https://klimatdatabasen.boverket.se/
Climate	10	Boverket Fabriksbetong, husbyggnad C32/40	Concrete	Beam, column, slab, wall, base plate	0,1480	0,0036	0,0045	0,1561	2350	347,80	8,46	10,65	366,91	#########	https://klimatdatabasen.boverket.se/
Climate	11	Boverket Fabriksbetong, husbyggnad C35/45	Concrete	Beam, column, slab, wall, base plate	0,1630	0,0036	0,0050	0,1716	2350	383,05	8,46	11,70	403,21	#########	https://klimatdatabasen.boverket.se/
Climate	12	Boverket Fabriksbetong, husbyggnad klimatförbättrad C35/45	Concrete	Beam, column, slab, wall, base plate	0,1220	0,0036	0,0038	0,1294	2350	286,70	8,46	8,88	304,04	#########	https://klimatdatabasen.boverket.se/
Climate	13	Boverket Fabriksbetong, husbyggnad C40/50	Concrete	Beam, column, slab, wall, base plate	0,1750	0,0036	0,0054	0,1840	2350	411,25	8,46	12,60	432,31	#########	https://klimatdatabasen.boverket.se/
Climate	14	Boverket Fabriksbetong, husbyggnad klimatförbättrad C40/50	Concrete	Beam, column, slab, wall, base plate	0,1310	0,0036	0,0041	0,1387	2350	307,85	8,46	9,52	325,83	#########	https://klimatdatabasen.boverket.se/
Climate	15	Boverket Fabriksbetong, husbyggnad klimatförbättrad C45/55	Concrete	Beam, column, slab, wall, base plate	0,1430	0,0036	0,0044	0,1510	2350	336,05	8,46	10,29	354,80	#########	https://klimatdatabasen.boverket.se/
Climate	16	Boverket Fabriksbetong, husbyggnad C45/55	Concrete	Beam, column, slab, wall, base plate	0,1890	0,0036	0,0058	0,1984	2350	444,15	8,46	13,56	466,17	#########	https://klimatdatabasen.boverket.se/
Climate	17	Boverket Fabriksbetong, husbyggnad C50/60	Concrete	Beam, column, slab, wall, base plate	0,2040	0,0036	0,0062	0,2138	2350	479,40	8,46	14,62	502,48	#########	https://klimatdatabasen.boverket.se/
Climate	18	Boverket Fabriksbetong, husbyggnad klimatförbättrad C50/60	Concrete	Beam, column, slab, wall, base plate	0,1530	0,0036	0,0047	0,1613	2350	359,55	8,46	11,00	379,01	#########	https://klimatdatabasen.boverket.se/
Climate	19	Boverket Fabriksbetong, husbyggnad klimatförbättrad C55/67	Concrete	Beam, column, slab, wall, base plate	0,1650	0,0036	0,0051	0,1737	2350	387,75	8,46	11,89	408,10	#########	https://klimatdatabasen.boverket.se/
Climate	20	Boverket Fabriksbetong, husbyggnad C55/67	Concrete	Beam, column, slab, wall, base plate	0,2200	0,0036	0,0067	0,2303	2350	517,00	8,46	15,77	541,23	#########	https://klimatdatabasen.boverket.se/
Climate	21	Boverket Fabriksbetong, husbyggnad C60/75	Concrete	Beam, column, slab, wall, base plate	0,2300	0,0036	0,0070	0,2406	2350	540,50	8,46	16,47	565,43	#########	https://klimatdatabasen.boverket.se/
Climate	22	Boverket Fabriksbetong, husbyggnad klimatförbättrad C60/75	Concrete	Beam, column, slab, wall, base plate	0,1730	0,0036	0,0053	0,1819	2350	406,55	8,46	12,41	427,42	#########	https://klimatdatabasen.boverket.se/
Climate	23	Boverket Hålbjälklag, HD/F	Concrete	Slab	0,1880	0,0417	0,0000	0,2297	1350	253,80	56,30	0,00	310,10	#########	https://klimatdatabasen.boverket.se/
Climate	24	Boverket Hålbjälklag, HD/F, klimatförbättrad	Concrete	Slab	0,1280	0,0417	0,0000	0,1697	1350	172,80	56,30	0,00	229,10	#########	https://klimatdatabasen.boverket.se/
Climate	25	Boverket Pelare RP, OP	Concrete	Column	0,2980	0,0417	0,0000	0,3397	2400	715,20	100,08	0,00	815,28	#########	https://klimatdatabasen.boverket.se/
Climate	26	Boverket Pelare RP, OP, klimatförbättrad	Concrete	Column	0,2240	0,0417	0,0000	0,2657	2400	537,60	100,08	0,00	637,68	#########	https://klimatdatabasen.boverket.se/
Climate	27	Boverket Balkar B, slakarmerad	Concrete	Beam	0,2480	0,0417	0,0000	0,2897	2460	610,08	102,58	0,00	712,66	#########	https://klimatdatabasen.boverket.se/
Climate	28	Boverket Balkar B, slakarmerad, klimatförbättrad	Concrete	Beam	0,1860	0,0417	0,0228	0,2505	2460	457,56	102,58	56,09	616,23	#########	https://klimatdatabasen.boverket.se/
Climate	29	Boverket Konstruktionsstål, alla sorter, 80 % primär råvara	Steel	Beam, column	3,1500	0,0765	0,1610	3,3875	7850	24727,50	600,53	1263,85	26591,88	#########	https://klimatdatabasen.boverket.se/
Climate	30	Boverket Konstruktionsstål, 100 % skrotbaserad exkl. legeringsämnen	Steel	Beam, column	1,1300	0,0765	0,0601	1,2666	7850	8870,50	600,53	471,79	9942,81	#########	https://klimatdatabasen.boverket.se/
Climate	31	Boverket Armeringsstål, obearbetad, 100 % skrotbaserad exkl legering	Steel	Reinforcement	0,7450	0,0765	0,0739	0,8954	7850	5848,25	600,53	580,12	7028,89	#########	https://klimatdatabasen.boverket.se/
Climate	32	Boverket Spännarmering, stål, 100% skrotbaserad	Steel	Reinforcement	1,2500	0,0765	0,0663	1,3928	7850	9812,50	600,53	520,46	10933,48	#########	https://klimatdatabasen.boverket.se/
Climate	33	Boverket Korslimmat trä, u 12 %, barrträ	Timber	Slab, wall	0,1200	0,0348	0,0077	0,1625	465	55,80	16,18	3,60	75,58	#########	https://klimatdatabasen.boverket.se/
Climate	34	Boverket Limträ, u 12 %, gran	Timber	Beam, column	0,1330	0,0348	0,0084	0,1762	434	57,72	15,10	3,63	76,46	#########	https://klimatdatabasen.boverket.se/
Climate	35	Tibnor Steel beams	Steel	Beam	0,4260	0,0570	0,0004	0,4834	7850	3344,10	447,45	3,38	3794,93	#########	https://api.environdec.com/api/v1/EPDLibrary/Files/3d8106d0-e518-4c0b-bd31-5f61ebdb27f7/Data
Climate	36	Håldäck Strängbetong	Concrete	Slab	0,1280	0,0128	0,0000	0,1408		0,00	0,00	0,00	0,00	#########	https://strangbetong.se/wp-content/uploads/2024/07/NEPD-6998-6380_Haldack1.pdf
Climate	37	Tibnor Hot finished structural hollow sections	Steel	Column	2,6000	0,0526	0,0000	2,6526	7850	20410,00	412,91	0,00	20822,91	#########	https://api.environdec.com/api/v1/EPDLibrary/Files/bfc7a87c-3dd8-49fd-9bf5-e807467b8f7b/Data
Climate	38	SSAB Micro piles	Steel	Pile	2,3800	0,0674	0,0000	2,4474	7850	18683,00	529,09	0,00	19212,09	#########	https://www.ssab.com/-/media/files/en/infra/epd-steel-piles.pdf?m=20220719085247
Climate	39	Setra KL Trä	Timber	Slab, wall	0,1333	0,0172	0,0015	0,1521	435	58,00	7,50	0,67	66,17	#########	https://www.setragroup.com/globalassets/bilder/2023/kl-tra/dokument/nepd-3329-1967_kl-tra-feb-22.pdf

