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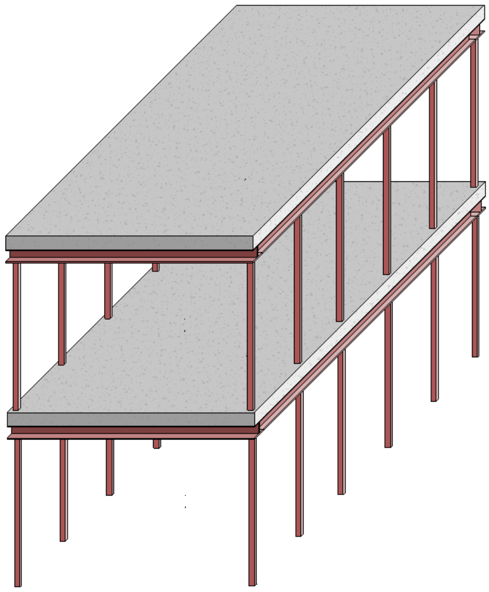

Prerequisites for Using Genetic Algorithm Optimization of Structural Systems in the Conceptual Design Phase

A study to design a database and investigate the prerequisites for software using genetic algorithms to optimize structural systems based on cost and environmental impact

Master's thesis in Structural Engineering and Building Technology

Sofia Klasson
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DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING

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Conceptual design database for genetic algorithms optimization
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Master's thesis in Structural Engineering and Building Technology
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Cover: Example of a structural system in a building consisting of slabs, columns, and beams.

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Abstract

The construction industry is undergoing a transformative shift toward environmental sustainability. This shift demands that building projects not only adapt to the traditional benchmarks of time and cost but also integrate considerations to minimize CO_2 equivalent emissions. In this context, the critical decision of selecting an optimal structural system during early design phases, such as the concept exploration phase, becomes essential for reducing the environmental footprint in the industry. Therefore, this study explores the possibilities of using genetic algorithms (GA), a kind of multicriteria optimization inspired by the evolution process, to support structural engineers during early design phases. The genetic algorithm's prerequisites for creating different structural systems are analyzed in this project. The solutions for the systems are evaluated based on material, production, and construction costs and CO_2 equivalent emissions. The necessary prerequisites and software design were investigated through workshops and questionnaires targeting experienced structural engineers. Based on the workshop and survey results, a structural design database was created, including aspects such as functionality and buildability. The database includes different elements, such as slabs, walls, columns, and beams. Further, information is implemented in the database, allowing the user to input requirements concerning the buildability, sound class, and fire class. The results from the workshop and surveys demonstrated the importance of including the buildability aspect in the software for the software to be functional. Overall, the software is considered to have the opportunity to become a useful tool for structural engineers during the conceptual design phase, with the approach of creating ideas. Instead of selecting one solution that is considered the most optimal, it would be preferable to present a range of solutions from which the user can choose the most fitting system for the specific project. Besides choosing between different materials, optimizing the material quantity of the total building is crucial to becoming environmentally beneficial.

Keywords: Conceptual design, genetic algorithms, structural system, optimization, database, buildability, sustainability, environmental impact.

Förutsättningar för att använda genetisk algoritmoptimering av stomsystem under den konceptuella designfasen
En studie för att utforma en databas och undersöka förutsättningarna för ett verktyg som använder genetiska algoritmer för att optimera stomsystem baserat på kostnad och miljöpåverkan.

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Sammanfattning

Byggbranschen genomgår en transformativ förändring mot miljömässig hållbarhet. Denna förändring kräver att byggprojektet inte bara anpassar sig till traditionella riktmärken för tid och kostnad utan också integrerar överväganden för att minimera utsläpp av CO_2-ekvivalenter. I detta sammanhang blir det kritiska beslutet att välja ett optimalt stomsystem under tidiga designfaser avgörande för att sänka branschens miljöpåverkan. Denna studie utforskar därför möjligheterna att använda genetiska algoritmer (GA), som är en multikriterieoptimering inspirerad av evolutionsprocessen, som ett arbetsstöd för byggnadskonstruktörer i tidiga designfaser. Detta projekt analyserar genetiska algoritmens förutsättningar för att skapa lösningar för olika stomsystem. Lösningarna för systemen utvärderas utifrån kostnader och utsläpp av CO_2-ekvivalenter. De nödvändiga förutsättningarna och designen av programvaran undersöktes genom workshops och enkäter riktade till erfarna konstruktionsingenjörer. Baserat på resultaten av workshpen och enkäterna skapades en designdatabas med aspekter som funktionalitet och byggbarhet inkluderade. Databasen består av olika element såsom bjälklag, bärande väggar, pelare och balkar. Vidare implementeras information i databasen, vilket gör att användaren kan ange krav på byggbarhet, ljudklass och brandklass. Resultatet från undersökningen visade vikten av att inkludera byggbarhetsaspekten i databasen för att uppnå en användbar programvara. Sammantaget anses programvaran ha möjligheten for att kunna bli ett användbart verktyg för byggnadskonstruktörer under den konceptuella designfasen, med syftet att skapa idéer. Istället för att programvaran ska generera en lösning som anses vara den mest optimala så föredras det flera lösningar presenteras, från vilka användaren kan utse det mest passande systemet för det specifika projektet. Förutom valet mellan olika material, har optimering av materialmängden i den totala byggnaden visat sig vara avgörande för att uppnå miljömässig hållbarhet.

Nyckelord: Konceptuell design, genetiska algoritmer, stomsystem, optimering, databas, byggbarhet, hållbarhet, miljöpåverkan.

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Sofia Klasson, Linn Kärvegård, Gothenburg 2024

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AI	Artificial Intelligence
BIM	Building Information Model
$CaCO_3$	Calcium carbonate
CaO	Calcium oxide
CLT	Cross Laminated Timber
CO_2	Carbon Dioxide
EPD	Environmental Product Declaration
GA	Genetic Algorithm
Glulam	Glued laminated timber
LCA	Life Cycle Assessment
LVL	Laminated Veneer Lumber
NO	Nitrogen Oxides
SCM	Supplementary cementitious materials
SLS	Serviceability Limit State
SO_2	Sulphur Dioxide
ULS	Ultimate Limit State

Nomenclature

Below is the nomenclature of indices, sets, parameters, and variables that have been used throughout this thesis.

Indices

i	Index material used

Symbols

A	Cross section area of a column or a beam
E	Modulus of elasticity
I	Moment of inertia
L	Length of a column or a beam
M_{Rd}	Design value due to bending moment
W	Section modulus
$F(x)$	Fitness function
$P(x)$	Penalty method
a, b	Weighting functions in a fitness function
f_y	The yield strength of steel
t	Thickness of a slab or a wall
q_L	maximum load that can be applied on the beam with the length L
$f(x)$	Objective function
$f_1(x), f_2(x)$	Objectives in a fitness function
$p(x)$	Penalty function

β	The buckling factor
χ_{LT}	Reduction factor regarding the lateral torsional buckling
γ_{M1}	Resistance due to instability
λ	Penalty parameter
ρ	Density of a material

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1
Introduction

The thesis is a pre-study investigating the prerequisites for software which will use genetic algorithms to optimize structural systems based on cost and environmental impact. This chapter introduces the different subjects on which the project will be based on and presents the purpose, aim and objectives, and methodology. Lastly, it presents the project's limitations and ethical, ecological, and social aspects.

1.1 Background

Since the construction sector accounts for approximately 20% of Sweden's CO_2 equivalent emissions, an adaption is crucial to be able to reach the climate targets about "Net Zero Emissions" by 2050 (Boverket, 2024). In addition, the number of buildings being built today is the highest since 1970 (Naturvårdsverket, 2023). In "The Roadmap for Fossil Competitiveness for the Swedish Construction and Civil Engineering Sector", released by *Fossilfritt Sverige* 2018, the construction industry collectively has agreed on a plan to reach the targets (Fossilfritt Sverige, 2024). The plan describes a gradual reduction of emissions, with one of the goals being to reduce greenhouse gases by half by 2030.

In 2022, a requirement for reporting climate declaration was introduced when constructing new buildings in Sweden, where the purpose is to make developers more aware of the environmental impact of the construction industry (Boverket, 2023d). Today, there are no maximum values for emissions, but they are planned to be added in the year 2027 (Boverket, 2020). Since a building contributes to emissions at different phases during its lifetime, and a holistic perspective is important, a life cycle assessment (LCA) is a usable tool.

1.1.1 Optimization of structural systems

A structural system is a load-bearing unit that transfers static, dynamic, and live loads to the ground. This applies to everything from residential construction to office buildings and hospitals, described as every building in a society. These structural systems can be designed in various ways, but the system's main structural elements are columns, beams, slabs, and load-bearing walls (Nobel, n.d.). Structural systems can be constructed using different materials, including concrete, steel, and timber.

A structural engineer is responsible for ensuring the structural load-bearing capacity of the structural system (Nobel, n.d.). That responsibility requires knowledge of each component of the system and an understanding of how the system functions as a whole. Factors such as capacity, contribution, interaction, and manufacturing of each element must be considered. The load-bearing calculation is performed to ensure all the different loads are properly transferred through the structural elements down to the ground. The loads vary due to the type of structural system, some examples of loads are snow load, wind load, self-weight, traffic load, imposed loads, and accidental loads. The loads release stresses in the elements, such as tension forces, compression forces, and shear forces. The complexity of these factors highlights the importance of skilled engineers in the construction process.

Selecting an optimal structural system is crucial to minimize the environmental impact and costs (Byggföretagen, 2024). When designing a structural system in the tendering process, a short deadline combined with a lot of manual work often limits the number of systems being evaluated. Embracing advanced methodologies, such as genetic algorithms (GA), offers a powerful solution. GA uses a technique inspired by natural evolution, and by using artificial intelligence, these algorithms navigate the complexity of sustaining construction. By implementing such a tool in the early process, more structural solutions can be analyzed, and the possibility of achieving a cost- and environmental-effective solution increases.

In the design process, factors beyond load-carrying and stabilization capacity are important. Construction cost is a critical consideration; excessive use of materials leads to higher, often unnecessary, company expenses. Environmental impact is another key factor, as some materials have less environmental impact than others, often due to differing production methods. To satisfy these requirements and achieve an efficient design, the structural system requires optimization.

1.1.2 Type of building

In the center of cities, multi-story buildings are commonly used for residential and office buildings (Boverket, 2023c). The demand for smaller shopping areas increases since the cities require more shops, such as grocery stores, pharmacies, restaurants, etc. An entrance floor with shops and service businesses requires a lot of windows and open spaces to facilitate marketing and natural daylight. Large, open areas with minimum interior walls are requested, challenging the structural system since most of the building's load will be carried down to the entrance floor. Greater loads demand greater dimensions or an increased number of columns and beams. Combining heavy loads with the long spans required can be challenging.

1.2 Purpose

The intention of this master's thesis is to improve the possibility of lowering costs and reducing climate impact in the construction industry. Using GA-based software during the design phase will increase the possibilities of choosing an optimised structural system regarding these factors. By investigating the prerequisites and creating a database, this thesis will perform the preparatory work and increase the possibilities for useful software.

1.3 Aim and objectives

This thesis work results in a database of different structural elements. The database will be made in Excel to be accessed and developed easily for future software. The database will be based on the current conditions in the industry, but by developing the database in Excel, the conditions can be changed. The user-friendly format in Excel will facilitate easy access, navigation, and ongoing updates, making it a valuable tool for professionals involved in structural design. The outcome aims to contribute to more precise and faster decision-making regarding cost and environmental impact in the exploration phase. The following objectives were used to define the purpose:

- What are the prerequisites for software utilizing genetic algorithms to optimize structural systems considering investment cost and environmental impact?

- How should the database be structured, and which data should be included to ensure a correct output of the future software?

- How could buildability be included in such software?

1.4 Methodology

An investigative approach will be used during the research. First, a literature study is performed to understand the different aspects of LCA, economy, and structural systems. Further, to understand how the database could be implemented into the software, similar existing tools are analyzed. Also, an interaction with structural engineers through workshops is carried out to consider the viewpoint of possible future users. This exchange intends to give an insight into which areas to focus on and what to consider during the database creation.

Henceforth, the data and aspects gathered are analyzed and form the basis for a training database. First, the CO_2 equivalent emissions for different materials are gathered. The database conducts whole elements, where standard dimensions in the construction industry are used. The elements used provide for buildability, where soundproofing is considered to ensure the software generates complete and functional systems. Second, data that considers costs and bearing capacities are collected in the database. The bearing capacities of different elements are calculated to generate different structural systems. The cost includes material, production, and construction costs.

1.5 Limitations

This thesis is limited to studying residential buildings. The model for the algorithm will be adapted for use in other buildings in the future. The focus is to create an effective model rather than test different buildings' performance. The reason for choosing to investigate residential buildings is to explore different structural systems' ability to adapt to different needs of designs throughout the stories. The design of a residential building is less flexible as the spaces for apartments have certain requirements to meet. Less flexibility leads to fewer geometric solutions, resulting in an easier software performance analysis.

The project focuses on selected profiles and materials based on the literature study and inputs from structural engineers. The project is limited to a study at a national level since the regulations from Eurocode are the design standard. In the thesis, only the structural system of the building is considered, not the foundation. Further, the outermost layer of the facade is excluded, as it is assumed to be constant regardless of the structural system.

1.6 Ethical, ecological and social aspects

The social sustainability mainly concerns the workshop study, which intends to include engineers from different roles and backgrounds in structural engineering. This is to generate a result as comprehensive as possible. The questionnaires were also made anonymously to protect the integrity of the individuals and increase the room for transparency and honesty. This project aims to create new prerequisites to decrease the environmental impact of the construction industry, where material use and CO_2 emissions are the two main areas.

2

Materials and Structural Elements

The following chapter presents a literature study regarding structural elements. The chapter contains theory about structural systems, presented with two different types of load-bearing systems: column-beam systems and load-bearing walls. Selected elements made of the most common materials used in construction, timber, concrete, and steel, are presented separately based on the material.

2.1 Structural systems

The structural system of a building is designed to carry all the loads a building is exposed to (Nobel, n.d.). Designing a structural system for a building involves many different possible solutions. A structural engineer is responsible for designing an optimized system that fulfills the structural requirements. Factors such as buildability, location, and span length are possible requirements affecting the choice of structural system, which make each project unique. This section presents two of the most common types of structural systems used in Sweden.

2.1.1 Column-beam system

A column-beam system is commonly used when large spans or independence concerning the facade is desired (Svenskt trä, 2015). The system consists of horizontal beams and vertical columns, shown in Figure 2.1. A floor slab placed on beams distributes the vertical loads to the beams, creating shear forces, bending moments, and occasionally torsion within the beam. The load is then transferred from the beams to the columns, acting like supports, which cause compression forces in the columns, which then carry the load to the foundation. With each additional floor adding a self-weight load, the columns at the bottom will be loaded with the highest weight. Column-beam systems allow the creation of large spaces both vertically and horizontally.

Further, a column-beam system must be supplemented to carry horizontal loads and transfer them to the foundation. One solution is adding bracing members such as trusses or shear walls/panels, where trusses are diagonally placed between two connection points (Fernandez, 2022a). These rigid elements are typically placed within walls and are needed to ensure the system's stability. By connecting several shear walls and connecting a shear core, fewer walls are needed (Doshi, n.d.). A core is often centered in the middle of a building, allowing a more flexible floor plan and creating more creativity regarding the facade design.

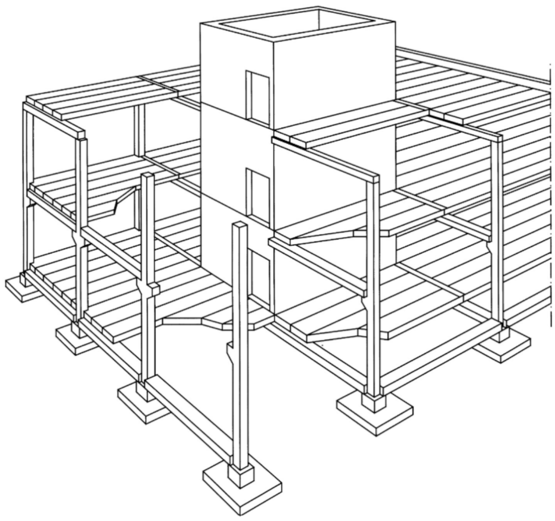

Figure 2.1: Column beam system (Fernandez, 2022c)

2.1.2 Load-bearing wall

Any wall that supports the structure, whether it is an internal wall or part of the facade, is considered a load-bearing wall (Farrovial, n.d.). The main function of these walls is to carry the load and ensure building stability. Load-bearing facades are one of the earliest elements to be constructed, allowing structures to maintain open interior spaces. The walls have to carry a large load for a long time without major deformations. Therefore, the material of these load-bearing walls is usually resistant material, such as stone, concrete, or steel. For smaller houses, timber is also a commonly used material for load-bearing walls.

The load increases due to the self-weight of each floor from the ceiling down past each story to the foundation (Farrovial, n.d.). An example of a system using load-bearing walls is shown in Figure 2.2. The appropriate thickness of a load-bearing wall is estimated to prevent collapse if the load exceeds the bearing capacity of the wall. Once a load-bearing wall has been placed, replacing it is more complex than for an interior wall. During renovations, identifying load-bearing walls is important to secure the stability of the structure. If this is not done correctly, it could lead to a collapse of the building. If demolition of the wall is non-negotiable, the structure can be prepared by supporting the span with a temporary beam.

The first approach to identify a load-bearing wall is the thickness, which is more robust than usual walls (Farrovial, n.d.). A load-bearing facade is located in the outer walls of the building and supports the ceiling. It can also be identified by the placement of the beams; any wall placed perpendicular to the beam's direction acts as its support. The walls can act as horizontal stabilizing and counteract the rotation of the building. Load-bearing walls are generally used in apartment buildings since they do not need to be complemented to provide sound insulation and good thermal conductivity. Each separating wall between the apartments is load-bearing in residential buildings, isolating the sound from external noise.

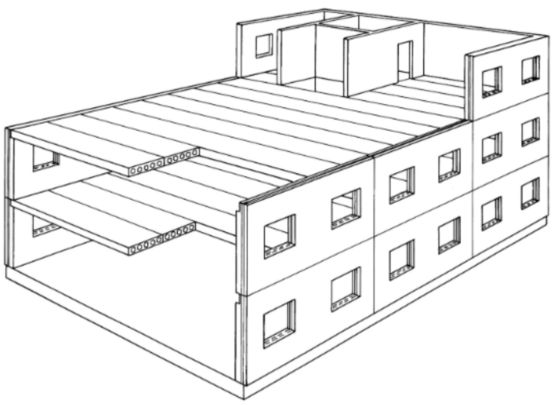

Figure 2.2: Load-bearing facade (Fernandez, 2022c)

2.2 Timber

One of the most common building materials in single-story residential buildings is timber. In Sweden, timber is the traditionally oldest used building material (Svenskt trä, n.d.-c). The material has been used in construction as various elements for many years. The quality of a wooden element can vary greatly depending on the wood type. The environment and location during the tree's growth make a difference in the final wooden product. Different treatments during the production process can also affect the component's properties.

Timber is the only renewable building material and has many environmental benefits (Ramboll, n.d.). It requires less energy during production and, thereby, releases less carbon dioxide emissions than steel and concrete. More environmental aspects are covered in a later chapter, specifically in Section 3.3 Another benefit is that timber is not as heavy as other building materials such as concrete and steel and, therefore, does not require as extensive delivery and construction processes. Since timber is a natural material, many experience a positive impact on comfort (Svenskt trä, n.d.-b). During favorable conditions, the materials' adaptability to temperatures and humidity is profitable, which leads to a good indoor climate.

Although timber is sustainable from an environmental perspective, it still has some disadvantages. Massive wood is a combustible material, and its strength can be weakened through, for example, microbial growth or an event of fire (Fahlander, 2020). The material also leads to a more intense fire progress and causes the spread to increase. During the 20th century, fires caused many destroyed wooden buildings, and laws were introduced with a maximum number of floors to prevent the fire from spreading and keep the fire manageable. Regardless of whether the fire could be extinguished, the buildings were filled with water, causing irreparable moisture damage. Fortunately, the development of fire protection has gotten better. A timber building can be complemented with concrete slabs as a hybrid solution to secure the structure on different floors from spreading fire. It is also more common to install sprinkler systems nowadays.

