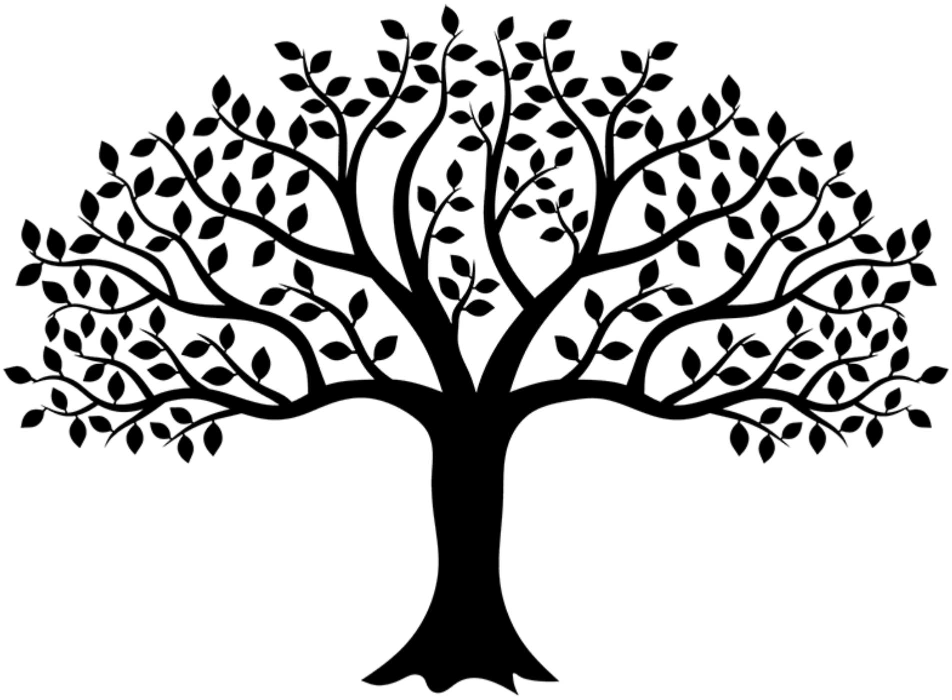

Multi-objective optimization of prefabricated slabs

A case study in parametric design

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

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DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
Division of Structural Engineering, Concrete Structures

CHALMERS UNIVERSITY OF TECHNOLOGY
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Master's thesis ACEX30

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Abstract

Starting in 2022, the Swedish government will introduce a new law, demanding climate declarations from developers of new buildings. Structural engineers have an important role when it comes to deciding on a suitable design that satisfies demands on climate impact, cost and efficacy. One may call this a multi-objective optimization problem.

The purpose is to contribute to the reduction of the climate impact in the design process. The aim is to present a method that can be used by structural engineers to choose the optimal prefabricated element with respect to climate impact and element costs. The objective is to create an algorithm able to vary parameters and produce a database with all possible solutions as output.

The investigation of this master thesis was divided into three different parts. The first part included a literature study on material, slab elements, climate analysis and optimization. After the literature study, the second part continued with generation of database including FE analysis, LCA calculation and cost estimation. The third part of this study consists of post-processing and presenting extracted results from the database through creation of scatter plots, linear regression and Decision Tree Models. The study presents a workflow possible of measuring optimality according to the established definition. The inclusion of more design and behavioural constraints will further improve the detail level of the study. The use of Decision Tree Models was found advantageous and further testing could lead to trained algorithm capable of predicting optimality of elements not originally part of the database.

Keywords: Climate impact, Life Cycle Analysis, Slab design, Finite Element, Full Factorial Design, Decision Tree Model.

Multi-objektiv optimering av prefabricerade bjälklag
En fallstudie i parametrisk design
Examensarbete inom masterprogrammet Structural Engineering & Building Technology
William Karlsson
Gabriella Zayton
Institutionen för arkitektur och samhällsbyggnadsteknik
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Sammanfattning

Under 2022 kommer den svenska regeringen att införa en ny lag som kräver klimatdeklarationer av byggherrar. Konstruktörer har en viktig roll när det gäller att besluta om en lämplig design som uppfyller kraven på klimatpåverkan, kostnad och effektivitet. Man kan kalla detta ett multi-objektivt optimeringsproblem.

Syftet är att bidra till att minska klimatpåverkan i designprocessen. Målet är att presentera en metod som kan användas av konstruktörer för att välja det optimala prefabricerade elementet med hänsyn till klimatpåverkan och elementkostnader. Målet är att skapa en algoritm som kan variera parametrar och producera en databas med alla möjliga lösningar som utdata.