Figure C5: An excerpt from the database, presenting the structure of GWP data.

D UI window

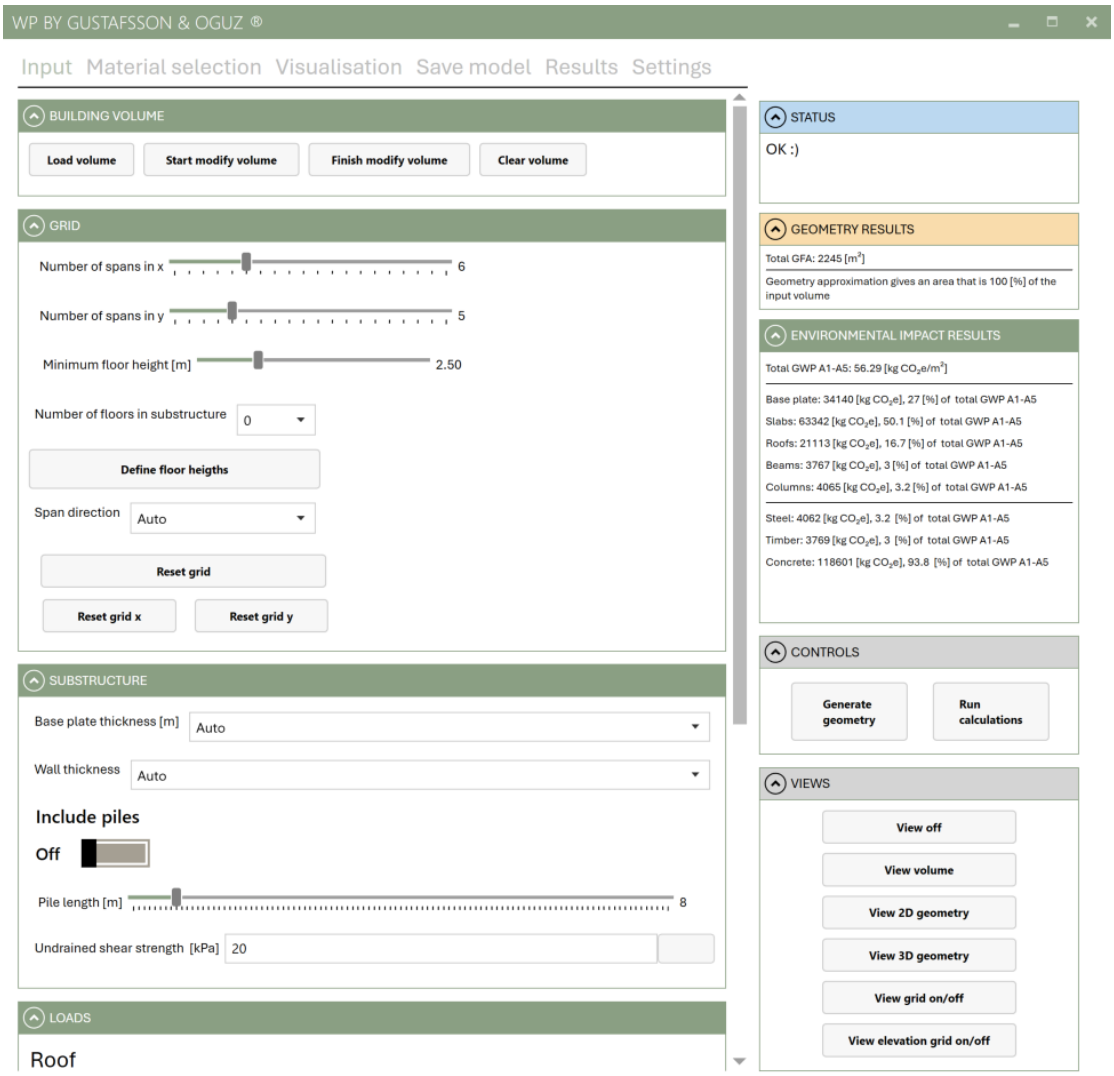


Figure D1: Human UI user interface - Input tab.