The structure of wood is anisotropic, which means that the material behaves differently and has different properties in different directions (Godonou, 2022). Natural characteristics such as knots and moisture content also influence the behavior of the specimen. Due to the direction of the fibers, timber behaves differently in compression, tension, and shear strength. The directions are categorized as longitudinal, tangential, and radial relative to the fibers. Both tension and compression strength are greater parallel to the grain than perpendicular. To compare vertical and horizontal load-bearing systems in timber, the vertical system usually consists of columns and studs (Svenskt trä, n.d.-a). Meanwhile, the horizontal system consists of beams and roof trusses. The most common types of columns and beams will be presented below.

2.2.1 Glued Laminated Timber

When constructing a timber structure, columns or load-bearing walls are used as vertical supports. The beams are subjected to horizontal and vertical loads, visible in the ceiling or built into the slab. The most used wood material for columns and beams is glued laminated timber (glulam) (Swedish wood, n.d.). The benefits of using glulam are expansive qualities, and the product is one of the strongest structural timber elements in relation to its weight. Glulam elements are composed of at least two glued pieces of wood. The fibers in the wood pieces are in a parallel direction to the length of the element. The products are either straight or curved, whereas the curved product requires thinner laminates than the straight one. The strength of a glulam material varies. Hence, the material is divided into classes. Since the highest stresses of compression and tension occur on the top and bottom of the beam, a higher strength class of the laminates is preferable there. A lower strength class can be used between these, as shown in Figure 2.3. Because of the strength, the span can be increased to great distances. The dimension of a glulam beam can be produced to a maximum span of 60m, with a cross-sectional dimension of 215x 2000mm (Svenskt trä, 2021b).

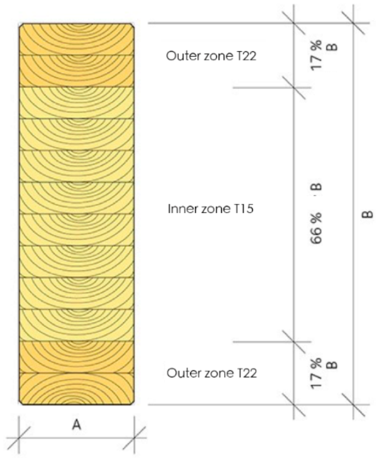

Figure 2.3: Glulam beam (Borgstrom & Fröbel, 2019)

2.2.2 Cross Laminated Timber

Cross-laminated timber (CLT) has a high load-bearing capacity and can carry large spans with high horizontal forces (Svenskt trä, n.d.-d). It can be produced with large cross-section dimensions. In addition, CLT elements have a suitable and stable surface for fastening and provide the opportunity for visible wooden surfaces. An element of CLT is made of at least three glued cross-laid laminates. The layers of laminates are directed at 90-degree in relation to the adjacent layer, shown in Figure 2.4 (Svenskt trä, 2017b). The outer layers are always oriented in the same direction, implying an uneven number of laminates, such as three, five, seven layers, and more. Since CLT is a versatile product, it can be used in various extents, but it is mostly used for floor diaphragms and load-bearing walls.

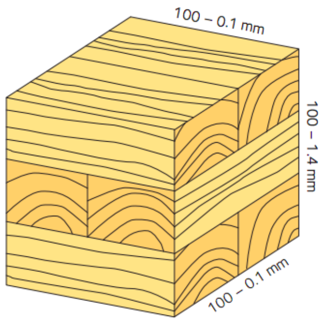

Figure 2.4: Cross laminated timber beam (Borgstrom & Fröbel, 2019)

2.2.3 Laminated veneer lumber

Laminated veneer lumber (LVL) is made of thin glued veneer laminates (Svenkt Trä, n.d.). The impact of disturbances and the variations in mechanical properties is lower, which increases the strength. The laminate's direction is ordered in the main load-bearing direction. Sometimes, a smaller amount of the veneers is produced perpendicular to the load-bearing direction, which increases the stiffness in the transverse direction. This is beneficial in elements such as floor slabs. The product is shown in Figure 2.5.

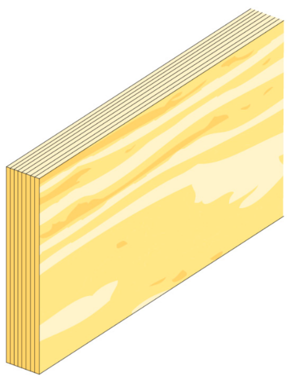

Figure 2.5: Laminated veneer lumber (Svenskt trä, 2021a)

2.3 Concrete

Concrete is one of the most used building materials because of its strength properties, durability, and flexibility (Easymix concrete, n.d.). The material comprises cement/binder, aggregates, water, and additions. By adjusting the ratio of these ingredients, desired characteristics can be achieved. Cement is the most common binder in concrete and consists of limestone, clay, and gypsum. It functions as a paste that binds the aggregate. The cement production starts with grinding limestone and clay into a powder, which is later heated in a kiln in 1450 °C (Gasdia-Cochrane, 2023). During this procedure, the chemical bonds in the limestone and clay are broken, and new bonds are later formed during hydration, creating clinker. This is then ground to a powder and mixed with gypsum, creating cement. The hydration process continues while the cement is mixed with water and aggregates.

Cement is the major source of CO_2 emissions from concrete (Naturskyddsföreningen, 2022). Hence, as much aggregates as possible should be achieved (Fernandez, 2022b). Also, because of the cost aspect, cement is the highest contributor to the cost of concrete. The strength properties of concrete are determined by the ratio of cement, aggregates, and water. A high water-cement ratio results in more liquid cement, while a lower water-cement ratio grants a viscous mix (K&E flatwork, 2023). Moreover, the size of the aggregates used affects the properties, where coarse aggregates increase the stability of the concrete. Further, coarse aggregates decrease the workability during the construction process. Also, it is essential to include fine aggregates to reduce the number of air voids, which decrease the strength of the material. Some factors during the production processes also influence the strength, and sufficient compaction is essential to avoid air voids. A temperature that is too high during drying quickens the process, leading to an incomplete chemical reaction. Lastly, concrete needs to be cured properly to ensure adequate bonding.

Concrete, unlike timber, is resistant to many external effects, such as fire and rotting, making it a durable building material. Another quality that makes concrete a favorable building material is its high thermal mass (Svensk Betong, n.d.). This allows concrete to absorb and store thermal energy and release heat when the temperature decreases. Because of this attribute, a more even temperature curve is achieved, and heat absorbed during the day can be released at night, decreasing the need for heating.

Moreover, concrete elements can either be cast on-site (in situ) or precast in advance in a factory. The use of precast elements has increased over the years, and the number of different structural elements being precast as well (Åfreds, 2018). It is especially common to use these elements in buildings with less demands regarding interior floor plans, such as car parks, shopping centers, and schools (Elliott, 2017). As mentioned, precast concrete elements are cast, cured in a factory, and transported to the construction site. The elements are cast separately and later joined, forming a finished structure on site. Whereas, in situ concrete structures are cast on the construction site. There are many advantages to using precast elements, where increased efficiency and time savings are two of the main.

Concrete slabs exist in different designs and have different properties. Some of these designs, such as hollow core, solid concrete, and filigree slabs, are presented and described in the following Sections.

2.3.1 Hollow core slab

Hollow core slabs are prefabricated pre-stressed slabs with round or more rectangular holes in the longitudinal direction. An example of a hollow core slab with round voids is shown in Figure 2.6. Concrete is strong in compression but is weaker in tension, when pre-stressing an element, the reinforcement is tensioned during production. The reinforcement is later released, generating compression forces in the concrete and increasing the tension strength of the element. Consequently, the risk of development of cracks is reduced (Great magtech electric, 2019).

Hollow core slabs are often produced with a width of 1200 mm, where several elements can be connected to create the desired width. The height can vary between 120 and 500 mm (Eilola, n.d.), and a span length of up to 18 m can be reached (Strängbetong, n.d.). Longer spans increase the flexibility of the building, allowing a change of activities without the need for remodeling. The voids in the slabs reduce the amount of concrete used, reducing the CO_2 emissions. The slab is pre-stressed at the bottom, whereas the top gets a rougher surface, which preferably is covered by a 20-50 mm concrete cover at the site (Svensk Betong, n.d.-b).

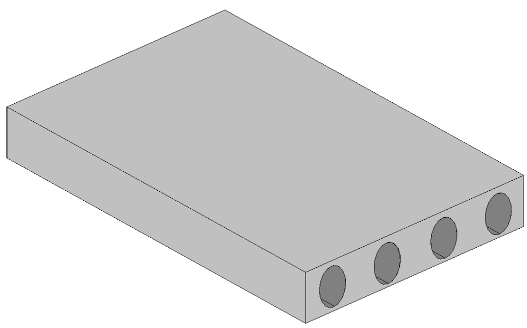

Figure 2.6: Hollow core slab

2.3.2 Solid concrete slab

As well as hollow core slabs, solid concrete slabs can be pre-fabricated and can be pre-stressed. A width of 3.2 meters can be achieved, and a pre-stressed slab can have a span length of up to around 10 m, whereas slack-reinforced slabs can be up to 5 meters. The large mass of the slab generates good insulation against the transfer of sound (Thors, n.d.). The pipes and electricity installation must be done before curing since the slab is completely solid. Consequently, the plan for constructing these installations must be done before casting, limiting the opportunity for late changes. Another option is to complement the slab with an installation floor, which will increase the thickness of the floor. Further, a solid concrete slab can also be cast in situ. When casting on site, the concrete slab is cast in a formwork. Using a cast in-situ slab provides flexibility since the installations are cast into the slab on-site, allowing for late changes regarding the placement of installations (Svensk Betong, n.d.-a). Also, by using cast in-situ concrete, seams can be avoided, which decreases the risk of thermal bridges. An example of a solid concrete slab is shown in Figure 2.7.

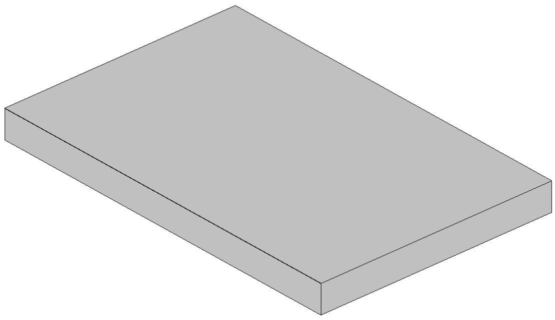

Figure 2.7: Solid concrete slab

2.3.3 Filigree slab

The bottom part of a filigree slab, shown in Figure 2.8, is pre-casted whilst the greater part is cast on-site (Svensk betong, n.d.). Like the solid concrete slab, the filigree slab can be pre-stressed or slack-reinforced. The reinforcement used is called lattice girder, which is cast into the pre-fabricated concrete during production. This reinforcement net interacts with the two concrete layers, creating a composite beam. By combining the two production methods, one can benefit from the flexibility of in-situ cast concrete and the advantages pre-casting brings, such as time reduction and quality-proofing (Prefabsystem, 2015). Furthermore, since the slab is cast on-site, pipes and electricity systems can be managed during casting on-site. Thus, difficult, expensive, and time-consuming modifications due to late changes of installations can be avoided.

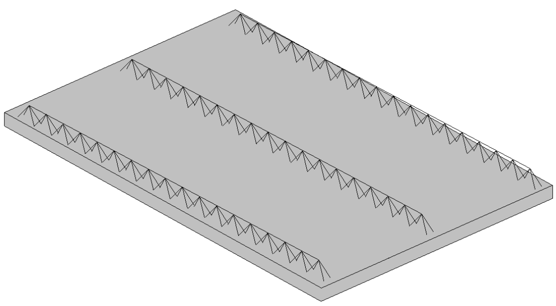

Figure 2.8: Filigree slab

2.4 Steel

Steel is a common construction material and one of society's most important industry-fabricated materials (Jernkontoret, 2019). Steel is not only an important component in the structural system but also during construction moments, such as in factories, trucks, tools, fasteners, and much more. Steel has a long service life, giving greater possibilities for reuse after demolition.

To receive the materials' desired properties, raw iron materials are essential during the manufacturing of steel (Jernkontoret, 2021). These raw iron materials consist of ore or scrap combined with alloying elements. In the production of ore-based steel, a reducing agent and a slag former are needed. Coal is used as the reducing agent, while lime serves as the slag former. Some of the steel's desired properties are, for example, corrosion and wear resistance. Steel structures can also be made stainless, and the difference in the materials is that stainless steel contains high levels of chromium (The Swedish Institute of Steel Construction, n.d.). The chromium enhances corrosion resistance, making stainless steel suitable in corrosive environments, such as acids and chlorides.

Steel structures require less material than timber and concrete buildings due to the high strength grade (ATAD steel structure corporation, n.d.). From the architectural perspective, steel offers significant creative opportunities. Since steel beams can handle extra long spans, the structure can manage to carry the load with fewer beams and columns. This flexibility provides more options for the layout of the floors and facade designs.

Some benefits of steel are that it is prefabricated, and there is little risk of damage during transport and handling (ATAD steel structure corporation, n.d.). The structures are fabricated in the factories as a total element and later transported and assembled on-site. Future structure alteration is possible since steel has the quality for a long life span. There is no risk of long-term effects of the material, such as for wood elements; wood is affected by bugs, termites, and mold, while steel is not. Structures are exposed to harsh weather conditions, and steel can manage to carry the load of powerful winds, heavy snow, and hurricanes with a smaller amount of material than concrete and wood.

The material is fabricated in different shapes to meet the specifications of a project. Various sizes and shapes, made by hot or cold rolling, are designed depending on the project's requirements. Steel components can be welded together on curved or flat plates. Some profiles used as columns can be hollow to stabilize and prevent buckling. Common steel shapes include I-beams, H-profiles, rectangular or circular hollow beams, and HSQ profiles.

2.4.1 Rolled structural sections

The steel could be either hot- or cold-rolled with different properties that affect the final steel product. Hot-rolled sections are produced at high temperatures and have a rough surface texture (SSAB, n.d.-a). The dimensions are less precise for hot-rolled sections than for cold-rolled. Cold-rolled steel profiles are recommended when the profile needs to be strong but lightweight with high thickness tolerance, straightness, and dimensional accuracy. Rolled sections are overall much used when constructing a building.

I- and H-beams are common steel profiles in a structural system (Yenaengineering, n.d.). Both steel profiles share similar mechanical properties and are often used in the same conditions. Although they are similar in appearance, they have different dimensional characteristics and load-bearing capacity, where the H-beam is better at resisting tension forces in compression while the I-beam is better at resisting lateral forces. Both steel profiles are prone to deformations in torsional, bending, and buckling.

The I-beams consist of two horizontal flanges and a connection vertical web, and the shape resembles the letter I as shown in Figure 2.9. An example of an I-beam is the IPE beam, often used for steel construction projects where the loads are heavy (Yenaengineering, n.d.). I-beams are extensively used as structural components in buildings to resist lateral forces. Those forces can, for example, be strong winds, where the beam shall prevent buckling during pressure. The weight of an IPE beam is lighter compared to a H-beam. This gives the IPE a lot of benefits with installation since it is more manageable. Such as easier relief from the machines and lifting cranes, which is a benefit.

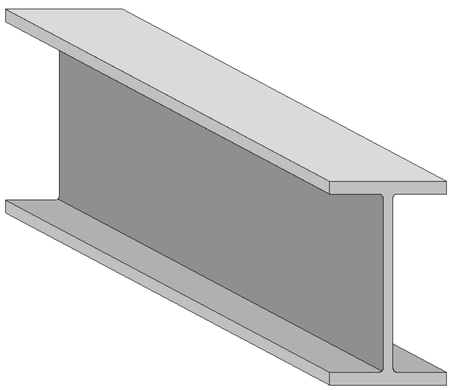

Figure 2.9: Example of IPE beam

The shape of an H-beam looks like the letter H with two side flanges and a vertical web, which can be shown in Figure 2.10. H-beams are well-suited to support loads of roofs and floors over long distances. (Yenaengineering, n.d.) Two commonly used examples of H-beams are HEA and HEB. The HEB beam is more rigid than the HEA beam. The beam can resist both tension and compression forces, making it ideal for structures that require support in the vertical direction. Due to the thicker web and flanges of the H-beam, it is heavier than the I-beam. The heavy weight can be challenging to manage during transport and construction on-site.

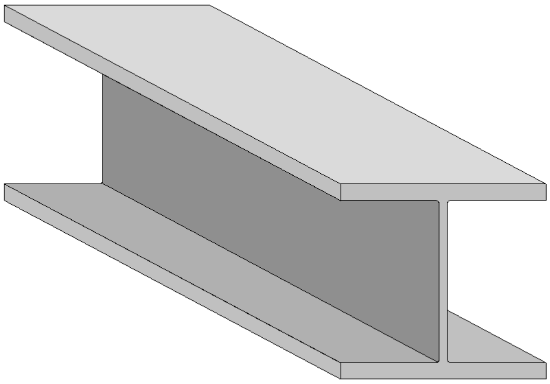

Figure 2.10: Example of HEA beam

2.4.2 Hollow structural sections

The most common shapes of structural hollow sections are rectangular, square, and circular with different thicknesses and sizes (SSAB, n.d.-b). These profiles has a high strength-to-weight ratio and behaves well in resistance to torsion, making it preferable to be used as a column. Compared to other steel profiles, a hollow core section requires less material due to its high strength-to-weight ratio, resulting in a lighter and cheaper solution. The geometry makes it able to withstand loads on various cross-sectional axes, providing great strength characteristics.

The production process of a rectangular steel section is formed at the pipework by either the steel's normalization temperature or the room temperature, depending on if it is a hot- or cold-rolled section (SSAB, n.d.-b). The product is shape-able at this temperature and can be formed into rectangular shapes with the desired corner radius (BE Group Sverige AB, 2022). The rectangular shape is shown in Figure 2.11. The steel has a homogeneous material structure regardless of the production method. It has the same characteristics throughout the whole cross-section. The rectangular and square profiles can be used as columns in structural systems.

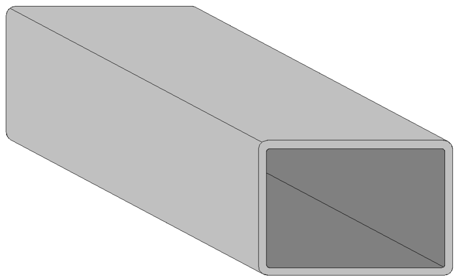

Figure 2.11: Rectangular hollow section

The circular hollow profile is also called steel pipe (SSAB, n.d.-c) and is presented in Figure 2.12. The process during manufacturing is the same as for rectangular shapes. The difference between these profiles is, for example, the load-bearing capacity in the axial direction, which is stronger for circular profiles (BE Group Sverige AB, 2022). The circular and elliptical hollow section is often used as support for bridge constructions. Due to its shape, it has high torsional stiffness and low wind resistance. In architectural aesthetics, the circular shape is preferred in exposed structures. The circular and elliptical profile can also be used in curved structures.

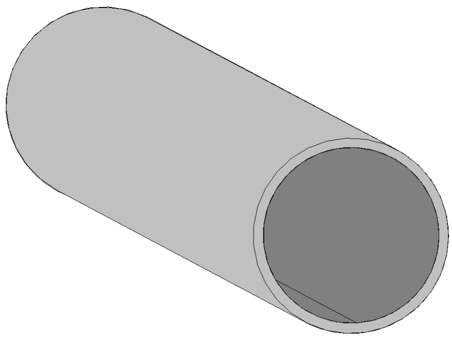

Figure 2.12: Circular hollow section

2.4.3 Welded structural sections

The design of the welded structural section can be customized to the function of the beam. It is preferable when the section's load capacity is under special difficulties (BE Group Sverige AB, 2022). Optimization of a welded structural beam can minimize the weight by 10%-20% compared to rolled sections (Stenmark, n.d.). Most of the time, the welding can be prefabricated, but in some cases, the welding has to be done manually in situ. The welding process is critical and requires high-quality execution of the weld (BE Group Sverige AB, 2022). Welding involves two steel components melted together, through heat with an additive material, into one unit. After melting, the weld is quickly cooled down by the surrounding's temperature. The most common welded structural section is the HSQ beam.