Studien delades in i tre olika delar. Den första delen inkluderade en litteraturstudie om material, bjälklag, klimatanalys och optimering. Efter litteraturstudien fortsatte den andra delen med generering av databas inklusive FE-analys, LCA-beräkning och kostnadsberäkning. Den tredje delen av studien består av analys och presentation av extraherade resultat från databasen genom att skapa spridningsdiagram, linjär regression och beslutsträdmodeller. Studien presenterar ett arbetsflöde som kan användas till att mäta optimalitet enligt den etablerade definitionen. Implementering av fler design-och beteendebegränsningar kommer att ytterligare förbättra detaljnivån i studien. Användningen av trädbeslutsmodeller visade sig vara fördelaktig och ytterligare tester kan leda till en tränad algoritm som kan förutsäga optimalitet av element som inte ursprungligen ingick i databasen.

Nyckelord: Klimatpåverkan, Livscykelanalys, Dimensionering av bjälklag, Finita Element, Fullständig Faktoriell Design, Beslutsträdmodell.

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Preface

This study presents a less common approach to optimization that can be applied on prefabricated slab elements regarding climate impact, cost and structural performance. This subject is niche and the authors of this study had to be creative in their approach to generate databases, automatic Finite Element design and apply fundamental machine learning. The study is a Master's thesis at the Department of Structural Engineering, Concrete Structures, Chalmers University of Technology, Sweden, carried out from January 2021 to June 2021. This project was made possible with the help and support of Associate Professor Rasmus Rempling as supervisor. Further support was given by Lisa Parg and Oskar Mangold, Structural Engineers at WSP. A special thanks to our supervisors for guiding and motivate us during these special circumstances of writing a Master Thesis during a pandemic. We also appreciate the input from engineers at different disciplines at WSP helping us through our writing.

William Karlsson & Gabriella Zayton, Gothenburg, June 2021

Acronyms

A1	Phase in Life Cycle Analysis regarding material production
A2	Phase in Life Cycle Analysis regarding transportation
A3	Phase in Life Cycle Analysis regarding production of elements
A4	Phase in Life Cycle Analysis regarding transportation
A5	Phase in Life Cycle Analysis regarding erection and installation
csv-file	Comma separated values - file
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide-equivalent
CLT	Cross Laminated Timber
EPD	Enviromental Product Declaration
FE	Finite Element
FEM	Finite Element Method
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
SLS	Service Limit State
struXML	File format in FEM design software developed by Strusoft
ULS	Ultimate Limit State
XML	Extensible Markup Language

Notations

Roman upper case letters

I	Total climate impact of an element region measured in kg CO_2-eq

Roman lower case letters

f	Notation for the objective function used to clarify performance of a structural design
i	Partial climate impact of an element region from a specific phase in the LCA measured in kg CO_2-eq
$k_{concrete}$	Climate impact per kg from varying concrete class in A1-A3 measured in kg CO_2-eq /kg
$k_{element}$	Climate impact per kg from a specific phase in the LCA measured in kg CO_2-eq /kg
$k_{reinforcement}$	Climate impact per kg from a specific phase in the LCA measured in kg CO_2-eq /kg
m^n	Total amount of experimental points in a Full Factorial Design
$m_{element}$	Element mass in kg
$m_{reinforcement}$	Reinforcement mass in kg
w	Object specific weight factor
x	Design variable or constraint used as input into the objective function
y	Response variable or constraint used as input into the objective function

1

Introduction

1.1 Background

The United Nations Department of Economic and Social Affairs (2019) has identified four “megatrends” that will impact the world’s population and therefore also the continuous sustainable development. The four megatrends impacting global demographics include population growth, even though the world’s population has started to grow in a slower pace, half the population growth is concentrated to only nine countries. Population ageing combined with increased life expectancy indicate that by 2050 the number of persons above the age 65 will have doubled the number of children under the age of five (United Nations Department of Economic and Social Affairs, 2019). Furthermore, two other megatrends are migration and urbanization that will have a big impact on population growth but also where people live.

With this continuous population growth, the construction industry faces the paradoxial demands created from heavy demands on producing housing, offices and shops often with cost effective budgets and short production times, simultaneously as carbon emissions should be kept at minimum.

> *The number of buildings in the world will double by 2060. It is like we are going to build a new New York City every month for the next 40 years. It is a gigantic amount of materials. Steel, cement, wood, all emitting greenhouse gases. We are going to have to figure out how to make all these things in a different way (Gates, 2019).*

Starting in 2022, the Swedish government will introduce a new law, demanding climate declarations from developers of new buildings. The purpose of this law is to reduce the climate impact from the construction stage of a building. To aid companies with creating declarations, the National board of housing, building and planning will distribute an open source database with generic climate data values for a wide range of resources and products used in construction (Boverket, 2020a). As of spring 2021, a pre-build of the database has been launched for companies during a testing period.

Consultants and entrepreneurs in Sweden are already adapting to this change in the industry. For example, consultants at WSP Sweden are adapting through an internal environment focused project group. They are in charge of long term projects, educating co-workers and developing new calculation tools. Clear and highly detailed calculations of climate impact and optimality are thought to become more and more advantageous to win competitive procurements in the coming years (WSP, 2021).