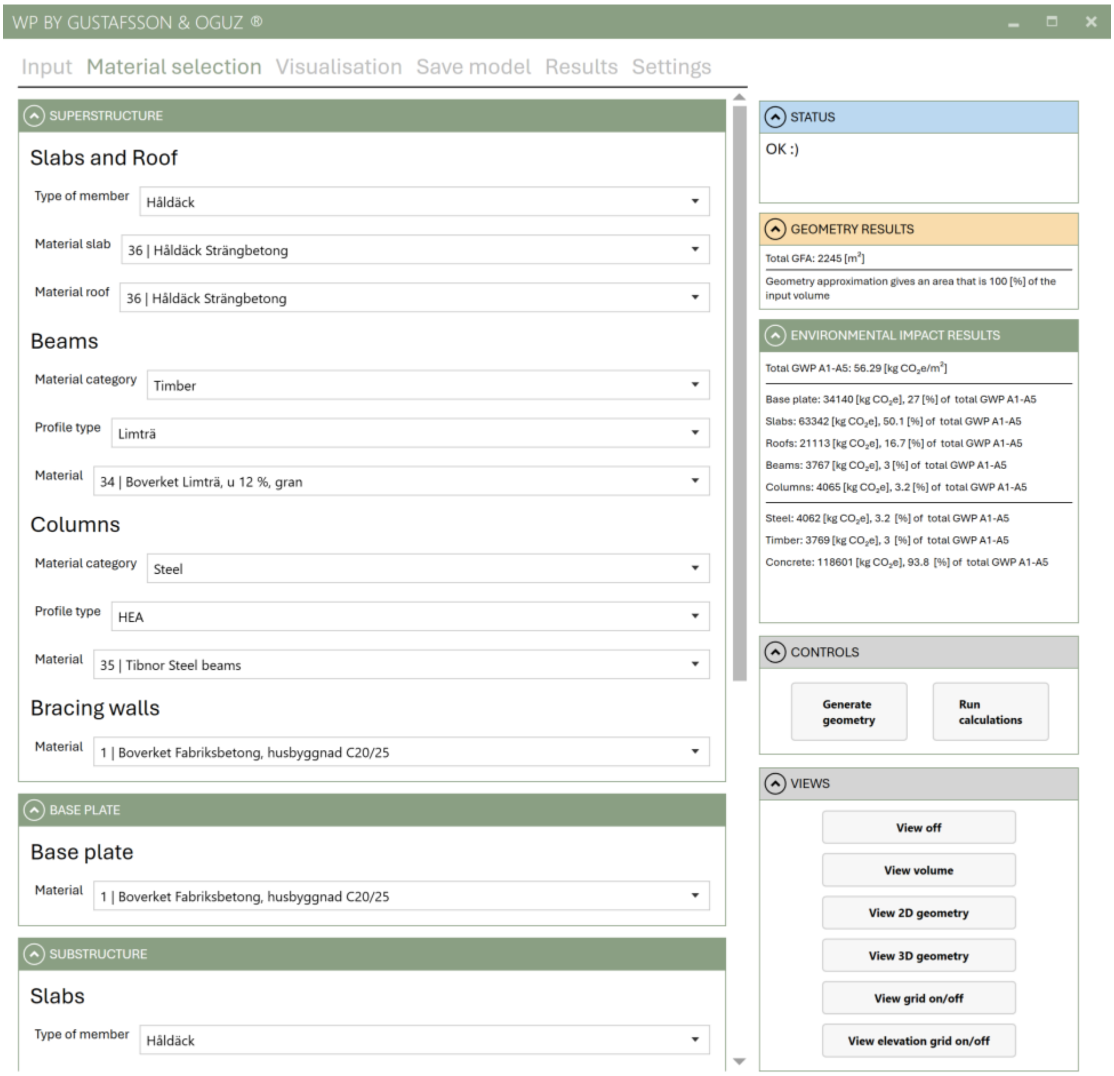


Figure D2: Human UI user interface - Material selection tab.