The HSQ beam is used together with different types of slabs, such as hollow core slabs and solid concrete slabs. Since the beam is placed in between the slabs instead of below, the HSQ beams can decrease the total slab height (BE Group Sverige AB, 2022). The shape of an HSQ beam increases the torsional stiffness of the structure and is often used in constructions with extraordinarily large spans and loads. The shape of an HSQ beam reminds of a hat-like shape, as shown in Figure 2.13.

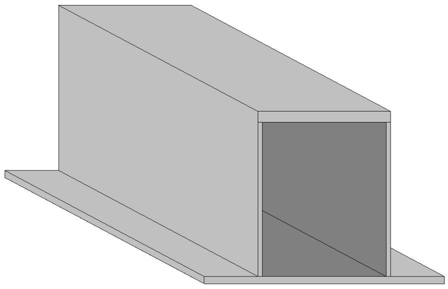

Figure 2.13: HSQ- beam

2.5 Load-bearing walls

The main load-bearing elements are described in previous sections. This section describes load-bearing walls and the supplementary materials that help provide better fire safety and sound insulation to the walls. When designing a load-bearing wall, the requirements of fire safety and sound insulation must be fulfilled, which can be done with several different solutions (Svenskt trä, 2017a). To achieve good sound insulation, all transitions and connections should be airtight. *The Swedish Institutes for Standards* has different requirements for different sound classes (Std Samhäll, 2024). The sound classes are sound class A to sound class D, where class A allows for the lowest decibel level. The minimum requirement for buildings is class C. Sound class D is only used in special circumstances and normally requires approval by local authorities. The sound environments of buildings are designed to protect the residents and users against disturbing noise, and sound class B is the most used sound class in residential buildings.

All materials are divided into fire resistance classes (Boverket PBL Kunskapsbanken, 2023). These classes describe the possibility of the fire spreading between different materials. It is used to secure the load-bearing capacity of the building in the event of a fire. There are two types of fire classes: how fast the fire spreads and how fast the material loses its bearing capacity. Both types are regulated by European standards. R15, R30, and R60 are examples of fire classes that describe how fast the element loses its bearing capacity. R stands for resistance, whereas the following number represents how the number of minutes an element can withstand the fire without losing its bearing capacity. The fire classes describing how fast the fire is spreading are ranked from class A1 to class F. Materials that do not contribute to fire development, such as concrete and stone, belong to class A. Materials that can prevent the spread of fire for a certain time, for example, painted gypsum boards and untreated wood panels, belong to class C or D. Materials that quickly cause the fire to spread are classified in class E, such as cellular plastic. Class F is for the worst fire-protected material.

Concrete walls and slabs can be precast, cast-in-situ, or a combination of the two. As mentioned earlier, concrete has good sound and fire resistance, eliminating the need for wall complements and reducing cost, maintenance, and time during production.

2.5.1 Solid concrete walls

A solid concrete wall can either be produced precast or cast in situ. Cast-in-situ walls are cast during construction at site, requiring a framework and time to cure, resulting in longer construction time (Prefabsystem, 2015). The curing process can take up to weeks and demands close monitoring. Also, the environment influences the curing time of the concrete. High humidity and lower air temperature slow down the curing process, and more time is needed (Gränne, Hedlund, Rapp, & Stelmarczyk, 2019). These aspects make the quality of the concrete more uncertain. On the other hand, the wall's properties can be adjusted for the specific project.

Precast concrete elements are cast in a factory, reassuring a high-quality wall, and are delivered directly to the site and ready for assembly. Further, the curing time in the factory is limited, and to shorten the curing time, precast elements may have a higher strength class than needed. To reduce the curing time, a reduction of water in the concrete mix is necessary, resulting in an increased amount of cement instead. The cement is the main contributor to the cost of the concrete; a concrete element with a higher amount of cement becomes more expensive. Moreover, as mentioned in Section 2.3, a higher amount of cement in the concrete mix generates higher CO_2 emissions.

An option of a cast in-situ and a precast solid concrete wall is shown in Figure 2.14 and 2.15, respectively. Both with dimensions for sound class B, if sound class C is wanted 20 mm less thickness is often accepted, more precisely a thickness of 180 mm and 200 mm respectively.

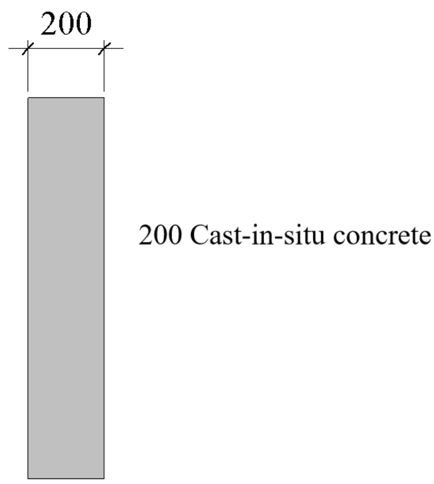

Figure 2.14: Cast-in-situ concrete wall

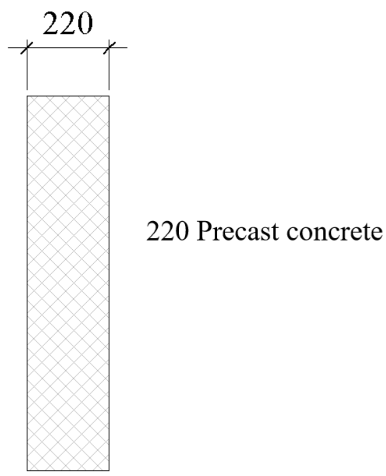

Figure 2.15: Precast concrete wall

2.5.2 Double wall

Like the filigree slab, a double concrete wall consists of a precast part, cast-in-situ concrete, and lattice reinforcement. Two panels are precast with connecting reinforcement, and the distance between these is decisive for the thickness of the cast-in-situ concrete part. On-site, the exterior panels act like a framework for the concrete poured in between. As mentioned in Section 2.3.3, there are several advantages to using a combination of in-situ-cast concrete, such as flexibility and high quality. Figure 2.16 shows a double concrete wall with sound class B.

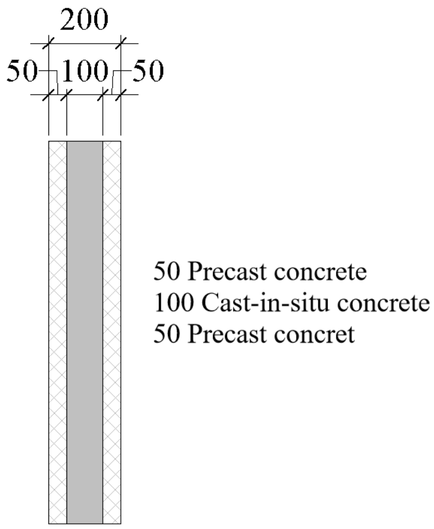

Figure 2.16: Double concrete wall

2.5.3 Sandwich wall

A sandwich wall, shown in Figure 2.17, consists of two reinforced concrete layers with insulation in between. By using concrete on both sides of the wall, good fire resistance and soundproofing are accomplished (Thomas Betong, n.d.). Concrete walls entail a steady indoor temperature due to the material's thermal properties, described in Section 2.3. Since the entire wall is pre-fabricated, the wall can be installed with electricity wires and windows put into place and painted before delivery, making the production at the site short and easy (K-Prefab AB, n.d.).

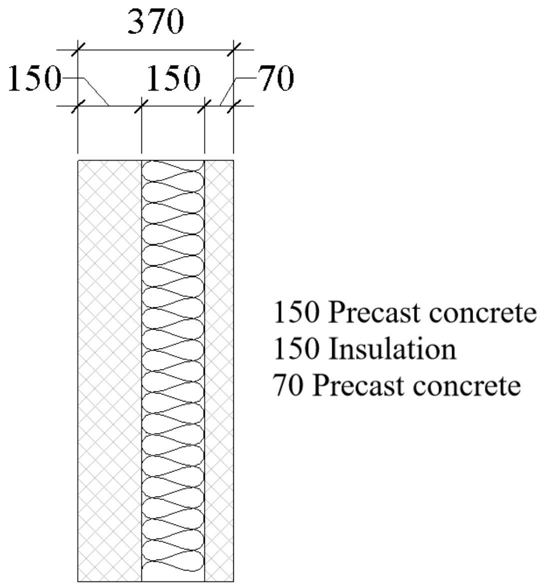

Figure 2.17: Sadwich wall

2.5.4 Solid wood walls

The structural elements of glulam and CLT can be used in load-bearing walls, but the wall has to be complemented due to the wood's low fire resistance. Two different types of walls are selected and presented. The first wall is a solid wood wall, shown in Figure 2.18, that consists of 15mm gypsum, 120mm CLT wood, 45mm of mineral wool, and an air gap of 10mm between the next repeated material on the other side. The wall has a total width of 370mm and has to carry its load during 90 minutes of fire. To protect the main load-bearing CLT element, fire protection of gypsum is added (Norgips, n.d.). To maintain sound class B, the isolation of mineral wool and an air gap is necessary.

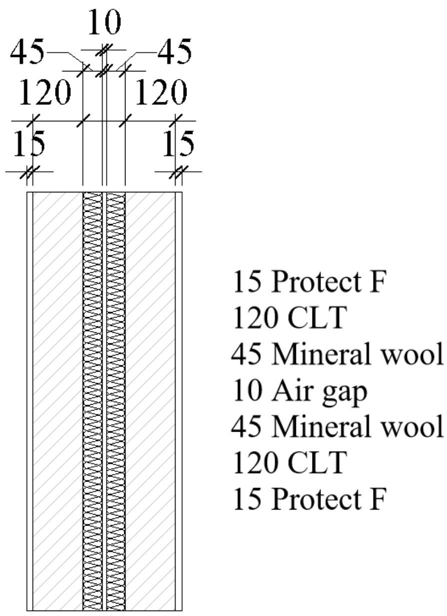

Figure 2.18: Solid wood wall

The second type of wall is a solid wood wall combined with timber studs. The first part, as shown in Figure 2.19, consists of the same as the first wall: 15mm gypsum, 120mm CLT wood, and 45mm mineral wool. The difference is a 20mm air gap with 95mm mineral wool, 95mm timber studs, 12mm plywood, and two boards of 15mm gypsum. The 15mm gypsum is also specialized to protect the structural element against fire for longer period of time than the 13mm gypsum (Norgips, n.d.). Each board of 15mm gypsum protects for 30 minutes; with two gypsum boards, it protects the load-bearing element for 60 minutes. This solid wood wall also fulfills the requirements for sound class B.

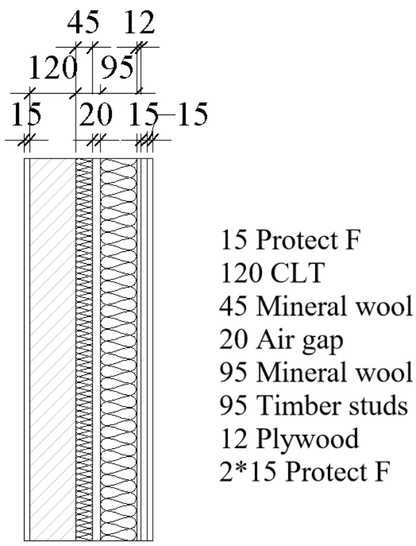

Figure 2.19: Solid wood wall with studs

2.5.5 Steel walls

Steel columns are used in the load-bearing wall, and to satisfy the demand for sound class B, the wall has to be complemented with gypsum. The steel column wall is built by a rectangular steel profile with mineral wool insulation of 150 mm and then three 15mm gypsum boards, shown in Figure 2.20. The thickness of the rectangular profile in this wall must be at least 6,3mm (Karlström, 2002). Steel is not a combustible material, but at high temperatures, it loses its load-bearing capacity (Norgips, n.d.). The larger and thicker the steel column is, the longer it takes to lose its load-bearing capacity, but at temperatures around 500°C, the steel retains only half of its original load-bearing capacity.

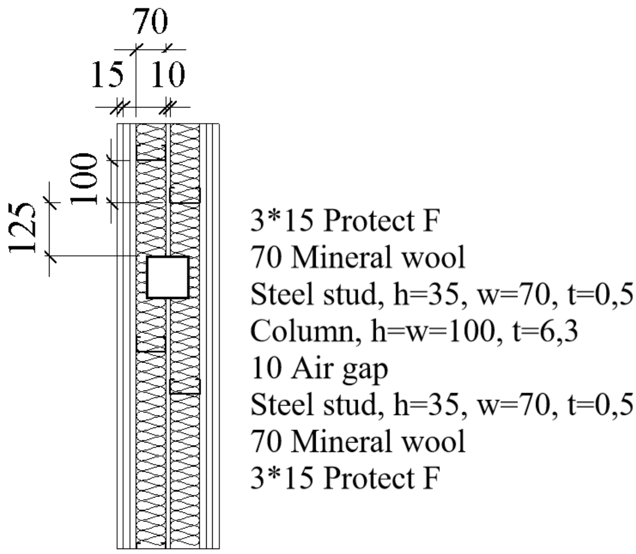

Figure 2.20: Steel wall with studs

3

Enivronmental impact

This chapter provides theory about structural systems' environmental impact and the differences in impact between materials and production methods during construction. It also describes life cycle assessment (LCA) and environmental product declaration (EPD) and how these are performed.

Each building contributes to a certain amount of carbon dioxide emission during its lifetime, the majority during the construction process (Boverket, 2019d). Material production demands a lot of energy, while transportation and construction contribute to fuel consumption. Several greenhouse gases contribute to the environmental impact. To be able to compare the emissions from different products or actions, greenhouse gases are recalculated to a single unit, CO_2 equivalent emissions.

The LCA data is compiled for a building to analyze the total environmental effect and which stage of the building's lifetime has the most effect on the environmental impact. The performance of an LCA in an early stage increases the possibility of reducing the environmental impact. An LCA can be processed in four stages: first, define the extent, then inventory resources, assess the actual environmental impact, and then interpret results.

To know the exact data, all projects do a resource compilation. This is often done in a financial calculator or digital model such as a building information model (BIM). These programs are gradually updated during the construction to follow up on the details. The program has to recalculate amounts to comparable units. The amount of each building component has to be converted to environmental impact, for example, square meters [m^2] to kilograms [kg]. These are then linked to various environmental data.

3.1 Life cycle assessment

Life cycle assessment (LCA) is often used to describe the environmental impact of a product during its whole lifetime. This process starts with "material extraction" and moves on to what is left after demolition. Another expression often used is "cradle to grave" (Matthews, Hendrickson, & Matthews, 2014). The life cycle assessment should cover all possible impacts, not only the material from the product produced but also factors such as transportation and resources used for production. A life cycle assessment is thus a comprehensive model, and a broad perspective regarding environmental impact is provided.

LCA is most often used during project planning of buildings or parts of buildings, where the construction and energy use in operation account for most of the emissions (Boverket, 2019a). Using an LCA at an early stage increases the possibility of controlling and reducing environmental impact. When performing an LCA, either generic or specific data can be used. Generic data is an average value for an element, whereas specific data represents the exact product used but requires more work to achieve. Often, generic data is used in an early stage and is later revised when further project planning is done (Boverket, 2019c).

As mentioned in section 1.1 Boverket has since 2022 requested climate declaration for every project made. To provide this information, an environmental product declaration (EPD) that specifies the LCA for a product can be used. In an EPD, the LCA is complemented with product category rules (PCR) specific for each product used and agreed upon between the different supply associations. The PCR includes guidelines regarding how the LCA should be performed and makes different EPDs for the same product comparable (Boverket, 2019b). The guidelines include boundaries for which processes and stages should be presented in the LCA. Further, what type of impact categories are current and some functional units describing amount and weight need to be addressed (The international EPD system, n.d.).

In the climate declaration, the climate screen should be considered, which includes parts that protect the building from the exterior environment, such as the roof, outer walls, foundation, doors, and windows (Boverket, 2023a). Also, all structural elements and inner walls should be covered. The foundation and parts, such as strengthening beams and ground insulation, are included, but other ground measures, such as piles and retaining walls, should be considered. The structural elements consider indoor and outdoor stairs, balconies, and ramps but not porches, which do not contribute to the climate screen of the building. Further, the climate screen includes inner doors, inner roofs, and inner walls.

3.2 The different stages

The Swedish Institute for Standards has divided the life cycle stages into different modules to identify processes and quickly enable product comparison (SIS - bygg och anläggning, 2011). The life cycle is first divided into four phases, *A, B, C, and D*, shown in figure 3.1.

A1-3 – Construction stage	A1 – Raw material supply
	A2 – Transport
	A3 – Manufacturing
A4-5 – Construction process stage	A4 – Transport
	A5 – Construction-installation process
B – Use stage	B1 – Use
	B2 – Maintenance
	B3 – Repair
	B4 – Replacement
	B5 - Refurbishment
	B6 – Operational energy use
	B7 – Operational water use
C – End of life stage	C1 – Deconstruction & demolition
	C2 – Transport
	C3 – Waste processing
	C4 – Disposal
D – Benefits and loads	

Figure 3.1: Different modules during a life cycle (Boverket, 2020).

As mentioned in Section 1.1, Boverket intends to 2027 introduce maximum values for CO_2 equivalent emissions during construction projects in to be able to reach "Net zero emissions" in 2045. Today, it is only required to provide a climate declaration for modules A1-5, including the process from raw material until finished construction. These limit values will be brought down gradually, starting with a limit of 20-30% lower emissions compared to the current limits for buildings. Moreover, Boverket also proposed including several other modules in the climate declaration to better represent the whole life cycle assessment. From module B, a suggestion is to add B2, B4, and B6; thus, these constitute a larger part of the total CO_2 equivalent emissions during a life cycle. Also, C1-4 is proposed to be included to bring further awareness and consideration regarding recycling and reuse.

As seen in Section 2, a structural member can be simple, like a solid concrete wall shown in Figure 2.14 and 2.15. Otherwise, containing several different layers of different materials, like a solid wood wall with studs represented in Figure 2.19. Since the climate declaration today includes modules A1-5, this thesis will focus on and discuss these further.

3.2.1 Module A1-A3

The modules A1-A3 constitute the construction stage of the material and elements. A1 contains the raw material supply, meaning the felling of timber or limestone quarrying. A2 includes the transportation of the raw materials to the factories, and A3 the manufacturing of the materials. Depending on how complete an element is when leaving the factory for the construction site, these modules contribute more or less to the total CO_2 equivalent emissions. For example, a precast concrete wall leaves the factory ready for assembly, whereas a cast-in-situ wall is transported as a liquid mass. Also, when choosing materials, all parts must be considered to obtain as low total CO_2 equivalent emissions as possible. A product may entail low emissions during raw material supply but is not locally produced, and long transportation is needed (Boverket, 2023b).

3.2.2 Module A4-A5

After the construction stage, the construction process stage starts, including A4 and A5, which represent the transportation from the factory to the construction site and the construction-installation process, respectively. The transportation in A4 only covers the transportation of the elements used for the construction, not the machines or sheds used. A5 includes all work made at the construction site, during building, fuels from machines, and in sheds. Further, the CO_2 equivalent emissions from any waste materials should be considered. Since choices apart from the material options also need to be regarded as the whole process should be planned (Sveriges rikstad, 2021).

3.3 The environmental impact from timber production

In the construction industry, wood from sustainable forestry is the only renewable building material (Swedish Wood, n.d.). Although regenerating trees takes between 100-200 years, the only resources needed for their growth are the sun and natural photosynthesis. The tree's life cycle begins with photosynthesis, which captures sun energy and releases oxygen (Swedish Wood, 2015b). Inside the tree, carbon dioxide from the atmosphere is converted into biomass. When dismantling wooden products, these could be reused, recycled, or used for energy recovery. The first priority is to find a way to reuse the material as much as possible to extend the lifetime. Wood is a great material since it can be ground down and remade into various other products. Waste material generated during production, such as wood chips, can be used to manufacture boards.