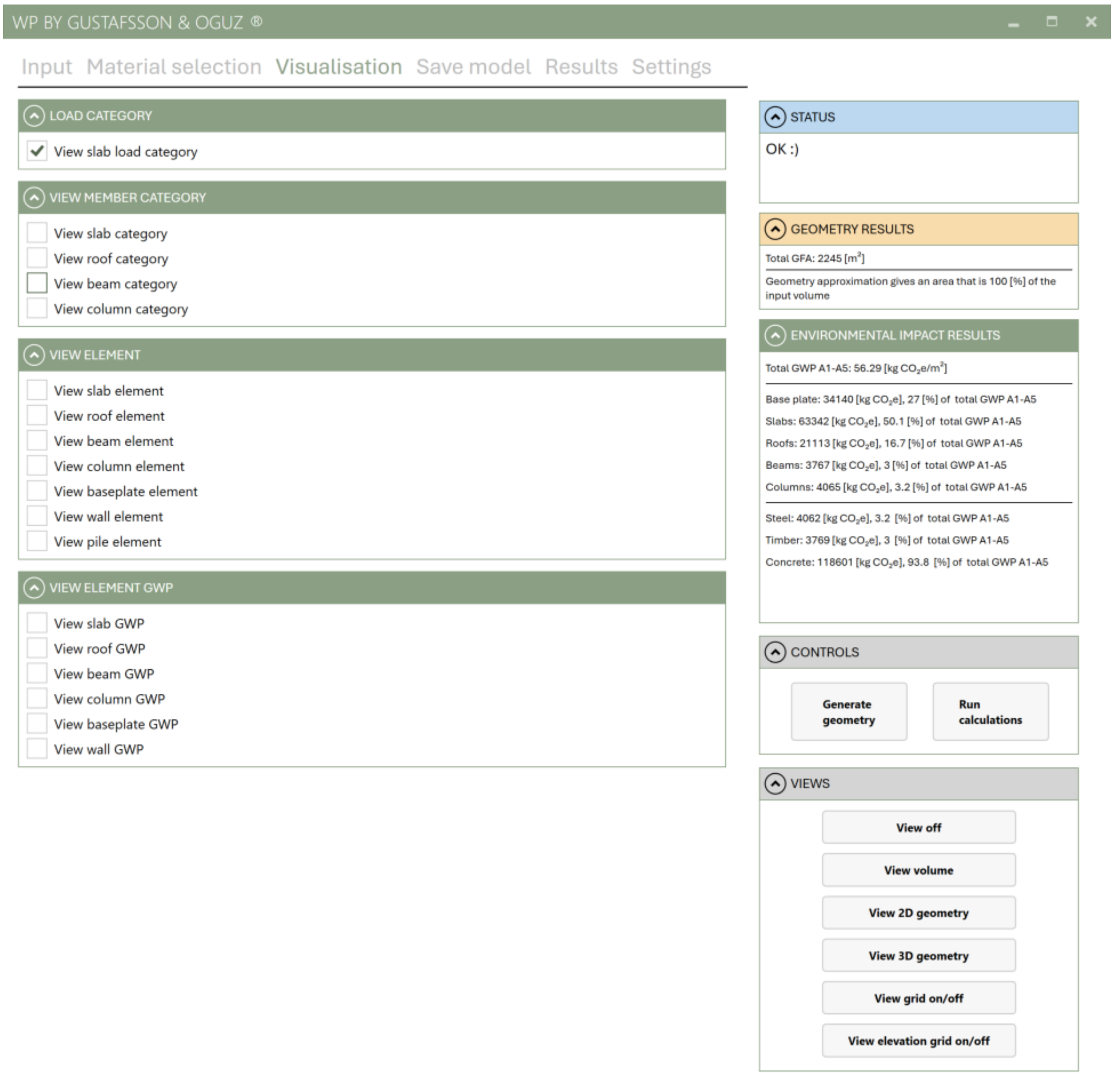


Figure D3: Human UI user interface - Visualisation tab.

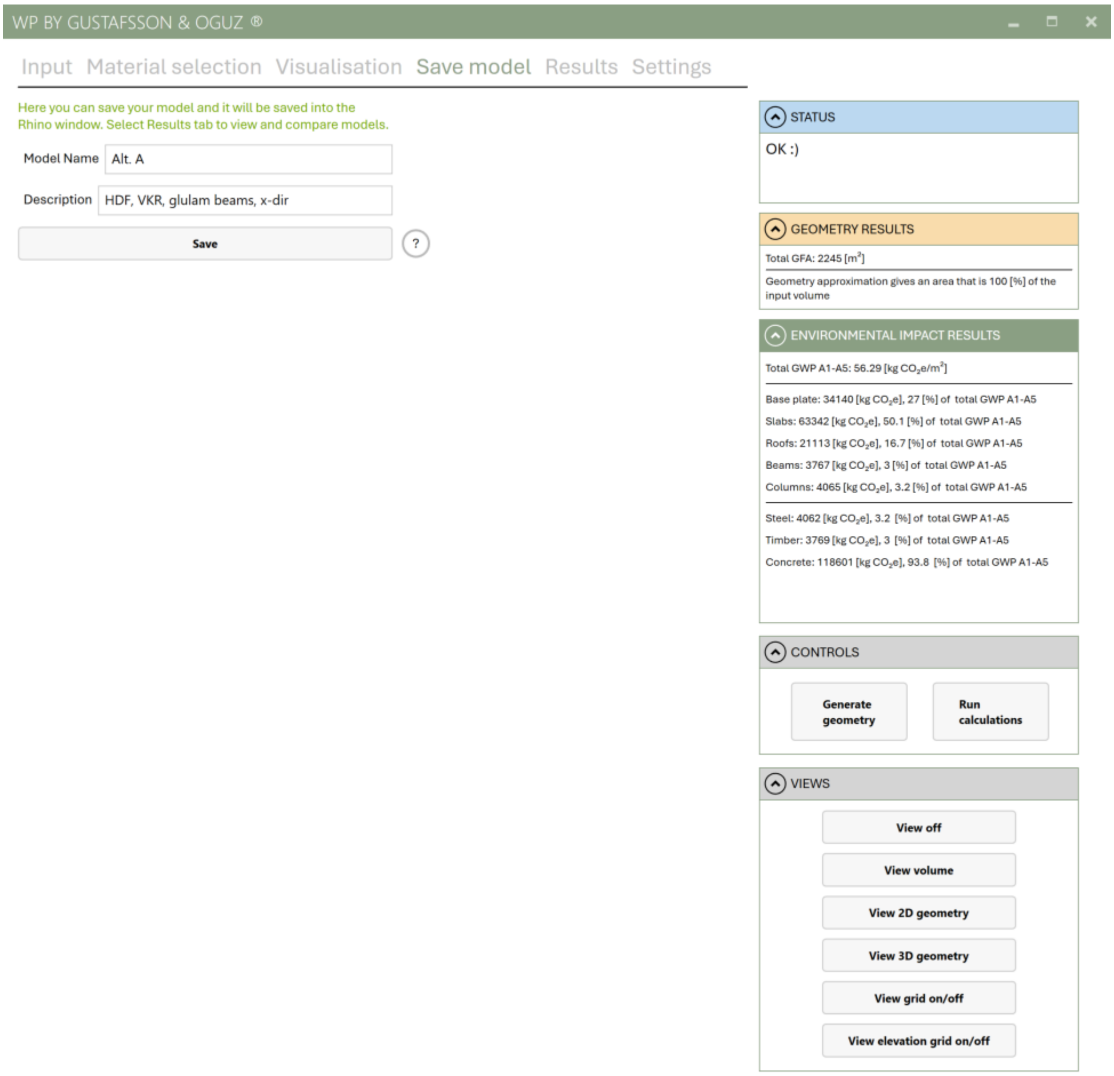


Figure D4: Human UI user interface - Save model tab.

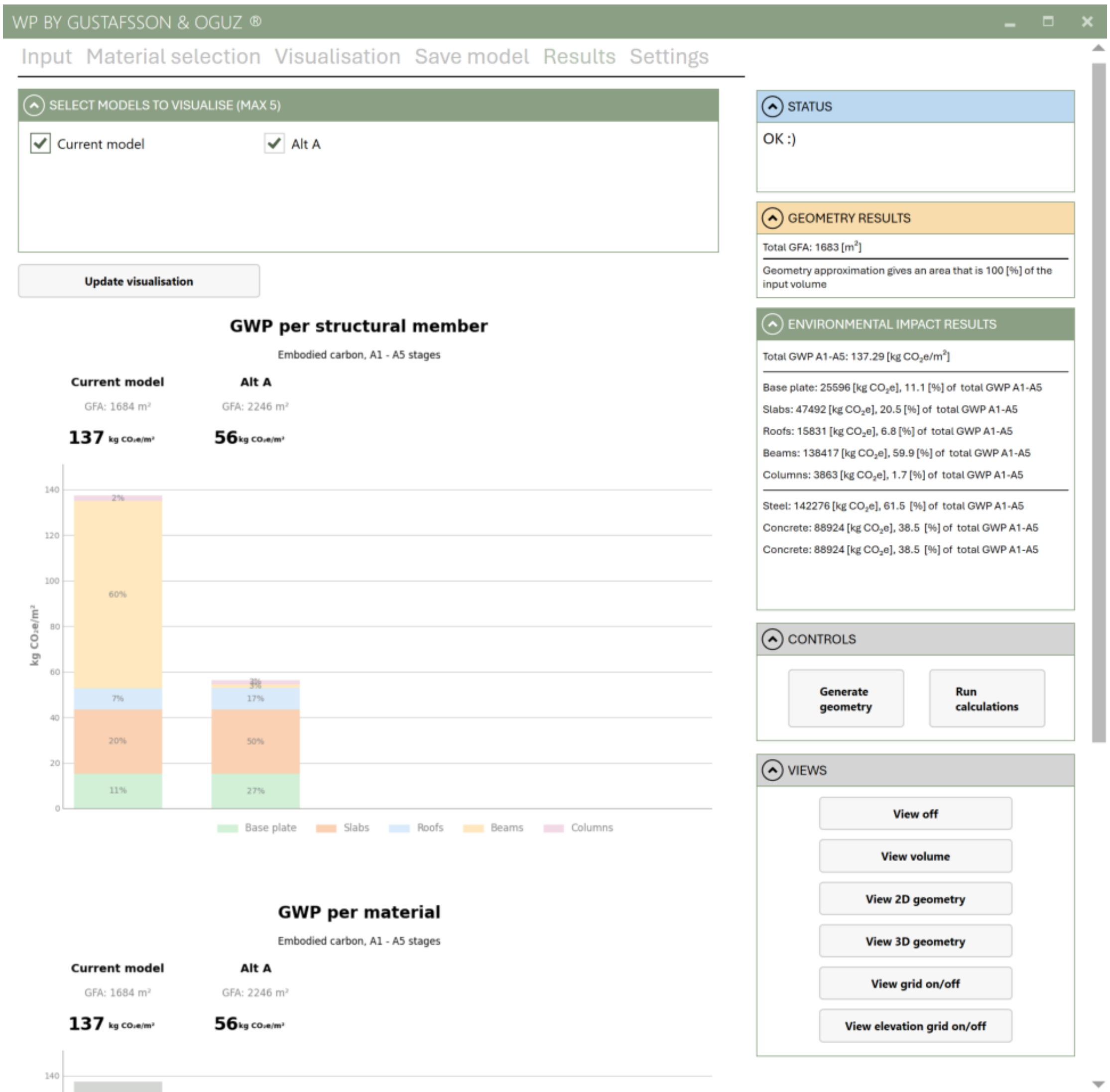


Figure D5: Human UI user interface - Results tab.

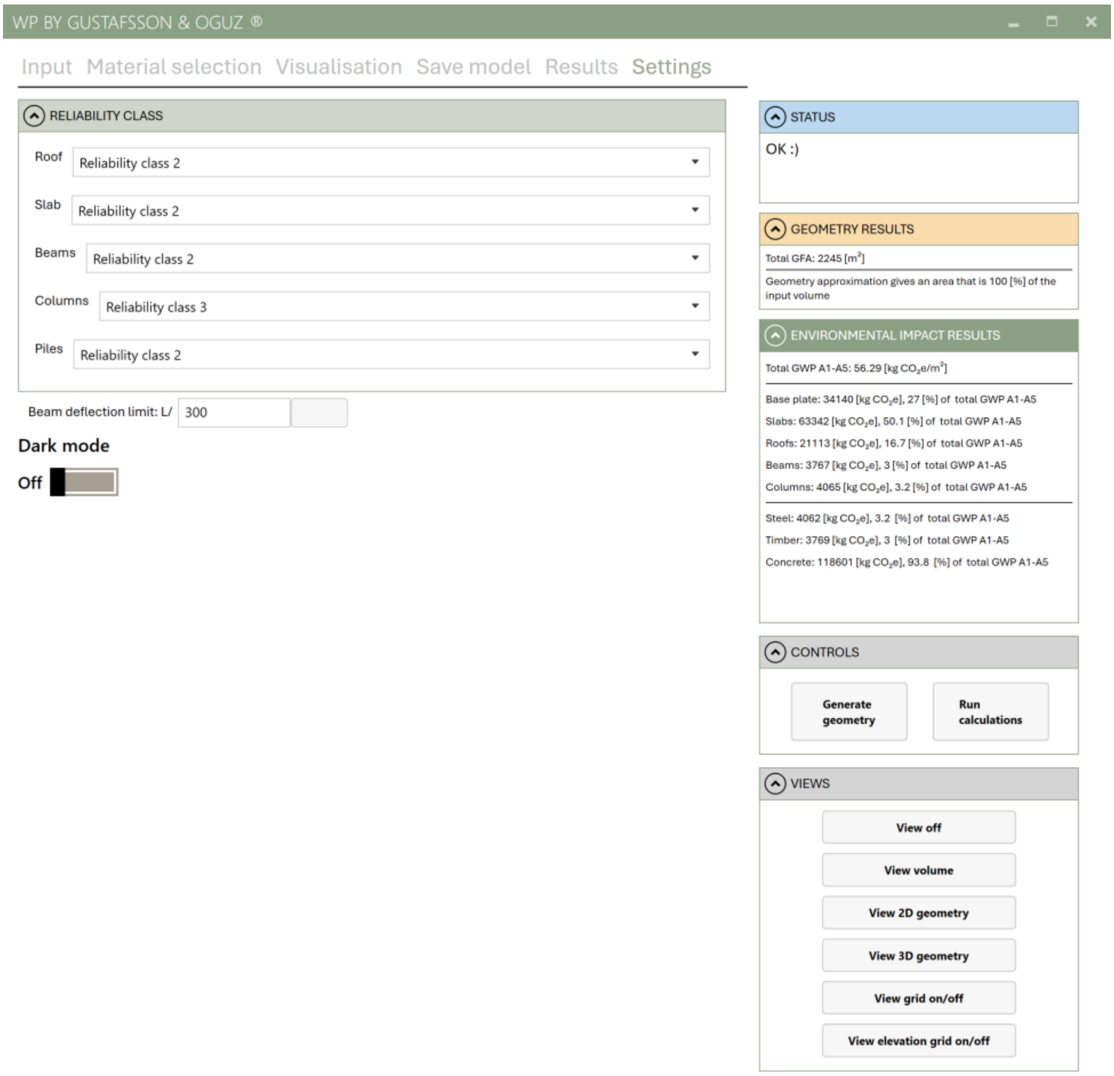


Figure D6: Human UI user interface - Settings tab.