The carbon is attached to the tree until it decays or burns. This process can occur naturally through forest fires or during energy extraction activities. In the case of long-term sustainable forestry, the carbon dioxide will be captured by a new tree and converted to biomass (Swedish Wood, 2015b). Consequently, the extracted energy is classified as carbon dioxide neutral. This is the major difference from other building materials, where recycling the material is necessary from a sustainable perspective due to unnatural production with non-renewable material. From a financial perspective, high-quality wood products can be reused. Common reused products could be doors, wood studs, or large beams.

When evaluating different possible material choices with, for example, the LCA method, the recoverable energy from timber can be considered a resource (Swedish Wood, 2015a). The difference in environmental impact depends not only on the material but also on the design and construction technique. There are several different aspects to take into account to achieve reduced environmental impact. Still, it's generally observed that the energy consumption from raw material extraction to the completion of a building is lower for wood construction compared to concrete or steel construction.

3.4 The environmental impact from concrete production

As mentioned in Section 2.3, concrete consists of aggregate, cement, water, and additions, where the cement process contributes to the significant part of the CO_2 equivalent emissions of the material. Cement production constitutes 8% of the world's total CO_2 emissions (The research institute of Sweden, n.d.). The major part of the CO_2 equivalent emissions from cement comes from the heating of the limestone. During the heating of calcium carbonate (limestone), $CaCO_3$, carbon dioxide, CO_2 is released. The remaining product is calcium oxide, CaO, which is later used as cement. If fossil fuel is used during heating, the high level of CO_2 equivalent emissions increases further. One ton of cement generates 700-800 kg of carbon dioxide (Naturvårdsverket, 2022).

To lower the CO_2 equivalent emissions of concrete, other binders with less environmental impact are more and more frequently used. Supplementary cementitious materials (SCM) is an umbrella term for supplements with the same binding qualities as cement. The two most commonly used SCM are fly ash and slag. Besides reducing CO_2 equivalent emissions, using fly ash in concrete brings several benefits. When using fly ash, less water is needed, and the risk for chloride penetration is reduced (Thomas, n.d.) Slag is a decay product from usage blast furnaces during steel production (Heidelberg Materials, n.d.). Using slag improves the long-term strength and increases the durability of the concrete (American Concrete Institute, n.d.). However, the short-term strength is lower compared to when only using cement and when including slag and fly ash. Further, even though the material cost is lower for both SCMs, the hardening time is longer, resulting in a higher construction cost. Due to the long hardening time, only a certain amount of the cement can be replaced by SCM. Today, a replacement of 65% of the cement can be used depending on the use of the concrete.

3.5 The environmental impact from steel production

Steel is produced from either iron ore or scrap, and its production contributes to different gas emissions, with carbon dioxide being the most significant (Jernkontoret, 2022). During the reduction of iron ore, the majority of carbon dioxide emissions are released. In production, blast furnaces and ironworks are used to reduce iron. When using blast furnaces, a reducing agent consisting of carbon, is needed. This process and the extraction account for approximately half of the energy consumption in the steel industry.

The high temperature released from the heat furnaces, combined with nitrogen, which is present in the air from the combustion of fuels, contributes to the formation of nitrogen oxides (Jernkontoret, 2022). Nitrogen oxides contribute to eutrophication, which damages the water and soil (Naturvårdsverket, 2024a). These oxides also irritate the human respiratory tract. Oil combustion in the industry increases sulfur dioxide emissions, which forms sulfuric acid. (Naturvårdsverket, 2024b). Sulfur dioxide can also cause respiratory issues, such as nitrogen oxides. In large quantities, sulfur dioxide can contribute to a negative impact on the seawater and also the quality of the drinking water.

Another influencing factor formed during manufacturing is the dust from metals such as zinc, chromium, and nickel (Jernkontoret, 2022). However, the filters for separating dust particles have improved with the development of purification technology. The filter development has led to a reduction in dust emissions. Resources from the seawater are used to cool the heat furnaces during heat treatment. While this process does not directly release harmful emissions, it can negatively impact the sea wildlife, which can be affected by rapid temperature increases in the water.

4

Genetic Algorithm

A genetic algorithm is a data management sorter inspired by natural evolution where the most adapted individual reproduces (Mallawaarachchi, 2017). Charles Darwin's natural evolution theory, proposed in the 20th century, involves a selection process in which the fittest genetics for the surrounding conditions propagate in a given environment, causing the less adapted individuals to die, which leads to improved development. The genetic algorithm process is based on different stages, presented in this project as identified solutions, fitness functions, selection-, crossing- and mutation phases.

This thesis explores the prerequisites of using genetic algorithms to generate different solutions for structural systems. The potential for the genetic algorithm is significant, as it can be applied in many different areas and improve factors such as the time aspect, material costs, environmental impact, and more.

4.1 Use of Genetic Algorithms

Genetic algorithms are common in information analysis of computer science, such as automated design and robotics (Baeldung, 2023). The algorithm can help the robot generate optimal decisions. Artificial intelligence (AI) can be trained to decide between those suggestions to find the most optimal solution. It is also useful in other areas, such as economics, scheduling tasks, marketing, and logistics. Manufacturing companies may have specifications on how a certain product should perform, and then GA can derive design proposals that satisfy these specifications. Vehicle routing can produce examples of transport systems that generate routes requiring the least resources. To make a successful product, the marketing has to reach the target group. The algorithms must sort the search history to match the product with the right customer to find the right target group. This could also be effective while putting a schedule together. For example, when a university has a lot of students and teachers with different courses in different lecture rooms that should match, the GA can generate solutions that fulfill the requirement.

Genetic algorithms have also been used for structural optimization purposes. Previous studies focus on the visualization of the structure and the geometry of grids to find the most optimized one regarding span length and sizing. In *A genetic algorithm tool for conceptual structural design with cost and embodied carbon optimization*, Kanyilmaz A. et al. (2023) designed a tool that uses genetic algorithms (GA) to analyze structural systems using different steel, concrete, and timber members. The tool was used to find the most optimized system based on cost and CO_2 equivalent emissions by letting GA create different systems in terms of geometry for each material. The result was that both cost and the carbon footprint could be reduced significantly by choosing well-fitted materials and structural systems.

Genetic algorithms solve specific problems implemented with a customized approach (Daniel Shiffman, 2012). The algorithm works similarly but can be applied and trained for different purposes. The most common ways to implement genetic algorithms are the traditional algorithm, interactive selection, and ecosystem simulation.

4.1.1 Traditional Algorithm

The traditional way to implement genetic algorithms is to sort a group of solutions based on a criterion that describes how adapted the solution is (Daniel Shiffman, 2012). This can be explained by, for example, figuring out a code. If a long list of numbers were presented, the task would be to figure out the combinations of these numbers. Finding the entire combination randomly would take a long time. However, if each correct number were indicated when matching the proper position, the algorithm would more likely be able to figure out the rest of the combination faster. In other words, the algorithm receives indications when it approaches the established criteria and thus can sort solutions by adaptation faster. Another way to explain traditional genetic algorithms is by imagining a population of solutions indicated by color scales, where each solution is presented with a specific color that presents the level of adeptness at the color scale. The scale could, for example, contain different shades of red, yellow, and green, where the red indicates a result far from the predicted criteria, while the green highlights that the convergence criteria are met.

4.1.2 Interactive Selection

Unlike traditional algorithms that analyze ready-made alternatives, interactive selection implements the process of generating solutions through user interaction (Daniel Shiffman, 2012). The algorithm is trained to evolve solutions based on the user's preferences. The interactive selection is, for example, generally used in visual perspectives where the user indicates which objects are preferred or not. Interactive selection can be described by imagining an album of images of a specific object. If the user chooses a particular type of appearance of this object, the algorithm can generate new images of the object that simulate these.

4.1.3 Ecosystem Simulation

In artificial intelligence research, the previously described implementations are discoverable, but not so much of the ecosystem simulation. In contrast, ecosystem simulation is an essential implementation of the genetic algorithm method (Daniel Shiffman, 2012). Genetic algorithms, in particular, include evolutionary theories that incorporate ecosystem modifications. Ecosystem simulation is a mathematical representation of an ecological system. The ecological system contains individuals divided into different populations and communities. These populations are studied through gathered data to predict the dynamics of a natural system. Many different individuals exist in the ecosystem, some of whom depend on each other's existence, and some do not. The factors that influence the surviving individuals are unpredictable and sometimes depend on entirely random factors. Therefore, training the algorithm to utilize variation and mutation functions is significant for ecosystem simulation. The primary purpose of the simulation is to study how the genes are passed on to a new generation by different individuals, whether it can be predictable or not, and then apply the method to the algorithm.

4.2 The algorithm process

For the algorithm to be generated, it must follow a process, shown in Figure 4.1. The process describes the identified population, selection phase, and reproducing process. The individuals in the population are evaluated throughout the process to achieve the matching criteria. The algorithm's process is carried out to improve the solutions, but in some cases, the initial individual may be the most adapted. Therefore, these individuals are also included in the evaluation.

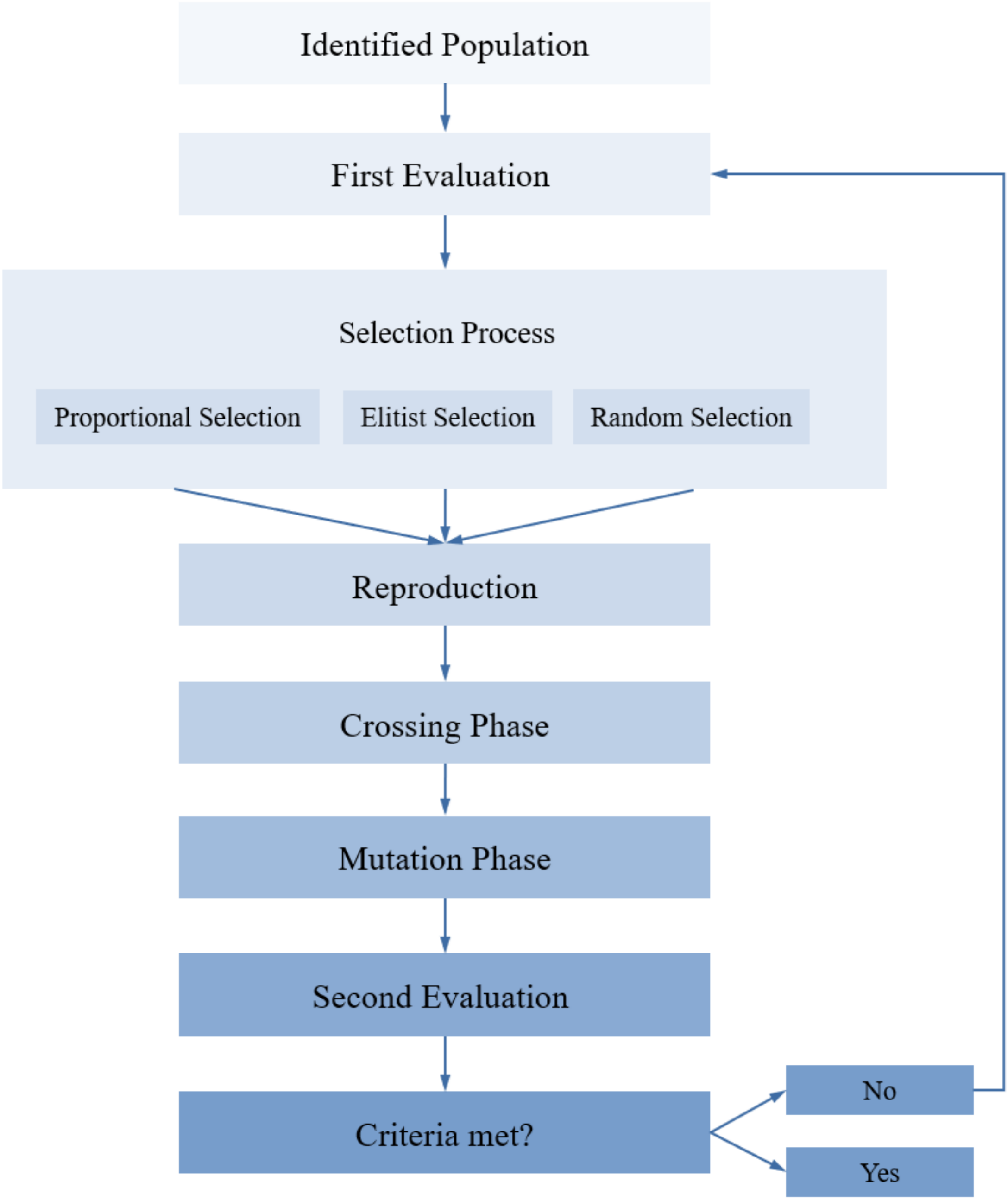

Figure 4.1: The process of the algorithm

4.2.1 Identified population

To create a population, it is necessary to include enough variants to achieve the final requested creature (A.E. Eiben & J.E. Smith, 2015). For the algorithm to create, for example, a specific word, the letters need to exist among the population to be possible for the word to be generated. Therefore, it is essential to have a broad base population. These populations can be generated by almost any object, from number combinations to a bicycle or a piece of visual art. Each creature or object has various properties that describe how it looks or behaves. When these properties are to be described, it can be done through genotype and phenotype. The genotype describes the structure of how the individual's characteristics are stored, for example, through the implementation of the code. On the other hand, the phenotype is what the trait itself is supposed to represent, such as color, height, or size.

4.2.2 Selection phase

A selection process identifies the most adapted individuals (A.E. Eiben & J.E. Smith, 2015). Different methods are used to generate a new population, for example, through various crossings and mutations. This procedure continues till the convergence criteria are matched. The selection phase is divided into the evolution and genetic algorithm- selection phase. The reproduction part includes the crossing and mutation phases.

Darwin's evolution theory describes the three main principles that must be implemented in the algorithm for natural selection to occur (Daniel Shiffman, 2012). Those three principles are heredity, variation, and selection. **Heredity** describes how traits of the creatures are passed over to the next generation of existence. The **variation** of properties among the population is necessary to develop the creatures. If all creatures in a population look and behave the same, the new generation will behave identically to the old generation. This results in no new combinations of properties, and the creatures will not evolve further. The **selection** phase describes which individuals in the population get the opportunity to pass down their characteristics to the next generation. Through the ages of evolution, this selection has depended on the ability to survive. It does not necessarily have to be the strongest, biggest, and fastest individual, but characteristics such as hiding or the ability to find food could be crucial.

The first step in the algorithm selection phase is identifying how well-adapted or "fit" the individuals are. The identification can be made through distributed points with a scale or by passing certain tests (A.E. Eiben & J.E. Smith, 2015). In nature, it is not a score of points that determines whether an individual survives. Still, when coding an algorithm, an object rating is required to sort the population according to performance. Once the scale identification has been performed, the selection is initiated. The selection can be done in several ways, for example, through random, elitist, or proportional selection.

The most straightforward method is **random selection**, which randomly pics the parenting individuals (A.E. Eiben & J.E. Smith, 2015). The transferred genes used for the new individual are also chosen randomly. When using this selection method, all individuals have an equal chance of passing their elements on to the next generation, ensuring a great diversity of solutions. This method generates many options that can be difficult to sort, but on the other hand, a wide variety among the solutions is generated, which is positive.

The **elitist selection** uses only the best-performed individuals to reproduce (Daniel Shiffman, 2012). This can be done in different runs, either by, for example, taking the best two individuals and generating multiple offspring or by selecting the 40% best performers and using these for reproduction. The runs can be determined depending on the size of the population. Suppose the population contains a large number of individuals. In that case, choosing a higher number of reproducers is preferable. Still, if the population only consists of, for example, ten individuals, it may be more reasonable to choose a specific number of reproducers. However, it can be challenging to decide where the limit of the amount of reproducers should be set. If the new generation is only produced by a small proportion of the population, it contradicts the variation principle.

Proportional selection compares the individual's fitness, where a high fitness value gives a greater chance of becoming a parent for the next generation (Daniel Shiffman, 2012). A usual way to demonstrate this is by a "wheel of fortune," where each solution with a fitness score is expressed as a percentage. This method is preferred since all individuals still have a chance to participate in the reproductive process but with different probabilities according to performance. Both score-based selection and variation are included in proportional selection, making it an excellent approach. Since lower-score solutions can contain some functional elements, these must not be eliminated. In the method, the individual with the highest score has the highest percentage to be chosen in the spinning wheel.

4.2.3 Crossing phase

When the initial reproducers are selected, the individuals are crossed to generate a new population (A.E. Eiben & J.E. Smith, 2015). Which crossing method is used affects the result of the new generation. Here are some of the most common crossing methods used for GA described. An unusual technique to use is, for example, to inherit properties from only one parent, which makes the newly generated individual the same. Otherwise, it is more common to use two parents who cross their genes to create an individual with specific characteristics. One way to cross the genes of two individuals is to take half of each and add them together (Daniel Shiffman, 2012). In this case, which specific genes must be taken from which parent must be determined. For example, if the object is a four-letter word, it can be decided that two letters from each parent are to be inherited. To increase the variants to an even greater extent, the crossing can be set to, for example, 75% genes versus 25% genes. All different percentage sizes can be used to develop the new generation. All genes could also be randomly selected between the parents.

4.2.4 Mutation phase

The mutation phase is a function of variations, which allows the new solutions to combine elements that differ from the parent solutions (A.E. Eiben & J.E. Smith, 2015). This is important due to the invention of new properties that otherwise would not have been combined. The mutation phase is optional as it is only necessary in some algorithms. Mutational elements cannot extend beyond the specified element in the initial population. However, an element can be generated as a mutation from a different existing individual that does not belong to the two selected parents (Daniel Shiffman, 2012). It is measured in the percentage probability of replacement of the element, such as 15%, 10%, 5%, 1%, or 0,1% probability.

4.3 Multi-objective problems

A multi-objective problem contains multiple objectives, which the solutions should consider. Some considerations must be made when trying to find the most optimized solution based on two objectives. The most optimized solution might not be the best if the criteria were considered separately. To represent the relationship between the objectives, a weighting of the criteria has to be considered to find the most optimal solution. A **fitness function** seen in Equation 4.1, is used to evaluate the weighting of the objectives, where the objectives f_1 and f_2 are multiplied by the weighting functions a and b. The weighting is not constant and depends on the current problem.

$$F(x) = af_1(x) + bf_2(x) \tag{4.1}$$

4.4 Flexibility of inputs

Inputs can be implemented based on fixed requirements to present relevant solutions. The inputs can either be a fixed value or implemented as a maximum-minimum span. Further, a penalty function can be used to include solutions that do not meet the demands of the inputs. A penalty function is used to lower the fitness of a solution that does not fulfill the set requirements of the inputs. The penalty method is described in Equation 4.2 where $f(x)$ represents the objective function, $p(x)$ the penalty function, and λ controls the penalty function.

$$P(x) = f(x) + \lambda p(x) \tag{4.2}$$

5

Methods

The study contains two different methods, shown in Figure 5.1, that support the research work and the prerequisite for creating the software. The first method, which is the workshop, is mainly used to receive opinions about how the software shall be designed and what parameters the structural engineer values. This is crucial to make the software user-friendly and with the correct conditions. The workshop was divided into a questionnaire part and a discussion part, presented in more detail in 5.1.2. The other method, which is the database, is where all the data is collected for future software. The database presents all the information necessary to create different structural systems. This includes structural bearing capacity, climate impact, and cost. The survey was divided into themes that were included in different categories presented below.

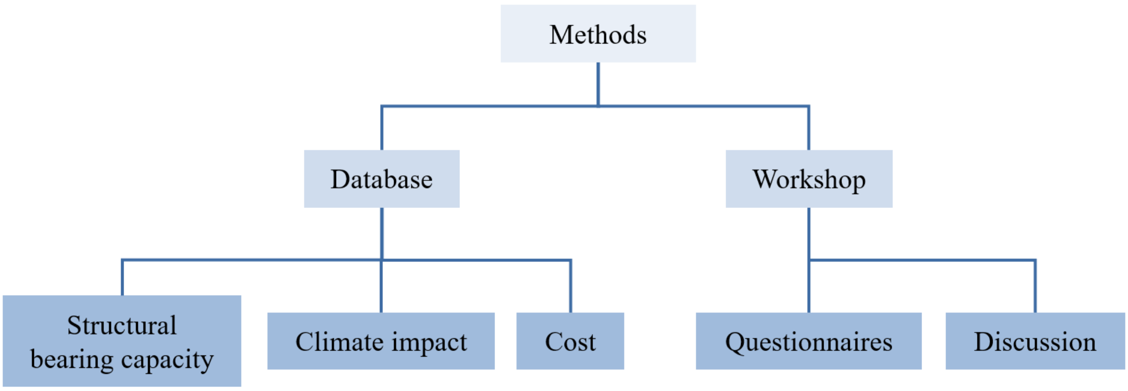

Figure 5.1: The method process

5.1 Workshop

Three separate workshops were conducted to gather information regarding what elements should be implemented, the design, and the structure of the software. The workshop method is effective for collecting data and information in a short period of time. Experts in the subject use it to form a vision of the possibilities of future software.