E Verification

	Name	Date
gh file:	WP-1.7-handCalc_Seb	2025-04-02

Input	
Floor height	3,0
spandir	x
nx	9
ny	4
baseplate t	0,3
wall t	0,25
n floor sub	1
SDL super	0
SDL sub	0
SDL roof	0,4
snow load	1,6
Reliability class	0,91
Load cat = A	2
slabs	
loadCombinationFactor_0	0,7
loadCombinationFactor_1	0,5
loadCombinationFactor_2	0,3
roof	
loadCombinationFactor_0	0.7
loadCombinationFactor_1	0,4
loadCombinationFactor_2	0,2
Cell length x	3,66
Cell length y	7,22
Brep box dimension (xyz)	32,9 x 28,9 x 7,4
deflection limit [mm]	24,06666667

corner

Hand Calc.					
	dead	variable	loadcomb ULS	self weight kN/m	Profile
roof load kN/m2	3,07104	1,6		2,6710	HD120/20
slab load kN/m2	2,6710	2		2,6710	HD120/20
beam lvl2 kN/m	6,6613032	2,928	5,75776765	1,04130	HEA340
column lvl1 kN	24,205015	10,57008	42,14760114	0,05257	VKR 60x60x3
beam lvl1 kN/m	5,9293032	3,66	5,92042165	1,0413	HEA340
column lvl0 kN	45,767509	23,78268	43,22214226	0,05257	VKR 60x60x4
support	208,84045	50,20788			
piles			303,6506593	0,108	RR75

corner

TOOL (WP)					
	dead	variable	loadcomb ULS	self weight kN/m	Profile
roof load kN/m2	3,1	1,6		2,6710	HD120/20
slab load kN/m2	2,7	2,0		2,6710	HD120/20
beam lvl2 kN/m	6,7	2,9	5,7894315	1,04130	HEA340
column lvl1 kN	24,4	10,6	42,14871926	0,05257	VKR 60x60x3
beam lvl1 kN/m	5,9	3,7	5,9520855	1,0413	HEA340
column lvl0 kN	45,4	23,8	43,32308114	0,05257	VKR 60x60x4
support	208,4	50,2			
piles			303,157266	0,108	RR75

	Difference
beam lvl2 kN/m	-0,032
column lvl1 kN	-0,001
beam lvl1 kN/m	-0,032
column lvl0 kN	-0,101
piles	0,493

Figure E1: Hand calculation verification of load takedown.

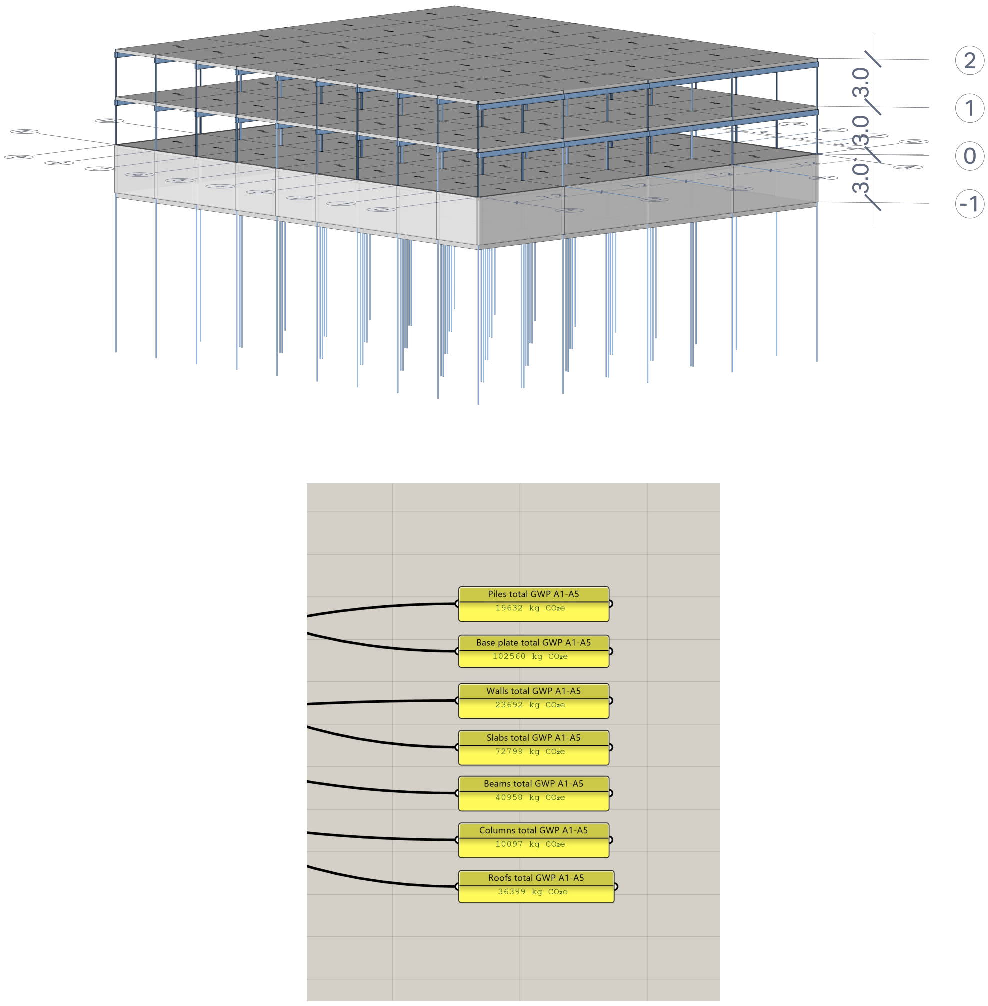


Figure E2: Model used for calculations and GWP results from the tool.

	Name	Date
gh file:	WP-2.2 GWP Verification Erik	2025-05-17

Input		
Floor height	3,0	
spandir	x	
nx	9	
ny	4	
baseplate t	0,3	
wall t	0,25	
n floor sub	1	
SDL super	0	
SDL sub	0	
SDL roof	0,4	
snow load	1,6	
Reliability class	0,91	
Load cat = A	2	
slabs		
loadCombinationFactor_0	0,7	
loadCombinationFactor_1	0,5	
loadCombinationFactor_2	0,3	
roof		
loadCombinationFactor_0	0.7	
loadCombinationFactor_1	0,4	
loadCombinationFactor_2	0,2	
Cell length x	3,66	
Cell length y	7,22	
Brep box dimension (xyz)	32,9 x 28,9 x 7,4	
piles?	yes	
pile length		10
Undrained shear strength		22

		Profile selected by tool	Material	Cross-section area/thickness/weight	Quantity [pcs]	Length/area	Total volume	A1-A5 impact	A1-A5 impact
Foundation									
Piles		RR75	38 | SSAB Micro Piles	0,001381 [m^2]	74	10 [m]	1,02194 [m^3]	19212,1 [kg CO$_2$e/m^3]	19634 [kg CO$_2$e]
Floor -1									
Foundation slab		Plate t=300 mm	7 | Boverket Fabriksbetong	0,3 [m]	1	950,435 [m^2]	285,131 [m^3]	359,7 [kg CO$_2$e/m^3]	102559 [kg CO$_2$e]
Wall	Along x	Wall t=250 mm	6 | Boverket Fabriksbetong	0,25 [m]	2	86,631 [m^2]	43,316 [m^3]	255,6 [kg CO$_2$e/m^3]	11073 [kg CO$_2$e]
	Along y	Wall t=250 mm	6 | Boverket Fabriksbetong	0,25 [m]	2	98,739 [m^2]	49,370 [m^3]	255,6 [kg CO$_2$e/m^3]	12620 [kg CO$_2$e]
Column		VKR 120x120x4,5	37 | Tibnor Hot finished st	0,00206 [m^2]	24	3 [m]	0,148 [m^3]	20822,9 [kg CO$_2$e/m^3]	3088 [kg CO$_2$e]
Floor 0									
Slab		HD120/20	36 | Håldäck Strängbetong	272,0 [kg/m^2]	1	950,435 [m^2]	258518 [kg]	0,1408 [kg CO$_2$e/kg]	36399 [kg CO$_2$e]
Beam		HEA 340	35 | Tibnor Steel beams	0,01335 [m^2]	32	7,219198 [m]	3,084 [m^3]	3794,9 [kg CO$_2$e/m^3]	11704 [kg CO$_2$e]
Column	Corners	VKR 60x60x4	37 | Tibnor Hot finished st	0,00088 [m^2]	4	3 [m]	0,011 [m^3]	20822,9 [kg CO$_2$e/m^3]	220 [kg CO$_2$e]
	Along facade	VKR 80x80x3,6	37 | Tibnor Hot finished st	0,00109 [m^2]	22	3 [m]	0,072 [m^3]	20822,9 [kg CO$_2$e/m^3]	1498 [kg CO$_2$e]
	Interior	VKR 100x100x4	37 | Tibnor Hot finished st	0,00152 [m^2]	24	3 [m]	0,109 [m^3]	20822,9 [kg CO$_2$e/m^3]	2279 [kg CO$_2$e]
Floor 1									
Slab		HD120/20	36 | Håldäck Strängbetong	272,0 [kg/m^2]	1	950,435 [m^2]	258518 [m^3]	0,1408 [kg CO$_2$e/kg]	36399 [kg CO$_2$e]
Beam		HEA 340	35 | Tibnor Steel beams	0,01335 [m^2]	40	7,219198 [m]	3,855 [m^3]	3794,9 [kg CO$_2$e/m^3]	14630 [kg CO$_2$e]
Column	Corners	VKR 60x60x3	37 | Tibnor Hot finished st	0,00067 [m^2]	4	3 [m]	0,008 [m^3]	20822,9 [kg CO$_2$e/m^3]	168 [kg CO$_2$e]
	Along facade	VKR 60x60x4	37 | Tibnor Hot finished st	0,00088 [m^2]	22	3 [m]	0,058 [m^3]	20822,9 [kg CO$_2$e/m^3]	1208 [kg CO$_2$e]
	Interior	VKR 80x80x3,6	37 | Tibnor Hot finished st	0,00109 [m^2]	24	3 [m]	0,078 [m^3]	20822,9 [kg CO$_2$e/m^3]	1634 [kg CO$_2$e]
Floor 2									
Roof		HD120/20	36 | Håldäck Strängbetong	272,0 [kg/m^2]	1	950,435 [m^2]	258518 [m^3]	0,1408 [kg CO$_2$e/kg]	36399 [kg CO$_2$e]
Beam		HEA 340	35 | Tibnor Steel beams	0,01335 [m^2]	40	7,219198 [m]	3,855 [m^3]	3794,9 [kg CO$_2$e/m^3]	14630 [kg CO$_2$e]

Pile	19634	[kg CO$_2$e]
Foundation slab	102559	[kg CO$_2$e]
Wall	23693	[kg CO$_2$e]
Slab	72799	[kg CO$_2$e]
Beam	40963	[kg CO$_2$e]
Column	10096	[kg CO$_2$e]
Roof	36399	[kg CO$_2$e]
Total GWP A1-A5	306143	[kg CO$_2$e]
Total GFA	2851	[m^2]
GWP A1-A5	107,4	[kg CO$_2$e/m^2]

Figure E3: Hand calculation verification of GWP.

F Tool inputs

	Option	Input parameter	Description	Input method	Datatype
Geometry	Mandatory	Building geometry	Overall volume of the building.	Volume from Rhino	BREP
	Mandatory	Number of spans in x- and y-direction	Number of spans in the x- and y-direction used to generate the grid.	Slider or numeric	Integer
	Mandatory	Minimum floor height	Initial minimum floor-to-floor height.	Slider or numeric	Float
	Optional	Add load-bearing walls	Initiate selection of grid lines to generate walls.	Button	Boolean
	Optional	Load-bearing wall thickness	Thickness associated with all load-bearing walls.	Drop-down	String
Substructure	Optional	Number of floors in sub-structure	Number of floors located below ground level.	Slider or numeric	Integer
	Optional	Span direction	Span direction of slabs.	Drop-down	String
	Optional	Foundation slab thickness	Thickness associated with the foundation slab.	Drop-down	String
	Optional	Wall thickness	Thickness associated with all external walls below ground.	Drop-down	Float
	Optional	Include piles?	Include piles in the structural system.	Toggle button	Boolean
	Optional	Pile length	Length associated with all piles for GWP calculation.	Slider or numeric	Integer
	Optional	Undrained shear strength	Undrained shear strength of the soil at the site.	Numeric	Float

Table E1: Overview of tool inputs.