The future workshop is a method developed by Robert Jungk, Ruediger Lutz, and Norbert R. Mullert and consists of four phases: the Preparation, Critique, Visionary, and Implementation phase (Jungk & Müllerts, 1998). The method is used as an inspiration for the structure of the workshop by first critically reviewing the challenges of the software. Later, discuss what opportunities the software could bring, and lastly, analyze what is needed for the software to be useful.

5.1.1 Workshop categories

The questions asked during the questionnaires and the discussion were divided into different categories; therefore, five categories were selected. These five categories are elements, fitness function, input/flexibility/outputs, usability, and future.

The first step to creating the database is to investigate which structural **elements** are most used by structural engineers and, therefore, should be implemented in the software. A literature study was performed to find the most useful elements from the websites of industry-known suppliers. The software is supposed to be able to adapt new structural elements in the future. The first questionnaire contained questions regarding various structural elements, and the participants stated on a scale how commonly used said elements are. The scale is a personal perception of how commonly the elements are used in projects.

The **fitness function** reflects how the user or the industry values the cost and CO_2 equivalent emissions aspects against each other. This was brought up during the discussion to understand how these factors are handled in different stages of the planning process and what affects the valuing. The fitness function impacts the fitness of a solution the software and, therefore, was an important theme to investigate.

To understand which factors the choice of a structural system is based on, a discussion considering possible **inputs** arose. The inputs are entered into the software, and the solutions performed should fulfill these requirements to be considered a useful tool. The **flexibility** considers to which extent the inputs need to be fulfilled. Some inputs might be assigned a set value early in the process and can not be modified, whereas other parameters may retain more flexibility. Which inputs belong to each category and how they should be handled in the software were an important investigation for the software to become relevant for structural engineers. How the **output** is presented is consequential in ensuring the trustworthiness of the software. Further, the output should describe the differences between elements and the result in cost and CO_2 equivalent emissions.

Usability is a theme raised to investigate to whom and at what stage the program can be helpful. The idea is that a structural engineer should be able to use the software as a fundamental basis when choosing structural systems. Therefore, a study was needed to understand how structural engineers prefer integrating the software into their work. The **future** theme explores potential adaptations the software might adopt in the future. The software should integrate further aspects in the future, making it important to study possibilities and features.

5.1.2 Workshop arrangement

The first method consists of three workshops, which include two parts: a quantitative study, where the participants got to answer questionnaires, and a qualitative study, which includes a discussion. All three included the same approach and material, where only the participants differed. The workshops were carried out in the following order:

- Questionnaire 1
- Presentation of the research and genetic algorithms
- A semi-structured discussion
- Questionnaire 2

The participants consisted of structural engineers with at least 10 years of experience in structural engineering and conceptual design. In each workshop, six participants were split into two groups during the discussion to include as many different opinions and thoughts as possible. One workshop included employees from a building contractor company and the other workshop consisted of employees from a consulting company. In Figure 5.2, the participant's experience is presented. Both the two questionnaires and the discussion included these five different themes described below.

The purpose of Questionnaire 1 was to gather information about how the construction industry works today and to collect information regarding design choices from a structural engineer. This questionnaire required no previous knowledge of genetic algorithms. Following a short presentation about the thesis and an introduction regarding genetic algorithms and the implementation in the software. The presentation intended to provide basic knowledge about the topic to facilitate the following discussion.

The discussion followed a semi-structured approach, focusing on predetermined topics while allowing for follow-up questions and including additional information beyond the direct questions. The workshop ended with Questionnaire 2, which included questions about the discussion to gather concrete thoughts and opinions about the different topics.

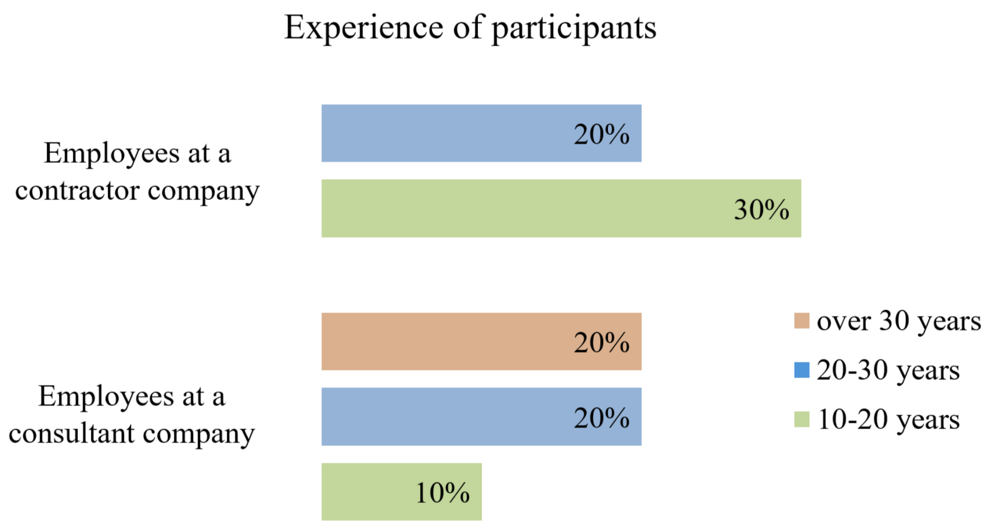

Figure 5.2: The participant's experience in years

5.1.3 Structure of questions

The questions used during the workshop are presented in Appendix A. Questionnaire 1 contained questions Q1-Q8, which are presented in Appendix A.1, Questionnaire 2 questions Q9-Q25 in Appendix A.2, and the discussion D1-D9 in A.3.

In Questionnaire 1, questions Q1 to Q6 were asked to gather information regarding what **elements** should be prioritized to implement in the software. A rating scale question was used for each structural element to understand the relation between how used the elements are. Question Q5 investigates if the same elements are often used due to the preferences of the construction company or if the options of structural elements are limited because of the architect's floor plan. This question was formed as a ranking question to understand the commonness of each factor that might affect the choice of structural element. Question Q6 was asked to identify if some element combinations should be avoided and whether certain elements should be excluded from specific parts of the building.

Questions Q8, Q20, and D3 studied the theme regarding **fitness function**. In question Q8 the participants got to estimate how the industry weighs the cost versus climate impact today. This question was asked to understand how the fitness function should be handled in the software. Further, in question Q20, the participants were asked whether the fitness function should be easily changed since the weighting could vary depending on the specific project.

In questionnaire 2, the aspect of **inputs, flexibility, and outputs** was explored through different questions. Questions Q9 to Q17 investigate how the inputs should be implemented in the software. The aspect is brought up to provide information regarding conditions that structural engineers usually must consider. The participants were asked to specify the desired level of precision for describing the input. To define how flexible the inputs shall be, questions Q18 and D2 discussed this topic. Lastly, questions Q21, Q22, and D5 addressed how the outputs should be presented. Depending on how the inputs are implemented, the output will be affected. The workshop discussed how structural system solutions should be presented and the level of detail required to ensure reliability for a structural engineer.

Questions Q7 and Q23 asked how **useful** the software is considered to be, whereas Q7 was asked in Questionnaire 1 before the introduction to the subject and Q23 after the presentation. The purpose was to receive information regarding whether the approach to the software changes when learning more and discussing the opportunities of the software. Question Q24 was an open-ended question asking how the software could ease the work of a structural engineer. The aim was to understand the opportunities participants envisioned the software could offer and to guide the design to achieve these objectives potentially. Further, question Q25 was asked to gather opinions considering the software's use and design challenges. Discussion questions D1-D4 and D8 also investigated the usability of the possible software.

Question Q19 collected ideas for **future** software approaches and other parameters used to evaluate the structural system. It also provides proposals for topics that may not have been already covered. The future aspects were also discussed during questions D6, D7, and D9 after the participants had received more information about the software.

5.2 Analyze

Throughout the workshop, the analysis has been handled thematically. Thematic analysis involves constantly and properly identifying connections between different answers to categorize them (Kvantila, n.d.). This method is a form of qualitative content analysis where data is sorted and organized according to distinct patterns. The questionnaire consisted of three types of questions, and an analysis was performed for each type of question. Partly through multiple-choice questions, some open-ended questions, and lastly, discussion questions. These three types of questions were used to achieve sufficient information. When performing the questionnaires, the information was gathered by the platform Survey Monkey. The data were analyzed differently depending on the type of questions, which are described below.

5.2.1 Multiple choice questions

The multiple-choice questions were designed to limit the answers to the same options. The limiting simplifies the process of analyzing the answers since it produces concrete results. The questions contained several choices of answers, making it easy to compare the results between different participants. The questions also introduced all the participants to the same ideas and created the same prerequisites for each participant. The data were collected by compiling the results and creating representative relationships between the alternatives. Where the answer with the highest score from the participants represents the highest-ranked answer. Based on the result, conclusions can be made if there is a pattern between certain participants and their answers.

The rating, likert, and ranking scales are examples of multiple-choice questions used in the questionnaires. In the rating scale, the participants rated a specific element's commonness in residential buildings. Rating questions were structured on a scale between zero and one hundred percent. The rating score for each element was compiled and compared to achieve a reasonable result. The likert scale, instead, was used for reasoning questions where the participants answered on what level they agreed with an argument. The scale of the agreement usually starts at a low extent and expands through five levels to a high extent. These questions are analyzed by calculating the average result of each agreement. Ranking questions consist of alternatives that can be ranked depending on which alternative best fits the question. For example, if there are five alternatives, these are ranked from the most relevant answer to the least relevant answer. Each ranking position corresponds to a certain score, where the alternative with the highest total score is considered the most representative answer.

5.2.2 Open-ended questions

To complement the multiple-choice questions, some open-ended questions were included, allowing participants to mention additional alternatives. This approach enabled participants to add their own options when the provided choices did not fully represent their views. The answers were written in text format by the participants, and no specific alternatives were implemented, which made the participants unaffected. The answers are then sorted and compared to each other, trying to discover similarities or differences. If either similarities or differences exist, reasons for influencing effects are discussed.

5.2.3 Discussion questions

The workshop included a discussion part, dividing the participants into smaller groups. The discussion was semi-structured, and some predetermined questions were asked to introduce topics. The discussions were recorded and then digitally transcribed. The transcription was made in a document, collecting all the discussion groups' answers. Similar to the previous analysis, the differences and similarities were discovered to categorize the themes of the topics and draw conclusions. Interpretations of the argument in the discussion were made to provide and generate compilations.

5.3 Database

To evaluate the structural systems against each other in the software, a database with information concerning costs and CO_2 equivalent emissions is needed. Therefore, climate data from Boverket is used to supply information regarding CO_2 equivalent emissions. The price for each structural member includes the material cost, production cost, and the cost of the construction work and it is provided by one of Sweden's biggest construction companies. Furthermore, interviews with LCA- and calculation experts to understand how calculations are carried out. Both cost and the CO_2 equivalent emissions are provided for each material separately and later assembled creating elements.

The structural systems generated will be based on the elements implemented in the database created, where each individual is a structural system consisting of slabs, walls, columns, and beams. The most used elements described in Chapter 2 and additional elements will form the population of structural systems used in the software. There are some constraints to the different elements. For example, different slabs have different maximum spans due to material properties. With an increase in the thickness of a slab, a longer span length can be achieved, but only up to the maximum span length. The different span lengths of the slabs affect the geometry for other structural members, e.g., a system with larger spans requires fewer columns or bearing walls, which in turn will have greater dimensions than a system with more vertical bearing elements. Different systems using the same elements with different dimensions can be analyzed to find the most favorable one.

The cost and CO_2 equivalent emissions depend on the amount of material used, which depends on several factors. To ensure a certain sound class, materials can either be added to an element or the thickness of the structural element can be increased. Moreover, a higher structural bearing capacity and longer span widths also increase the amount of material. The database will, therefore, be provided with information to guarantee these inputs will be met. Further, standard dimensions for structural elements will be used to ensure buildability.

5.3.1 Climate impact

The database is made in Excel to be easily accessible and user-friendly. Excel is an industry-leading spreadsheet program that is commonly used (Microsoft, n.d.). In the database, the elements are divided into four categories: slabs, load-bearing walls, columns, and beams. In each of these categories, the materials are presented for every element.

The option of adding climate-improved concrete is available, reducing the environmental impact in A1-3, the production stage. The user can choose between 0% 10%, 20%, 30%, or 40% climate-improved concrete. This means that the CO_2 equivalent emissions from the concrete will be reduced by the assigned percentage. A higher sound class is achieved for concrete and solid timber elements by increasing the structural element or adding additional material, such as step-sound carpets. The fire resistance class can be increased by adding gypsum fire boards, insulation, or painting. The thickness and, therefore, the amount of material used will change depending on the sound class.

The environmental impact will be represented by CO_2 equivalent emissions, which in the Boverkets climate database are presented by the unit [kgCO_2e/kg] and are provided for modules A1-3, A4, and A5 separately. The unit later used in the software to compare elements will be a generic value represented by the unit [kgCO_2e/m^2] or [kgCO_2e/m] depending on the element. For each material in each element, the CO_2 equivalent emissions have been calculated.

$$\sum m_{i,CO_2} = (e_{i,A1-A3} + e_{i,A4} + e_{i,A5}) \cdot m_{i,material} \tag{5.1}$$

Where:

- i=each material included in the element
- m_{i,CO_2} is the climate impact for each material presented in, [kgCO_2/m^2] for slabs and walls, and in [kgCO_2/m] for columns and beams
- $e_{i,A1-A3}$, $e_{i,A4}$, and $e_{i,A4}$ is the generic factor for each module for each material presented in [kgCO_2/kg]
- $m_{i,material}$ is the mass of each material presented in [kg/m^2] for slabs and walls, and in [kg/m] for columns and beams

5.3.2 Cost and bearing cpacity

The cost of the structural elements is provided by one of Sweden's biggest construction companies. Further, information regarding dimensions, span length, and bearing capacities are gathered from suppliers. To increase the number of systems generated, the database will be provided with different dimensions for each element. Information regarding the structural bearing capacity of each element will need to be implemented in the software to allow the model to present systems that withhold the assigned load. Further, the bearing capacity depends on how the element is structured, as well as the amount of material. Which in turn determines the material cost and environmental impact. In addition to the material cost, the cost also includes the shipping cost and the cost of assembling the structure on-site.

The cost was expressed in different units for each material used: concrete and timber were given in [SEK/m^3], and steel in [SEK/kg]. The cost that will be implemented varies with each element type; slabs and walls will be presented as [SEK/m^2] and beams and columns as [SEK/m]. Therefore, recalculations were made to achieve the desired units. Three different calculations were used: for beams and columns made of steel Equation 5.2, for beams and columns made of timber or concrete 5.3, and for slabs and walls made of timber and concrete 5.4. Further, the cost of some elements was received as a total cost for the whole element.

$$\sum Cost_i[SEK/m] = A_i \cdot \rho_i \cdot Cost_{i,p}[SEK/kg] \tag{5.2}$$

$$\sum Cost_i[SEK/m] = A_i \cdot Cost_{i,p}[SEK/m^3] \tag{5.3}$$

$$\sum Cost_i[SEK/m^2] = t_i \cdot Cost_{i,p}[SEK/m^3] \tag{5.4}$$

Where:

- $Cost_i$ is the total cost each material
- A_i is the cross-section area of a column or a beam element presented in [m^2]
- t_i is the thickness of each material in a slab or a wall presented in [m]
- ρ_i is the density for each material presented in [kg/m^3]
- $Cost_{i,p}$ is the cost provided for each material

The data regarding bearing capacities implemented in the database are handled differently for each element type. The span lengths are used for slabs and critical load for columns, walls, and beams. The slabs will be exposed to the same live load ($2kN/m^2$) regardless of their position within the building. Whereas, the beams will be exposed to different loads depending on the distance between the beams. The columns and walls will be subjected to different amounts of loads as a result of the number of floors above.

The procedure for obtaining information regarding bearing capacities varied due to the data found. For steel columns, the compression resistance N_{Rd} and the critical buckling load N_{cr} were calculated according to Equation 5.5 and 5.6, and the minimum value were set to the bearing capacity, shown in 5.7. The calculations performed have followed the European Standard, SS-EN 1993-1-1:2022 – *Design of steel structures*.

$$N_{cr} = \pi^2 \frac{E \cdot I}{(\beta \cdot L)^2} \tag{5.5}$$

$$N_{Rd} = A \cdot f_y \tag{5.6}$$

$$N = min(N_{cr}, N_{Rd}) \tag{5.7}$$

Where:

- E is the modulus of elasticity, $E = 210GPa$ for steel
- I is the moment of inertia
- β is the buckling factor, the column is assumed to be pivoted in both ends, $\beta = 1$
- L is the length of the column, using the length of 2.5 m
- A is the cross-section area of the column
- f_y is the yield strength of the steel, using steel S355, $f_y = 355 \cdot 10^6 kN/m^2$

For the steel beams the moment capacity was checked. Cross-sections within classes 1 or 2 may have developed plastic mechanisms. Hence, a plastic analysis of the cross-section is used. Whereas an elastic analysis is used when a cross-section belongs to class 3. A maximum load q at a certain length of the beam will be implemented in the software to make the calculation process easier. The maximum load is decided by the requirement for the deflection and the bearing capacity. The limit for the deflection is set to $L/300$. Whichever of these loads are the lowest will be implemented as the maximum load q for a decided length L.

$$M_{Rd} = \chi_{LT} \cdot W \cdot \frac{f_y}{\gamma_{M1}} \tag{5.8}$$

$$q_L = min\left(\frac{M_{Rd} \cdot 8}{L^2}, \frac{384 \cdot E \cdot I \cdot W}{5 \cdot L^4}\right) \tag{5.9}$$

Where:

- M_{Rd} is the design value due to bending moment
- χ_{LT} is a reduction factor regarding the lateral torsional buckling. The cross sections are assumed to be prevented from lateral torsional buckling, χ_{LT}=1.0
- W is the section modulus, W_{pl} and W_{el} are used for plastic and elastic analysis respectively
- γ_{M1} is the resistance due to instability. When calculating the moment capacity γ_{M1}=1.0
- q_L is the maximum load that can be applied on the beam with the length L
- L is the length of the beam

6

Results

As for the method, the results are structured into two parts: the outcomes from the workshops and the calculations included in the database. Both parts are presented below.

6.1 Workshop

The workshop results are presented as quantitative data from the questionnaires in the form of charts and qualitative data from the discussions. The results are divided into themes and presented in each category. The themes contain a summary of the discussion supported by quotes from the participants. The results from the quantitative data are also presented within each category.

6.1.1 Elements

The factors that mainly govern the choice of structural element are aspects such as the architect's floor plan, the entrepreneur's preferences, and the client's desire. The participants got to rank the factors, and the factors were given a ranking score from 1 to 6, where the highest ranked factor received the score 6, whilst the lowest ranked score received the score 1. The result shown in Figure 6.1 is the average ranking score from all participants. The architect's floor plan can sometimes be strict, significantly limiting the number of structural system options. However, a participant described the situation: "A dialogue with the architect at an early stage is crucial for expanding the range of options and influencing the choice of the structural system." In certain cases, contractors may favor the most familiar and straightforward structural systems to construct. In certain cases, contractors may favor structural systems if they find them familiar and straightforward to construct.

The clients rarely specify any major requirements for the structural system, but they may express preferences regarding material choices or floor plans. Other factors were discussed, such as project stage, contracting type, and personal preferences. However, these aspects do not seem as significant as the previously mentioned factors.