	Option	Input parameter	Description	Input method	Datatype
Loads	Mandatory	Load category	Selection of the use category for each floor.	Drop-down	String
	Mandatory	SDL slabs superstructure	Superimposed dead load on slabs in the superstructure.	Numeric	Float
	Mandatory	SDL slabs substructure	Superimposed dead load on slabs in the substructure.	Numeric	Float
	Mandatory	SDL roof	Superimposed dead load on roof slabs.	Numeric	Float
	Mandatory	Snow load on ground	Characteristic value of snow load on the ground for the given location.	Drop-down	Float
Material	Mandatory	Type of member slabs superstructure	Selection of slab and roof category in the superstructure.	Drop-down	String
	Mandatory	Material slab superstructure	Associated material for slabs in the superstructure.	Drop-down	String
	Mandatory	Material roof	Associated material for roofs.	Drop-down	String
	Mandatory	Material category beams superstructure	Selection of beam category in the superstructure.	Drop-down	String
	Mandatory	Profile type beams superstructure	Selection of specific profile for beams in the superstructure.	Drop-down	String
	Mandatory	Material beams superstructure	Associated material for beams in the superstructure.	Drop-down	String
	Mandatory	Material category columns superstructure	Selection of column category in the superstructure.	Drop-down	String
	Mandatory	Profile type columns superstructure	Selection of specific profile for columns in the superstructure.	Drop-down	String
	Mandatory	Material columns superstructure	Associated material for columns in the superstructure.	Drop-down	String
	Mandatory	Material foundation slab	Associated material for the foundation slab.	Drop-down	String

Table E2: Overview of tool inputs (continued).

	Option	Input parameter	Description	Input method	Datatype
Material	Optional	Type of member slabs substructure	Selection of slab category in the substructure.	Drop-down	String
	Optional	Material slab substructure	Associated material for slabs in the substructure.	Drop-down	String
	Optional	Material category beams substructure	Selection of beam category in the substructure.	Drop-down	String
	Optional	Profile type beams substructure	Selection of specific profile for beams in the substructure.	Drop-down	String
	Optional	Material beams substructure	Associated material for beams in the substructure.	Drop-down	String
	Optional	Material category columns substructure	Selection of column category in the substructure.	Drop-down	String
	Optional	Profile type columns substructure	Selection of specific profile for columns in the substructure.	Drop-down	String
	Optional	Material columns substructure	Associated material for columns in the substructure.	Drop-down	String
	Optional	Material walls	Associated material for external walls in the substructure.	Drop-down	String
	Optional	Type of pile	Selection of pile category.	Drop-down	String
	Optional	Material pile	Associated material for piles.	Drop-down	String

Table E3: Overview of tool inputs (continued).

G Grasshopper script

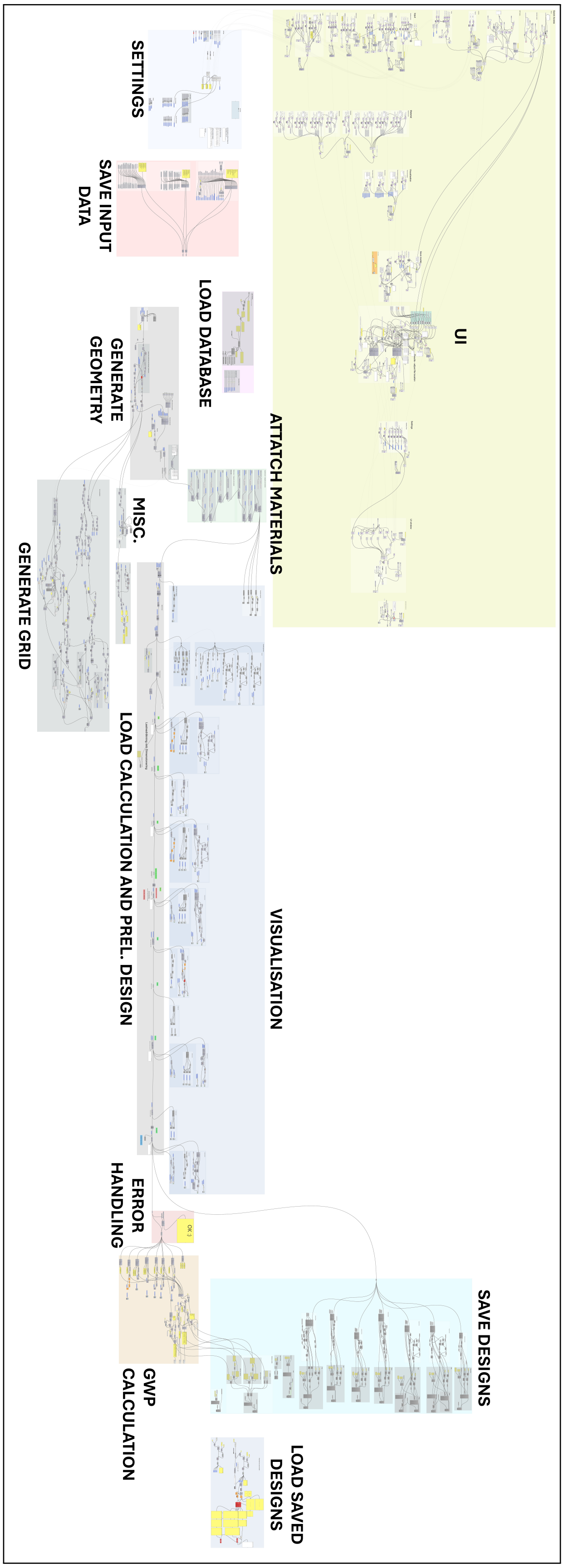


Figure G1: Overview of Grasshopper script.

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