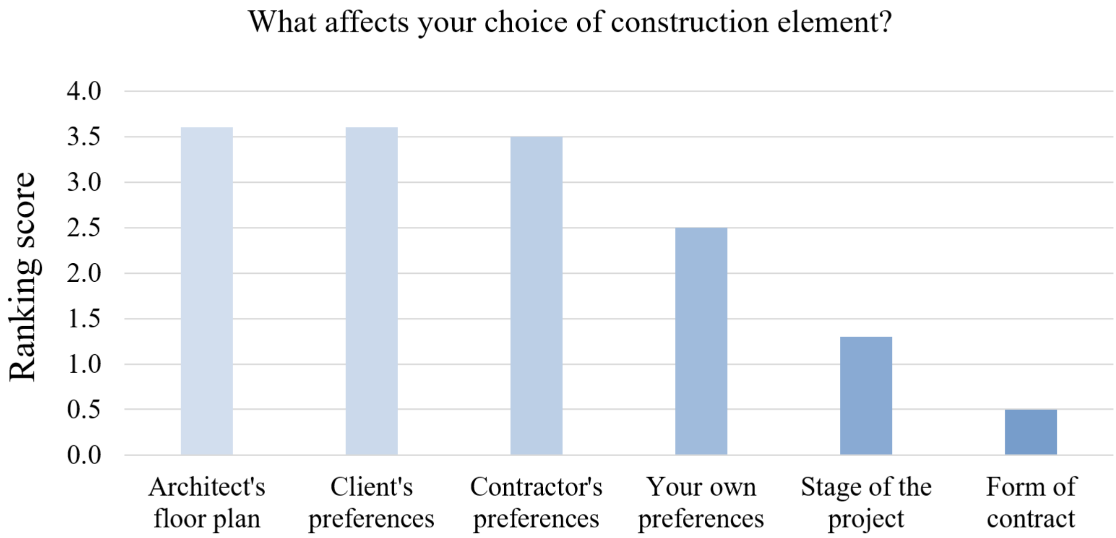

Figure 6.1: Results from the most influencing factors

When the structural systems are assembled in the software, the structural elements will be combined in numerous ways. A discussion was held on whether these combinations should be controlled or combined randomly. It was most argued that structural systems should be randomly generated to introduce new combinations. One participant argued: "If the combinations were to be controlled, only a limited number of systems would be generated. The risk of eliminating certain combinations may limit the generation of alternative solutions beyond the current ones already used." Further, if some element combinations were to be avoided, it was discussed that it would be due to environmental reasons. This was explained through, for example, that wood should not be exposed to moisture-prone environments. But apart from situations where certain elements can not function in a specific environment, all permitted element combinations would preferably be generated.

From the first questionnaire, great differences between the usage of structural elements in residential buildings are noticeable. Figure 6.2 presents the results from the participants' use of different slabs types. The top three highest-rated slab elements clearly show how concrete stands out as the most common material for slabs in today's construction industry. The result is more scattered among the walls, which can be seen in Figure 6.3. Here, a lightweight wall with steel columns is the most common, followed by different concrete walls and two alternatives to wood walls. When analyzing the columns results, most participants prefer to use VKR or KKR steel columns, as shown in Figure 6.4. Concrete elements are highly ranked in this category, while the glulam and circular steel columns share almost the same low score. Lastly, the results regarding the usage of beams are presented, revealing that most elements share similar scores. Notably, LVL (Laminated Veneer Lumber) is used in very few cases, as shown in Figure 6.5.

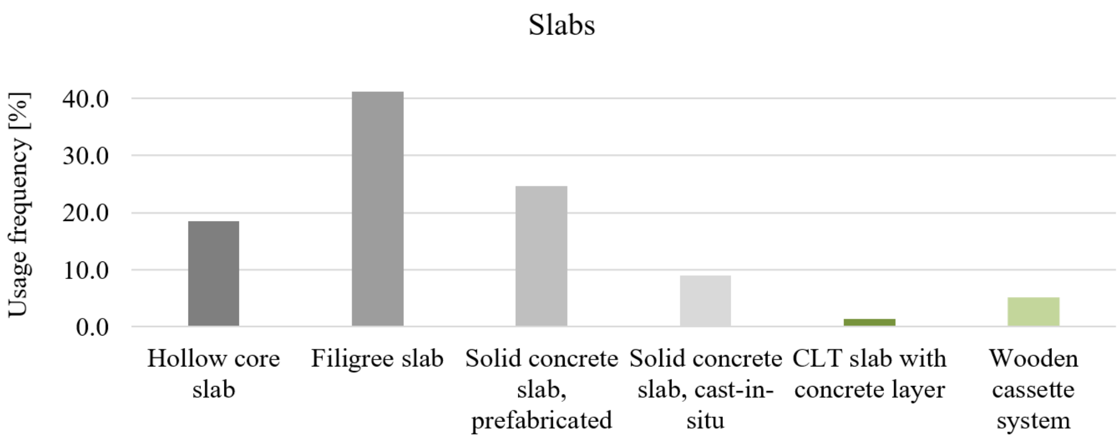

Figure 6.2: Result from the most used slabs in residential buildings

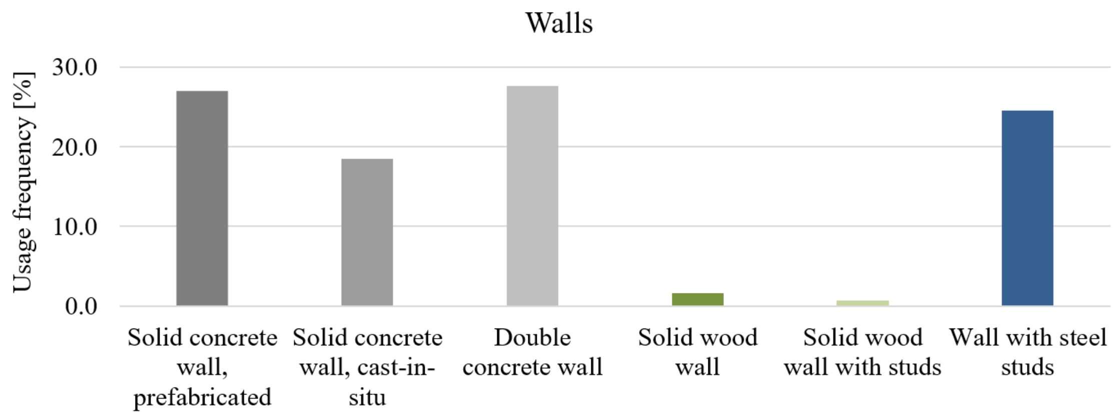

Figure 6.3: Result from the most used walls in residential buildings

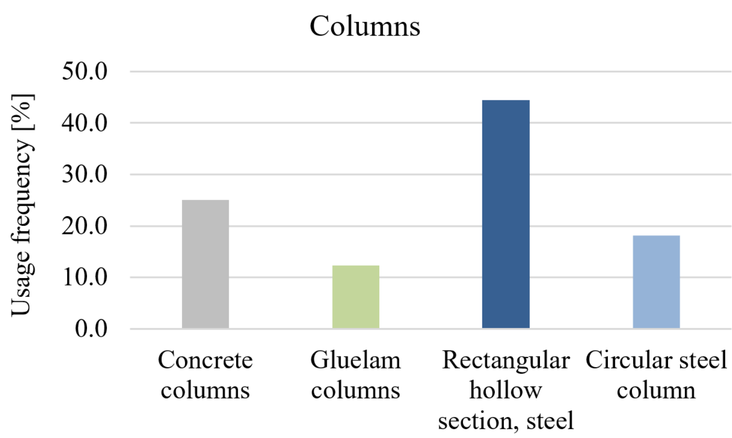

Figure 6.4: Result from the most used columns in residential buildings

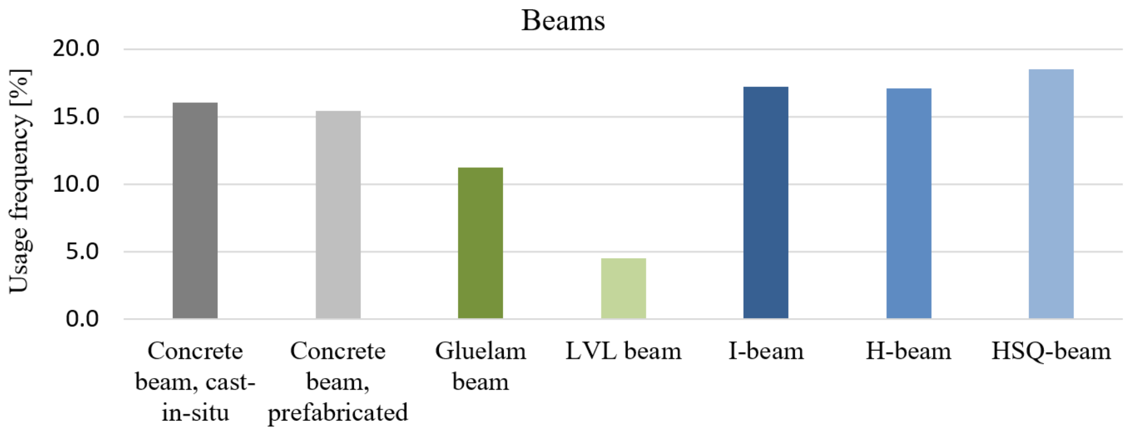

Figure 6.5: Result from the most used beams in residential buildings

6.1.2 Fitness function

During the workshops, participants were asked how they would estimate the industry's prioritization of cost versus environmental impact in today's construction projects. The average result was 76% cost and 24% environmental impact, shown in Figure 6.6. It was mentioned that during tender calculations, winning the contract is prioritized, which is done by presenting the cheapest proposal. Hence, the environmental impact comes secondary. Once the tender is won, the priority shifts to minimizing CO_2 equivalent emissions as much as possible within the budget. Further, the participants claim that, through experience, the clients have not been willing to lower the CO_2 equivalent emissions because of the increased cost it entails. However, they argued that a switch toward a higher prioritization of environmental sustainability had been seen in the last years due to increased awareness. Moreover, the construction companies have internal restrictions and limits regarding CO_2 equivalent emissions.

When asked about the usefulness of controlling the fitness function in the model, the participants generally responded that it would be valuable. The response ratio is shown in Figure 6.7. One participant said: "Because of the shift of prioritization from the tendering process to the planning process, a representative shift of the fitness function would be beneficial." Also, it was discussed that different projects have different environmental impact restrictions, strengthening the importance of allowing the user to define the fitness function.

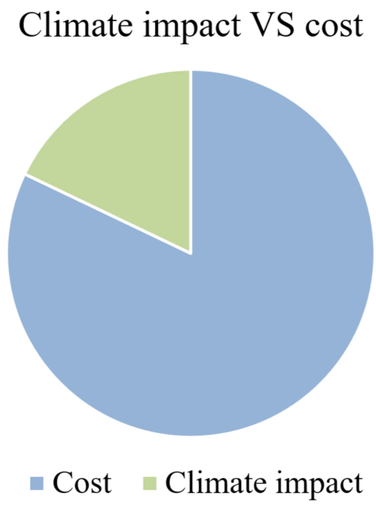

Figure 6.6: How the participants would estimate how the industry value cost and environmental impact today

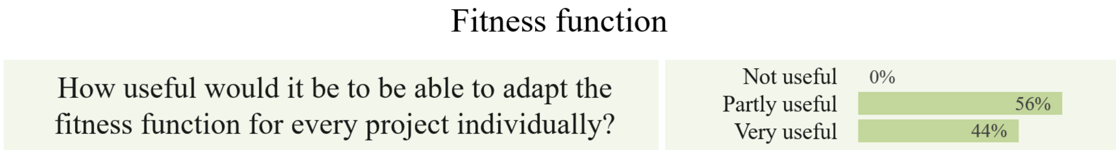

Figure 6.7: How useful the possibility of adapting the fitness function is considered to be

6.1.3 Inputs, flexibility, and outputs

Inputs

During Questionnaire 2, the participants were asked what inputs they would consider relevant and how they should be implemented in the software. Regarding how the inputs *number of floor plan*, *the total height of the building*, and *total ground area* should be implemented in the software, the distribution of the answers collected is shown in Figure 6.8. The general opinion was that the user should be able to enter a maximum and minimum value. Also, the *floor height* was discussed, and the participants wanted to be able to choose between 2,40 m, 2,50 m, 2,60 m, and 2,70 m as an input.

Since some materials are not suitable for some environments, the overall opinion regarding the implementation of *materials* was that it would be desired to either prevent certain materials from or assign particular materials to specific environments. Further, the participants wanted to be able to choose a specific *sound class* since regulations define sound classes for a building depending on the activity it provides. The last input discussed was *span lengths*, which showed that a clear majority wanted to be able to assign a maximum and minimum length. Additionally, the precision of options when entering a span length was discussed, and the most common answers were steps of 0,1 m and 0,5 m. Lastly, the participants were asked if any other input would be considered useful to add, where fire resistance classes were mentioned.

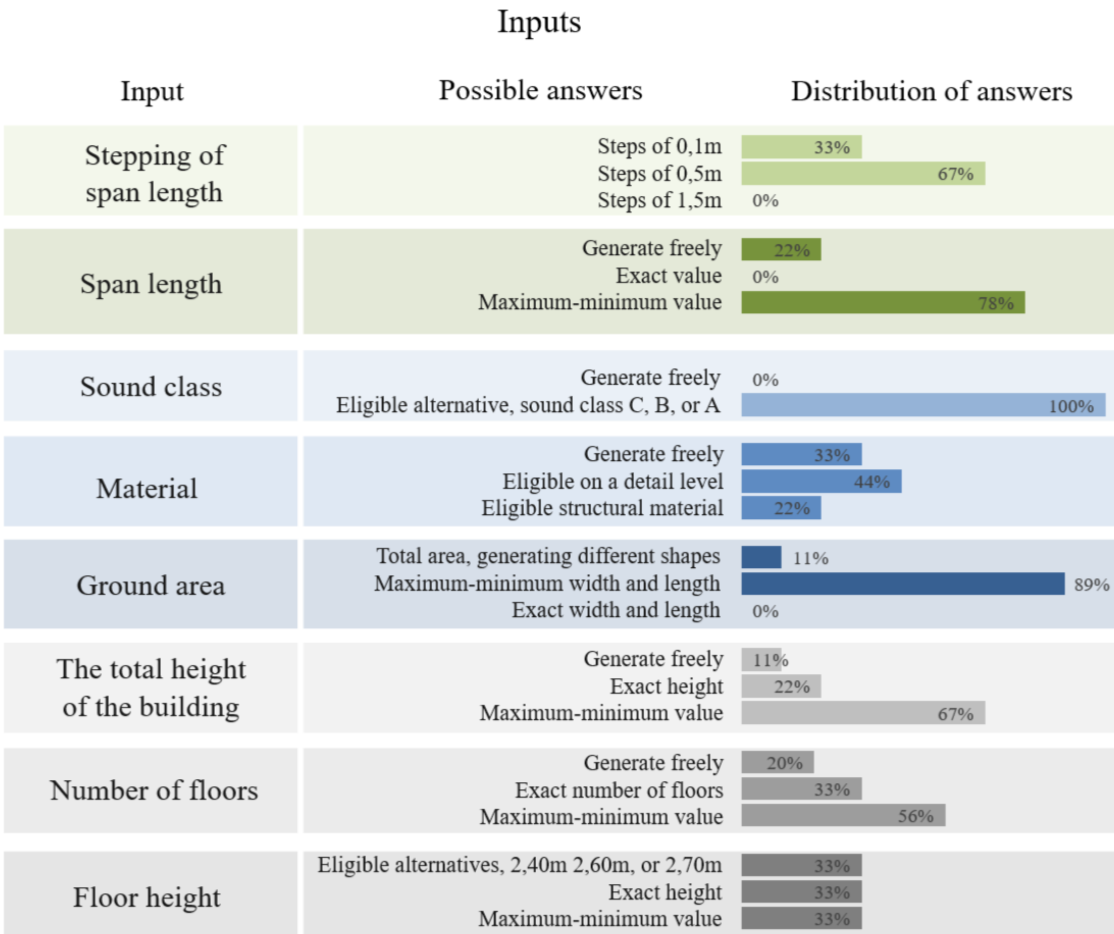

Figure 6.8: Result from the different inputs preferable types of answer

Flexibility

The participants were given a short introduction to the use of penalty functions. Where a penalty would be used to lower the fitness of a solution due to how well the solution fulfills the requirements from the inputs. The approach was positive, as shown in Figure 6.9, and in the discussion, the overall viewpoint was that solutions should not be excluded. If the solution space is decreased by too strict inputs, the possibility of finding optimized solutions would be decreased.

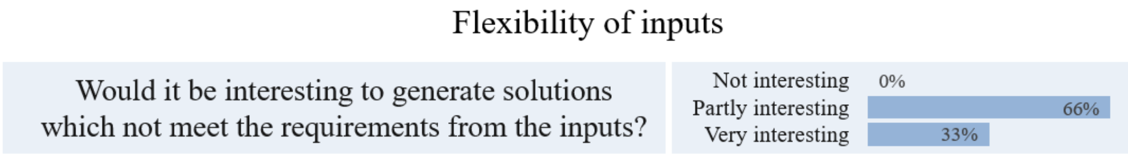

Figure 6.9: Result from the participant's interest in flexible inputs

Outputs

In Questionnaire 2, the participants were asked to rank suggestions of possible outputs based on which would guarantee sufficient software trustworthiness. The participants got to rank the factors, and the factors were given a score from 1 to 5, where the highest ranked factor received the score 5, whilst the lowest ranked score received the score 1. The result shown in Figure 6.10 is the average score from all participants. The highest-ranked answers were solutions space and a 3D model of the structural system. During the discussion, it was mentioned that the output is important to ensure others, such as clients, of a certain solution. Therefore, the output should show the differences between the systems pedagogically. Further, to ensure the user of the software's credibility, the participants would want to be able to track the solution, allowing them to understand which parameters contributed to the presented result.

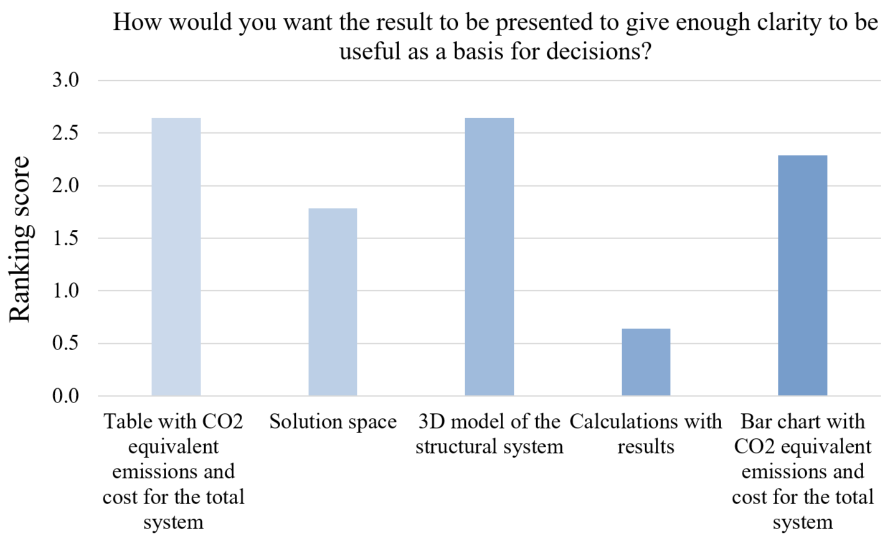

Figure 6.10: Presentation of results from the preferable outputs

6.1.4 Usability

To maximize the usefulness of the future software, it was discussed that it should be introduced early in the tender process. The participants argued that the structural engineers should present options for the structural system before the architect finalizes the design.

The discussion concluded that the program should preferably not be too complicated to avoid the software being burdensome and slow. This was mostly argued to prioritize user-friendliness and focus on analyzing the system as a whole based on the cost and climate impact aspects. It was mentioned that the need for a program with perfect structural calculations that include every type of load case is not necessary during the conceptual design phase. One participant described: "Structural engineers perform detailed calculations later in the process, and at an early stage, the main focus is generating ideas and creativity." Results regarding the usefulness of the software are presented in Figure 6.11 and 6.12, which shows that the majority of the participants believe that this program would facilitate their work to a partly high extent. The question was asked before and after presenting information regarding genetic algorithms and the software's possibilities. The answers before the presentation are presented in Figure 6.11 and the answers after the presentation in Figure 6.12. Facilitated parts of the work were discussed in the questionnaire, which was described as making quick decisions, generating more options, and demonstrating motivational documents.

The discussion highlighted that the requirements are stricter when designing a residential building, which contributes to reduced flexibility. The living spaces are usually predetermined, and fewer options to alternate the structural system are available. A discussion regarding the differences in designing residential buildings compared to other buildings was discussed. For example, in an office building, the need for flexibility is greater due to the need to adapt the building to different tenants. A participant said: "When designing a flexible floor plan, most office buildings are designed with large spans and minimal load-bearing interior walls. This leads to more complex structural solutions, and software that can generate multiple options would have been very helpful." It was discussed that the same conditions apply to other commercial buildings, such as industries and schools. School buildings are in great need of changing the premises' purpose, as the classes' size and needs can vary greatly. Another participant commented: "A school also requires different conditions in certain spaces, such as a sports hall or a chemistry lab, which affect the structural system." The participants considered that software would have been even more useful in finding structural solutions in these types of buildings.

One of the questions addressed potential challenges and barriers to the software. Participants believed that if the software became too complex and difficult to use, its adoption would be low. Another aspect brought up the difficulty of managing the surrounding environment since the software would not consider external conditions, such as location or ground conditions. A slightly more recurring problem will be updating the material prices. These depend on many factors that are controlled by, among many things, the market, demand, and inflation. Lastly, they mentioned that engineers generally have a large need for control in their work and, therefore, find it difficult to trust new software.

The level of agreement	Assigned number:
To a high extent	1
To a partly high extent	2
To a medium-high extent	3
To a partly low extent	4
To a low extent	5

Table 6.1: *Representation of the expressed level of agreement for question Q7 and Q23*

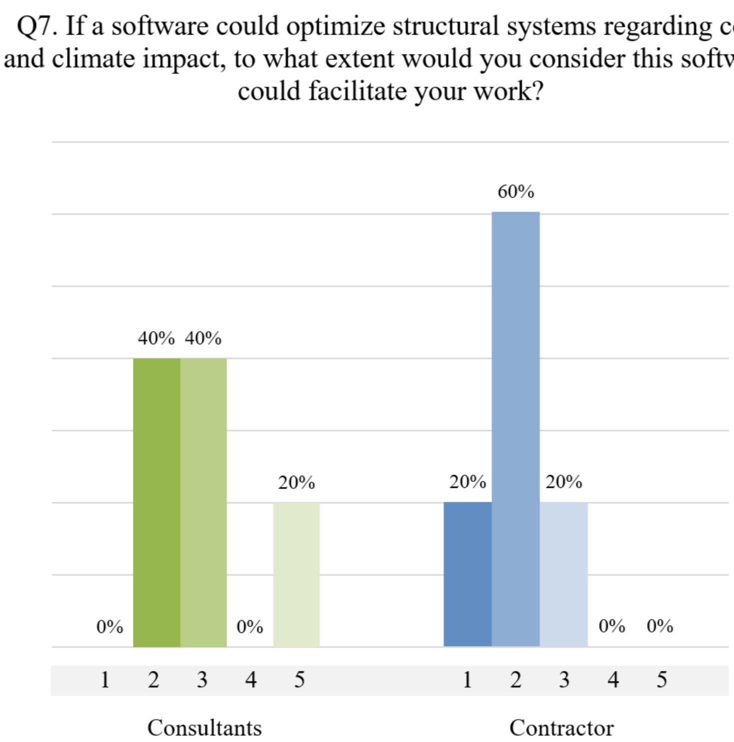

Figure 6.11: Presentation of result from usability aspect before information regarding genetic algorithm and the software possibilities

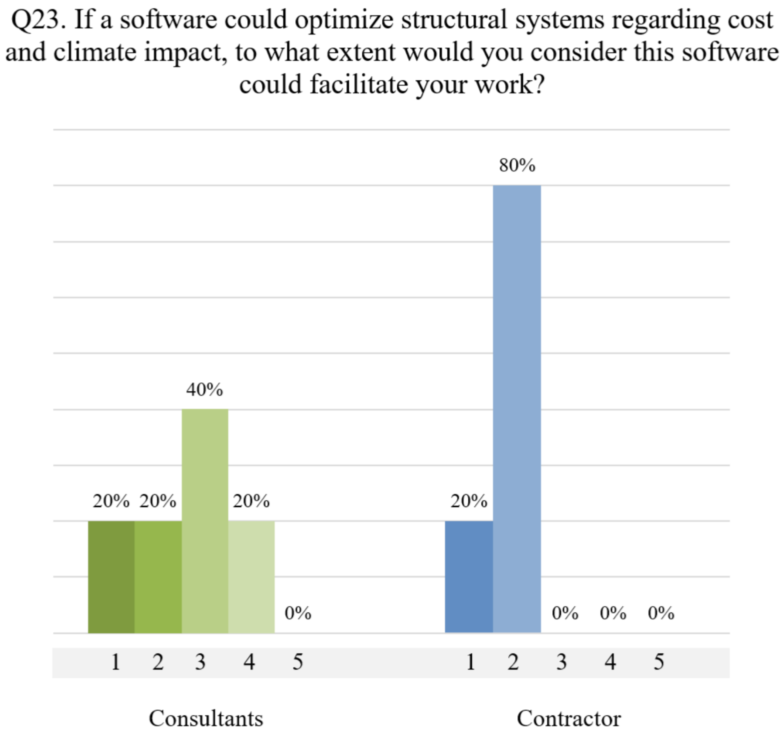

Figure 6.12: Presentation of result from usability aspect after information regarding genetic algorithm and the software possibilities

6.1.5 Future

A question addressed the interest in receiving information regarding choices, difficulties, and feedback from previous projects with similar input data. The discussion described that structural engineers often refer to previous projects and review details to adapt solutions to a new project. An overall conclusion was described by a participant: "In cases where the design choices are based on personal preferences rather than on technical characteristics, it may be necessary to receive information regarding reasons for certain decisions." To implement this approach, there was a discussion on whether the software could be enhanced in the future with a feature allowing engineers to provide feedback and explain their decisions on whether the suggested system was used or not.

Another discussed topic was whether to consider additional aspects beyond cost and climate. The construction time and construction method were discussed as two additional possible aspects. However, some argued that finding reliable data on these topics would be difficult.

6.2 Database

As mentioned in Section 5.3, the implementation varies based on the element type. The following sections provide examples of the information that will be implemented into the software and the database structure. *X* demonstrates the element presented, where the difference is the material's dimensions or characteristics. S1-s3 presents an HD/F slab in three different dimensions, and w1-w4 presents a load-bearing timber wall in four different strength classes. Further, c1-c4 represents a VRK column in four dimensions, and b1-b4 presents an IPE beam in four different dimensions.

The cost is presented as a total amount, encompassing material costs, production costs, shipping costs, and on-site assembly costs. Generally, the cost does not increase substantially with the element's size unless additional machinery, such as cranes, is required.

In Table 6.2 and 6.3, an example of how the information regarding slabs is structured in the database. As the total height will be an input in the software, the total thickness of the slab will be an important parameter to consider when generating solutions in the software. Whereas a low height of the slab will decrease the total height of the building with the same floor height. The mass of the slab is essential because it contributes by its self-weight to the load applied on the beam, deciding what dimensions of the beam are needed. The structural member thickness represents the material deciding the bearing capacity. The minimum and maximum span lengths are based on the load the slab can carry without exceeding the bearing capacity and the requirement for deflection.

HD/F slab with 50mm concrete layer

X:	Total thickness [mm]:	Structural member thickness [mm]:	Mass [kg/m^2]:
s1	250	200	450
s2	315	265	560
s3	370	320	520

Table 6.2: *An example of the structure regarding slabs from the database, part 1*

X:	Min. span length [m]:	Max. span length [m]:	Cost [SEK/m^2]:
	HD/F slab with 50mm concrete layer		
s1	6	9	1437
s2	7	12	1517
s3	9	15	1597

Table 6.3: *An example of the structure regarding slabs from the database, part 2*

As for the slabs, the total thickness of the load-bearing walls is needed to ensure that the inputs for the floor area in the building are met. Also, the wall's mass is needed as the self-weight will be applied as a load to the walls or columns below. The bearing capacity is presented as kN/m wall. Table 6.4 and 6.5 show an extract from the database as a load-bearing timber wall. For timber, the bearing capacity of an element depends on the strength class used. Here, the elements are presented for strength class C24, as it is the most used strength class.

Load-bearing wall with timber studs 145mm x 45mmm

X:	c distance [mm]:	Total thickness [mm]:	Structural member thickness [mm]:
w1	450	298	145
w2	600	283	145

Table 6.4: *An example of the structure regarding load-bearing walls from the database, part 1*

Load-bearing wall with timber studs 145mm x 45mmm c600mm

X:	Mass [kg/m^2]:	Bearing capacity [kN/m]:	Cost [SEK/m^2]:
w1	18.9	140.5	888
w2	27.8	187.4	1135

Table 6.5: *An example of the structure regarding load-bearing walls from the database, part 2*

The bearing capacity for columns will be implemented as kN for each column, as shown in Table 6.6 and 6.7. The loads from the beams and walls above will decide how many and what dimensions are needed. Either a decided number of columns is set, and the dimensions depend on the load each column should be able to withstand or the dimensions of the column are fixed, and the number of columns is dependent on the load.

VKR column

X:	Dimensions [mm]:	Thickness [mm]:	CS area [mm^2]
c1	80 x 80	6.3	1810
c2	90 x 90	6.3	2070
c3	100 x 100	6.3	2320
c4	80 x 1400	6.3	2570

Table 6.6: *An example of the structure regarding columns from the database, part 1*

VKR column

X:	Mass [kg/m]:	Bearing capacity [kN]:	Cost [SEK/m]:
c1	14.2	263.2	881
c1	16.3	405.4	1008
c1	18.2	506.3	1129
c1	20.2	289.1	1251

Table 6.7: *An example of the structure regarding columns from the database, part 2*

Regarding the beams, instead of using the bearing capacity, a maximum load at a certain length of the beam will be implemented in the software. This is to ease the process of generating the systems in the software. The maximum load is either limited by the deflection requirements or the bearing capacity, whichever is the lowest. Table 6.8-6.10 presents the database structure regarding beams. Here, the lengths 5 m, 10 m, and 15 m and the maximum load is shown.

IPE-beam in steel

X:	H [mm]:	W [mm]:	t_f [mm]:	t_w [mm]:	R [mm]:	CS area [mm^2]
b1	80	46	5.2	3.8	5	764
b2	100	55	5.7	4.1	7	1032
b3	120	64	6.3	4.4	7	1321
b4	140	73	6.9	4.7	7	1643

Table 6.8: *An example of the structure regarding beams from the database, part 1*

IPE-beam in steel				
		Maximum load at a L [kN/m]:		
X:	Mass [kg/m]:	L=5m:	L=10m:	L=15m:
b1	6	1.63	0.1	0.02
b2	8.1	3.48	0.22	0.042
b3	10.4	6.46	0.4	0.08
b4	12.9	7	0.44	0.086

Table 6.9: *An example of the structure regarding beams from the database, part 2*

IPE-beam in steel		
X:	Moment capacity [kNm]:	Cost [SEK/m]:
b1	8.3	372
b2	13.9	502
b3	21.5	644
b4	31.3	800

Table 6.10: *An example of the structure regarding beams from the database, part 3*

6.2.1 Climate impact

The climate impact is presented separately for the modules A1-A3, A4, and A5. X represent the different materials used in each element. In Table 6.11 and 6.12, the climate impact of an HD/F slab is shown. The thickness of the concrete layer cast on the slab after construction determines the achieved sound class. Shown in Table 6.12, modules A-A3 constitute the largest part of the total CO_2 emissions of the slab. However, the ratio varies due to the material and element used. As mentioned in Section 5.3.1, how the climate impact is presented varies due to the element; for slabs and walls, it will be presented as $kgCO_2/m^2$ whereas for columns and beams as $kgCO_2/m$.

Climate impact of a HD/F slab

X:	Materials:	Climate improvement:	Sound class:	Thickness [m]:
m1	Concrete C35/45	40%	B	0.07
m2	Hollow core floor			0.265

Table 6.11: *Example from the database regarding climate impact, part 1*

Climate impact of a HD/F slab

		Generic factor [$kgCO_2/kg$]:				
X:	Mass [kg/m^2]:	A1-A3:	A4:	A5:	Total:	Generic [$kgCO_2/m^2$]:
m1	164.5	0.10	0.004	0.005	0.11	17.6
m2	357.75	0.13	0.032	0	0.16	57.4
						74.9

Table 6.12: *Example from the database regarding climate impact, part 2*

7

Discussion

An overall analysis regarding the **use of the different elements** indicates that concrete is generally the most used material for slabs and walls. Some of the reasons for this may be the high durability of the material, the fact that long spans can be achieved, and the low cost of the material. Further, the material can easily be formed into different shapes, and when being cast on-site, concrete can be used to create uniform surroundings. Compared to timber, no additional materials are needed for concrete to accomplish the same requirement, such as sound and fire class. Moreover, climate-improved concrete, which uses Supplementary Cementing Materials (SCM), is more widely used than corresponding methods for steel. Also, the supply of climate-improved concrete is bigger.

Regarding columns and beams, steel was considered to be the most used material. Due to the high strength of steel, smaller dimensions of the material are needed compared to concrete and timber. A lower beam height results in a lower total floor height, making it possible to either lower the total building height or add another additional floor if the building is high enough. The reason for opting out of timber elements may be that the material does not fulfill the abovementioned requirements. The material requires larger dimensions, affecting other elements; for example, if thicker slabs are used, the total height increases, leading to more material used for the facades. Further, more material requires more transportation, which increases the cost and CO_2 equivalent emissions.

Amongst the stated factors that may affect and limit the choice of possible structural systems, the architect's floor plan was considered to be one of the factors that affected the choice of the structural systems the most. For residential buildings, the floor plan regarding locations for apartments is often decided by an architect in an early stage, making requirements for span length before a structural engineer is involved. By including a structural engineer earlier in the process, together with the software, the number of fitting structural systems could increase. And in turn the potential to decrease the environmental impact and cost increases. Similarly, by including and informing the client regarding the benefits and disadvantages of specific systems, the chances of retrieving a beneficial system increase.

There is great complexity in **combining different elements** that have not been combined to the same extent as other common combinations. New and untested combinations lack experience values, which can be a reason why new combinations often are opted out. The participants generally expressed the need for the invention of new element combinations. The desire was augmented by the fact that to achieve development in the industry, new solutions need to be used, and no combinations should, therefore, be removed.

Preventing materials from certain locations would be beneficial due to material properties and exposed environments. Preferably, the software would also allow the user to assign elements on a detail level. For example, the user could prevent solutions that use timber in the basement or steel in the roof.

The **fitness function** presents how cost versus environmental impact is valued during a project. The approach towards environmental impact does change during the project process. At the beginning of the process, cost is the most important aspect since the company wins projects based on cost. Later, when the project is ongoing, the environmental impact aspect is crucial. Lowering the environmental impact to the fullest extent within the same budget requires optimization of the structural system. On the other hand, some projects have requirements regarding environmental impact from the beginning. In those cases, the weighting of cost and impact is important to compensate for both of the aspects. Furthermore, stricter values established by *Boverket*, in the form of maximum CO_2 equivalent emissions, will be implemented for the industry in the near future, demanding a change in the approach to these parameters. Due to the differences and future requirements, it is highly valuable to have a fitness function that can be modified for each structural system.

The results from this study show that structural engineers would like to change the fitness function during the progress of the projects. It would also be beneficial to evaluate how changes in the fitness function impact the algorithm's choice of optimal structural system. When changing the inputs of the fitness function, the structural system will most likely generate a new type of structural system. If the software could present those results compared to each other, it would benefit the structural engineer during the determination process. To make it possible, the software has to generate solutions quickly and be able to store older solutions for comparison.

The software must be **user-friendly** and provide correct design choices for the structural engineer to trust the software's reliability. The role of a structural engineer includes discovering innovative solutions. This mindset reflects the opinion of not wanting to weed out any solutions at an early stage. However, as the result of this study shows, structural engineers prefer to have many solutions to choose from. Still, the actual decision of which final solution to proceed with shall not be automated but left to a structural engineer to make. The approach is to create software that is user-friendly and generates solutions quickly to speed up the decision-making process. The intended use is as decision-support in the early stages and not as complete design software.

In the **future**, the software could expand by integrating other aspects besides cost and environmental impact. Since a project often has a time limit, including time as an evaluation aspect would be of interest. However, time depends on which elements are combined; assigning a time to a specific element would be unrepresentative. Since the element itself does not represent the total construction time but how the element should be assembled together with another element, the time aspect depends on the combinations. If all combinations had been tested and a pattern between the elements in relation to time could have been analyzed, then a time aspect could have been implemented. However, assembling data regarding time for all these combinations is time-consuming and would become difficult to analyze. Also, time is affected by factors such as logistics and the supplier's delivery time, making the time factor difficult to integrate into the software. However, in the future, when a structural system from the software is built, the time could be implemented in the software and be used as an indication of the expected construction time for the next project using the same system.

Another factor discussed for the software to consider was the production method. Different companies at different locations may have varying experiences with different materials and production methods. For example, a company located in the north of Sweden may have a lot of experience in steel. In contrast, a company in south Sweden may have experience in the production method of cast-in-situ concrete. The fact that a company is experienced in a specific area often leads to faster production, which in turn leads to lower project costs. For this reason, it would be preferable to have an input where the user could choose a production method, and the software would only generate solutions with that specific method.

During the planning process, **previous projects** are often used as references. This approach would be useful to implement to pass on experiences about a specific system in the software. However, prerequisites vary from project to project, and accordingly, no restrictions should be implemented on the software. The experience should rather be applied as feedback in the form of a comment. The feedback can consist of challenges, positive experiences, or reasons for not selecting the solution. If so, the software would consider human factors that sometimes are decisive in decisions, which is an aspect the data can not provide by itself. This feature would also provide tracking of projects and evaluation of how the construction process progressed.

This thesis considers only the construction stage (module A1-A3) and construction process stage (module A4-A5) when calculating the **life cycle assessment**. The choice of only including modules A1-5 is based on the current requirements from *Boverket*. This limitation might generate a misleading comparison; thus, the whole life cycle is not presented. Implementing the remaining modules during further software development would provide a more accurate representation of the actual environmental impact. However, the modules included represent the majority of an element's total CO_2 equivalent emissions.

The climate impact data used in this thesis is generic, representing average values obtained from *Boverket*. Consequently, the data implemented in the software may differ from the actual environmental impact. If, instead, environmental product declarations (EDPs) were to be included, more exact data of the CO_2 equivalent emissions could be achieved. EPDs, presented by suppliers, would result in data that varies depending on the supplier used for the project. Consequently, the database and the software must accommodate various data sources. Additionally, depending on the project's location and the supplier, transportation methods and distances will vary, leading to differences in CO_2 equivalent emissions. Given these factors, achieving more precise environmental impact data would entail a complex implementation process requiring further consideration.

Due to the influence of numerous factors on an element's price, obtaining a representative **cost** is challenging. Unpredictable factors, such as delivery and weather, can significantly impact construction time, making it difficult to obtain an accurate cost. For example, the curing time of cast in-situ concrete is strongly dependent on the temperature. Further, if additional machines such as cranes are required due to the element's weight, the cost increases drastically. Also, the material prices may differ locally, as well as the transportation changes depending on the location of the construction site.

Like the climate database, the cost depends on the suppliers used for the specific project. As mentioned earlier, teams consisting of construction workers may have more experience in a certain production method, and thereby, the time can be decreased. Decreased construction time results in a lower cost for the total structural system. Further, the cost used in this thesis only considers the material, production, and construction, while potential maintenance costs are not considered. Furthermore, factors like inflation, supply, and demand contribute to cost variability, necessitating ongoing updates similar to those required for the climate database.

Generating the system may not be the most difficult part, but considering all aspects of construction and **buildability** is challenging. It was mentioned during the workshop that the installation parts can be cast into slabs, which creates a lower floor height. The floor height affects the total height of the building, which in turn is determined by the choice of slabs. If a slab is too thick, the number of floors manageable within the total height of the building could be too low. When designing a residential building, clients often want as many floors as possible in their determined total building height. If the number of floors is not maximized, the budget may be negatively impacted due to having fewer apartments or office spaces available for rent. This motivates by getting as much living space as possible to generate the most money per square meter, making it important to investigate optimizations.

It is also highly valuable to maintaining high standards for sound insulation, to minimize the risk of tenants being disturbed by external noise. If the software could generate solutions comparing sound class B to sound class C, the relation between an increased or decreased level of sound class and cost could be received. Then, other technical aspects, such as fire class, could be implemented and compared to analyze the value of designing buildings with higher comfort and standards. The comparison reconnects to the flexibility of the inputs, which anticipates that the flexibility should be used to a high extent. Low flexibility may be beneficial when the requirements are extraordinarily strict, but overall, to be able to compare solutions, the input must be flexible.

Two workshops were conducted, differing only in the **the participants**: one with employees from a consultant company and another with employees from a contractor company. All participants had backgrounds in educational and professional roles. In general, their questionnaire responses were not influenced by the type of company they worked for. However, the question regarding the software's usability differed from the others. In this question, the participants were asked to what extent the software could facilitate their work. The employees at the contractor company were generally more positive regarding the expected usability than the employees at the consultant company. The difference could be due to several aspects; one aspect could be that contractors have access to more constructability data, making it easier to visualize how the software could facilitate their work. Another aspect could be that employees at consultants might not as often have a free choice of the structural system's design; it is already predetermined by either the contractor company or an architect, making the software's facilitation of their work lower.

7.1 Implementation of Genetic Algorithms

Genetic algorithms produce a population of different solutions for structural systems. The population consists of individuals, which represents a total structural system. To implement genetic algorithms in the software, software coding must be managed. A procedure for how the implementation could be done is presented as a suggestion:

The process begins with the database, which consists of all selectable elements designed in different dimensions. This base constitutes the entire population of elements. For these to create the first generation of structural systems, values of both the inputs and flexibility in the form of a penalty function are needed. Specific desired inputs will ensure that elements with dimensions not meeting the requirements from the inputs are excluded from further processing. A potential penalty function allows adjacent dimensions to the set input to participate in the process. The first basic population of total structural systems is selected through those inputs, but the crossing of elements is generated randomly to create the first population. Then, the first evaluation of the structural systems is carried out, whether the systems meet the requirements or not, all systems from the identified population are qualified to proceed to the next process.

The selection phase can be carried out with predetermined requirements through the evaluation. Proportional selection would be the most appropriate implementation since it considers evaluation criteria and variation. In the selection, each system will be evaluated and assigned to a certain score. These scores are then compared to each other, and the system with the highest score has the greatest chance of reproducing. The proportional selection does not exclude any solutions since the systems with low scores are still included but with a smaller chance of reproduction, which is great for the aspect of variation.

After the reproducing structural systems have been selected, the crossing phase is introduced. The crossing phase must consider different load-carrying abilities since some systems may be column-beam systems, and some use load-bearing walls. The crossing will, therefore, not be generated randomly at this stage but with a focus on suitable elements and material combinations. At the reproducing stage, mutations can also be included, depending on the user's demand. The mutation can, in that case, use elements from the database that were not considered eligible in the first population. The mutation can be used to different extents where the user optionally determines the extent to a certain percentage of possibility. According to the strong desire for new inventions of combinations, the mutation function is preferred to exploit. The reproducing will continue until enough systems are qualified for the requirements. Lastly, the procedure ends with all systems that passed the requirement again being evaluated and compared to existing systems.

The systems crossed are complete structural systems that can withstand the applied load as a whole. When systems are crossed, and new systems are developed, the dimensions and location of elements might not be transferable without any adjustments. For instance, if two systems are crossed and columns from one system are used together with a slab from a system with a longer span length, the element must be modified to be compatible. How these adjustments should be performed must be further investigated to perform reliable software.

As mentioned in the previous section, the floor plan for apartments is often set before a structural engineer is involved. Hence, this information will need to be transferred into the software. One approach is to import the floor plan from an existing program into the software, requiring the software to be capable of receiving this data. Another option is to create a feature where the user can apply the floor plan directly to the software. By considering an already existing floor plan, the available options for adapting structural systems will be at a lower extent. Therefore, engaging in discussions with architects about the factors influencing the decision to establish a specific floor plan would be beneficial. If the primary objective of creating a floor plan is to attain a particular apartment area, adding an input where the user could implement the apartment area would expand the range of structural system options available.

Finally, the outputs of the solutions must be visualized, and according to the workshop results, most participants prefer a table or bar chart with CO_2 equivalent emissions and cost for the total system. Both outputs, shown in Table 7.1 and Figure 7.1, make it easy to compare different solutions. One suggestion with high scores is a 3D model of the structural system. Visualizing several solutions as 3D models requires more advanced programming and a longer time to present a result, which may result in slower software. Another suggestion is a solution space where different system values are compared to each other, shown in Figure 7.2. It could be optimal to present the result in multiple ways, for example, by presenting both a table and the solution space.

Structural system	Cost [SEK/BTA]	CO_2 emissions equivalent [$kgCO_2$/BTA]:
A	22000	300
B	27000	260
C	17500	350
D	29000	220
E	30000	250
F	25000	330
G	35000	200

Table 7.1: *Table with cost and CO_2 emissions equivalent for the total system*

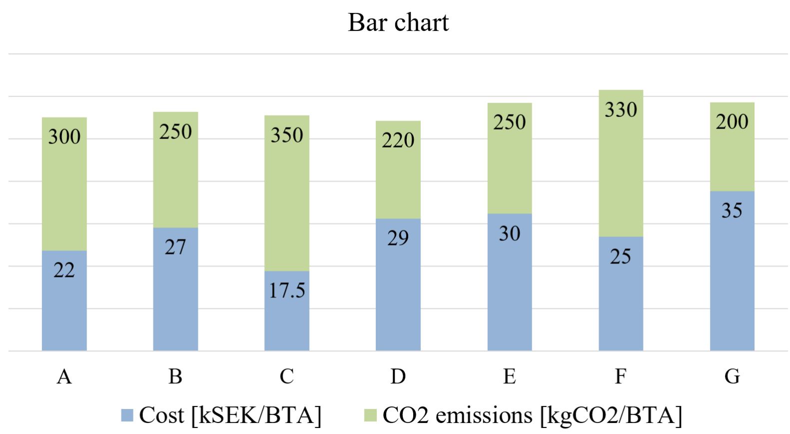

Figure 7.1: Example of results shown in a bar chart

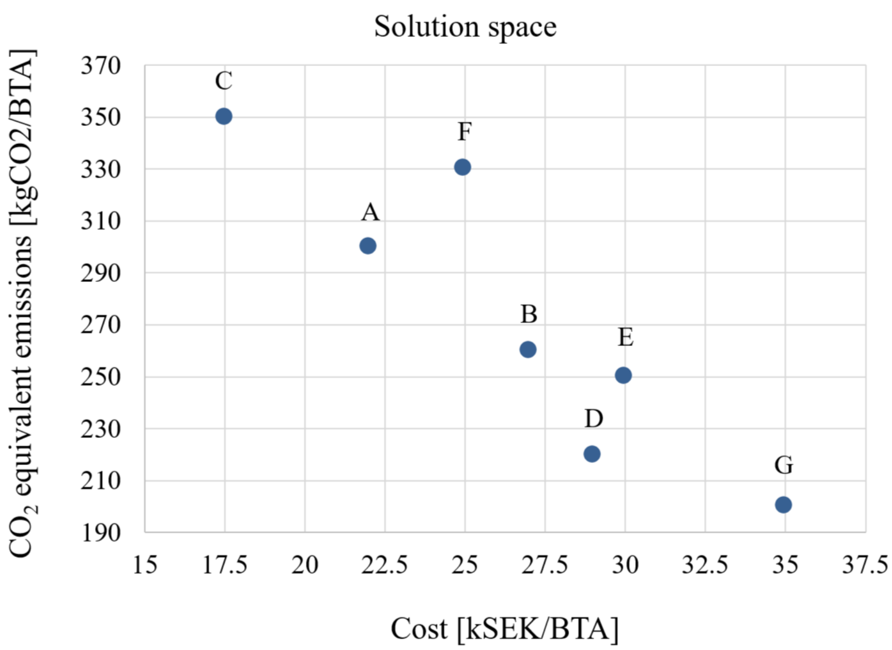

Figure 7.2: Example of results shown in a solution space

8

Conclusion

Overall, the software is considered a useful tool for structural engineers when creating conceptual designs. Instead of selecting one solution considered the most optimal, it would be preferable to present a range of solutions from which the user can choose the most fitting system for the specific project. For the software to be considered useful, it must be simple and easy to use and provide sufficient reliability.

Several factors must be considered when creating software that utilizes genetic algorithms to optimize structural systems based on investment cost and environmental impact. The software must be provided with costs and CO_2 equivalent emissions to be able to evaluate the structural elements and, in turn, compare the different systems.

To ensure a correct output of the future software, the database has been provided with costs, CO_2 equivalent emissions, and bearing capacities. The information has been assembled for each element in different dimensions. The information regarding costs and climate impact must be allowed to be updated for the result to stay relevant. Bearing capacities have been presented in various units, depending on the most suitable format for later integration into the software. Further, the database has been provided with different dimensions for each element to limit the risk of an element being excluded due to insufficient bearing capacity or span length.

To ensure buildability, the elements in the database have been provided with information regarding fire class and sound class based on the requirements they meet. The user will be able to specify which classes the building shall fulfill. However, external factors such as ground conditions and available space at the specific location have not been taken into account and are left for the structural engineer to consider.

8.1 Future research

To improve future software, several aspects must be considered. As previously mentioned, the architect's floor plan significantly influences the available structural systems. Therefore, the method of integrating this information needs to be carefully examined. Additionally, the process for updating costs from different suppliers must be investigated. Further, the interaction between structural systems must be considered during the crossing phase. Where element adaption during the generation of new structural systems to create complete and functional systems needs investigation. Adding a feature in which the user could implement and receive feedback regarding a specific system is considered beneficial.

This thesis explores opportunities to optimize structural systems based on costs and environmental impact. In the future, it would be valuable to consider additional factors, such as construction time and production methods. Further studies are needed to determine how this information should be gathered and integrated into the software.

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A

Questions asked at the workshops

The following questions were asked at the workshops. The questions included in Questionnaire 1 and Questionnaire 2 are presented in sections A.1 and A.2, respectively. In A.3, the question discussed during the discussion is presented.

A.1 Questionnaire 1

Q1. To what extent do you use these slabs when designing structural systems?

- Hollow core slab
- Filigree slab
- Solid concrete slab, prefabricated
- Solid concrete slab, cast-in-situ
- CLT slab with concrete layer
- Wooden cassette system

Q2. To what extent do you use these walls when designing structural systems?

- Solid concrete wall, prefabricated
- Solid concrete wall, cast-in-situ
- Double concrete wall
- Solid wood wall
- Solid wood wall with studs
- Wall with steel studs

Q3. To what extent do you use these columns when designing structural systems?

- Concrete columns
- Gluelam columns
- Rectangular hollow section, steel
- Circular hollow section, steel

Q4. To what extent do you use these beams when designing structural systems?

- Concrete beam, cast-in-situ
- Concrete beam, prefabricated
- Gluelam beam

- LVL beam
- I-beam
- H-beam
- HSQ-beam

Q5. What effects your choice of construction element?

- Architect's floor plan
- Client's preferences
- Contractor's preferences
- Your own preferences
- Stage of the project
- Form of contract

Q6. Are there any material/element combinations that you avoid?

Q7. If a software could optimize structural systems regarding cost and climate impact, to what extent would you consider this software could facilitate your work?

- To a high extent
- To a partly high extent
- To a medium-high extent
- To a partly low extent
- To a low extent

Q8. How do you experience the weighting between cost and climate impact in the construction industry today?

A.2 Questionnaire 2

Q9. How would you want to implement the input for the number of floors in the software?

- Maximum-minimum value
- Exact number of floors
- Generate freely

Q10. How would you want to implement the input for the total height of the building in the software?

- Maximum-minimum value
- Exact height
- Generate freely

Q11. How would you want to implement the input for the floor height in the software?

- Maximum-minimum value
- Exact height
- Generate freely
- Eligible alternatives such as 2,40m 2,60m, or 2,70m

Q12. How would you want to implement the input for the ground area in the software?

- Exact width and length
- Maximum-minimum width and length
- Total area, generating different shapes

Q13. How would you want to implement the input for the materials in the software?

- Eligible structural material
- Eligible on a detail level

- Generate freely

Q14. How would you want to implement the input for the sound class in the software?

- Eligible alternative, sound class C, B, or A
- Generate freely

Q15. How would you want to implement the input for the span length in the software?

- Maximum-minimum value
- Exact value
- Generate freely

Q16. How would you want to implement the input for the stepping of span length in the software?

- Steps of 1,5m
- Steps of 0,5m
- Steps of 0,1m

Q17. Are there any other inputs you would want to base the data on?

Q18. Would it be interesting to generate solutions which not meet the requirements from the inputs?

- Very interesting
- Partly interesting
- Not interesting

Q19. This software optimises structural systems based on climate impact and cost. Would it be interesting to implement other criteria? If yes, what criteria?

Q20. How useful would it be to be able to weigh the fitness function for every project individually?

- Very interesting

- Partly interesting
- Not interesting

Q21. How would you want the result to be presented to give enough clarity to be useful as a basis for decisions?

- Table with CO2 equivalent emissions and cost for the total system
- Solution space
- 3D model of the structural system
- Calculations with results
- Bar chart with CO_2 equivalent emissions and cost for the total system

Q22. Do you have any other suggestions on how the result could be presented?

Q23. To what extent would this software be useful in your work as a structural engineer?

- To a high extent
- To a partly high extent
- To a medium-high extent
- To a partly low extent
- To a low extent

Q24. How would this software facilitate your work as a structural engineer?

Q25. What do you think would be the biggest challenge for using this software?

A.3 Discussion

D1. Do you make different choices when designing multistory residential buildings compared to when designing other types of buildings?

D2. How flexible should the inputs in the software be?

D3. How should the fitness function be handled? Should it be changeable?

D4. To whom would the software be useful?

D5. How should the result be presented?

D6. Would it be interesting to be able to see the choice of structural systems from previous projects?

D7. Would it be interesting to receive feedback from a structural system used in previous projects?

D8. What challenges do you see with the usage of the software?

D9. This software optimizes structural systems based on climate impact and cost. Would it be interesting to implement other criteria? If yes, what criteria?

B

Bearing capacity calculations

In the following appendix, the calculations regarding bearing capacity made, is presented.

IPE-beam

Calculation of cross section classes

Geometry of the beam:

$h := 100 \cdot 10^{-3}\ m$

$b := 55 \cdot 10^{-3}\ m$

$tf := 5.7 \cdot 10^{-3}\ m$

$tw := 4.1 \cdot 10^{-3}\ m$

$R := 7 \cdot 10^{-3}\ m$

$hw := h - (2 \cdot tf) = 0.089\ m$

$A := (hw \cdot tw) + (2 \cdot tf \cdot b) = (9.903 \cdot 10^{-4})\ m^2$

Yield strength:

$fy := 355 \cdot 10^{6}\ Pa$

Parameters used to decide the cross section class of the web:

$d := hw - 2 \cdot R = 0.075\ m$

$$\varepsilon := \sqrt{\frac{235 \cdot 10^{6}\ Pa}{fy}} = 0.814$$

$$Web := \left\| \begin{array}{l} \text{if } \dfrac{d}{tw} < 72 \cdot \varepsilon \\ \quad \| \text{“Web in CS class 1”} \\ \text{else if } 72 \cdot \varepsilon > \dfrac{d}{tw} < 83 \cdot \varepsilon \\ \quad \| \text{“Web in CS class 2”} \\ \text{else} \\ \quad \| \text{“Web in CS clss 3”} \end{array} \right\| = \text{“Web in CS class 1”}$$

Parameters used to decide the cross section class of the flanges:

$$c := \frac{b}{2} - R - \frac{tw}{2} = 0.018\ m$$

$$Flanges := \left\| \begin{array}{l} \text{if } \dfrac{c}{tf} < 9 \cdot \varepsilon \\ \quad \| \text{“Flanges in CS class 1”} \\ \text{else if } 9 \cdot \varepsilon > \dfrac{c}{tf} < 10 \cdot \varepsilon \\ \quad \| \text{“Flanges in CS class 2”} \\ \text{else} \\ \quad \| \text{“Flanges in CS clss 3”} \end{array} \right\| = \text{“Flanges in CS class 1”}$$

IPE-beam

Section modulus:

$$W\_pl := 39.4 \cdot 10^3 \ mm^3$$

$$W\_el := 34.2 \cdot 10^3 \ mm^3$$

$$W := \left\| \begin{array}{l} \text{if } \dfrac{c}{tf} < 10 \cdot \varepsilon \wedge \dfrac{d}{tw} < 83 \cdot \varepsilon \\ \quad \| W\_pl \\ \text{else} \\ \quad \| W\_el \end{array} \right\| = \left(3.94 \cdot 10^4\right) \ mm^3$$

Moment capacity

$$M\_ed := \left\| \begin{array}{l} \text{if } \dfrac{c}{tf} < 10 \cdot \varepsilon \wedge \dfrac{d}{tw} < 83 \cdot \varepsilon \\ \quad \| W\_pl \cdot fy \\ \text{else} \\ \quad \| W\_el \cdot fy \end{array} \right\| = 13.987 \ kN \cdot m$$

Circular column

Geometry of the column:

$d := 168.3 \cdot 10^{-3}\ m$

$t := 8 \cdot 10^{-3}\ m$

$L := 2.5\ m$

$$A := \left(\left(\frac{d}{2}\right)^2 - \left(\frac{(d-2\cdot t)}{2}\right)^2\right) \cdot \pi = 0.004\ m^2$$

Yield strength:

$fy := 355 \cdot 10^{6}\ Pa$

Elastic modulus:

$E := 210 \cdot 10^{9}\ Pa$

Buckling factor:

$n := 1$

Moment of inertia:

$$I := \left(d^4 - (d - 2\cdot t)^4\right) \cdot \pi = \left(8.303 \cdot 10^{-4}\right)\ m^4$$

Critical buckling load:

$Nc\_Rd := A \cdot fy = \left(1.43 \cdot 10^{3}\right)\ kN$

Compression resistance:

$$N\_cr := \frac{\left(\pi^2 \cdot E \cdot I\right)}{(n \cdot L)^2} = \left(2.753 \cdot 10^{5}\right)\ kN$$

The load used:

$N := min\left(Nc\_Rd, N\_cr\right) = \left(1.43 \cdot 10^{3}\right)\ kN$

Rectangular column

Geometry of the column:

$b := 300 \cdot 10^{-3}\ m$

$t := 12.5 \cdot 10^{-3}\ m$

$L := 2.5\ m$

$A := b^2 - (b - 2 \cdot t)^2 = 0.014\ m^2$

Yield strength:

$fy := 355 \cdot 10^6\ Pa$

Elastic modulus:

$E := 210 \cdot 10^9\ Pa$

Buckling factor:

$n := 1$

Moment of inertia:

$$I := \frac{b^4}{12} - \frac{(b - 2 \cdot t)^4}{12} = \left(1.984 \cdot 10^{-4}\right)\ m^4$$

Critical buckling load:

$Nc\_Rd := A \cdot fy = \left(5.103 \cdot 10^3\right)\ kN$

Compression resistance:

$$N\_cr := \frac{\left(\pi^2 \cdot E \cdot I\right)}{(n \cdot L)^2} = \left(6.579 \cdot 10^4\right)\ kN$$

The load used:

$N := min(Nc\_Rd, N\_cr) = \left(5.103 \cdot 10^3\right)\ kN$

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