Structural engineers have an important role when it comes to deciding on a suitable solution that satisfies demands on climate impact, cost and efficacy. One may call this a multi-objective optimization problem. Engineering in its essence is to search for optimal solutions (Wetterberg, 2020). Perhaps the structural engineers' constant desire to optimize may contribute towards building a new New York a month in the future, efficient and cheap but also with a low climate impact. This study will focus on the multi-objective optimization of prefabricated slab alternatives due to their relatively significant impact on climate impact and cost of a structure.

1.2 Purpose, aim and objectives

The purpose is to contribute to the reduction of climate impact in the design process. The aim is to present a method that may be used by structural engineers to choose and compare optimal prefabricated element with respect to climate, element costs and structural performance in an early project stage. This method will include creation of a custom algorithm able to vary parameters and produce a database with all possible solutions as output. This database will then be analyzed both manually by the authors but also using basic machine learning techniques. The presented method's applicability as well as advantages and disadvantages will be discussed in detail.

1.3 Research questions

- Which parameters are vital when it comes to optimization of prefabricated slab alternatives and in what order should they be prioritized to be chosen to reach a certain optimality?
- What information and what kind of generalized data is presented in databases today?
- What kind of information or generalized data could be added to databases to improve the use in complex comparisons of structural elements?

1.4 Limitations

In order to investigate the mentioned issues, the following aspects are set to limit the study:

- Optimization on element level analysis
- Prefabricated slab elements of type hollow core, filigree, solid concrete and CLT
- Rectangular geometry of slab area
- Rectangular geometry of slab element cross section
- Residential houses with spans between 4-20 meters
- Life cycle analysis including stages A1-A5
- Climate data obtained from WSP Sustainability group and the National board of housing, building and planning
- Climate impact calculated as CO_2-eq
- Costs of elements calculated as net cost obtained from the annual Building Masters Calculation tool and the calculation software Bidcon distributed by Elecosoft
- Project location is assumed to be ideal with 0-10 km transportation to construction site

1.5 Methodology

The investigation of this master's thesis was divided into three different parts. The first part consists of a literature study, see Chapter 2-5. In Chapter 2 the materials concrete, steel and timber are presented in detail with relevant information leading into the next chapter. Chapter 3 presents some of the most common prefabricated slab elements that will be used in the study. In this chapter are properties of each element presented including normal span ranges, thickness and net cost. Data of material cost and element cost were retrieved from the annual Building Masters Calculation tool and the calculation software Bidcon distributed by Elecosoft. The theoretical study continues in Chapter 4 with literature presenting how climate impact was analyzed through Life Cycle Analysis and explains what information can be gathered from Environmental Product Declarations. Chapter 4 also presents the climate database used in the thesis, which was retrieved from the National board of housing, planning and building open database (Boverket, 2020a). The last chapter in the literature study includes general definition of the term optimal, alternative approaches to slab optimization and general information on methods used to analyze large databases (See Chapter 5).

With the information presented in Chapter 2-5 a base knowledge was established for performing optimization of different slabs with regards to climate impact, cost and structural performance.

The second part of the investigation consists of implementing the knowledge gathered for the literature study and perform a full factorial design. This part of the study would result in a final database with as many individual slab designs as possible including their climate impact, cost and structural performance. The first step was to establish Finite Element models (FE models) in FEM design according to the reference project (see Section 6.1 for reference project). Models for filigree, solid slab and CLT slab where designed in FEM design. The modelling of slabs was made in the software program FEM Design where relevant geometry, loads and load cases were implemented. Design checks according to Eurocode was performed in FEM Design. The output was exported as csv-files to later be used for analysis and validating that the model acts according to expectations. Hollow core elements structural performance was alternatively taken from general tabular data due to FEM design lacking the ability to perform design checks on hollow core elements.

When each model was established a custom-made algorithm written in python (see Chapter 6) was used to iterate climate calculations, cost calculation and FE analysis results for varying element designs and sending the collected information as an entry to a database.

The third part of this study consists of post-processing and presenting extracted results from the earlier stage, see Chapter 7. The database is presented with general statistical information including average values of key parameters. Normalized climate impact and cost are presented in two-dimensional scatter plots. Additional plots presents the same plots in three-dimensional scatter plots with the inclusion of maximum utilization on the z-axis. The database was thereafter analyzed through a machine learning method called decision tree modelling to predict the influence of each parameter and create plots that can be used as aid when it comes to decision making on designs in an early stage. The Decision Tree Models were also used as proof of concept to show the models capability to predict element designs optimality which are not included in the database.

Research questions along with results from the previous chapter can be seen in Chapter 8 and the final conclusions from the study are presented in Chapter 9.

2

Slab Element's Materials

2.1 Concrete and its components

Concrete is defined as a man-made stone material which consists of a blend of mixing gel materials, coarse-fine aggregate and water (Zhang, 2011). However, the most commonly used concrete in the construction industry according to Zhang (2011) is the cement concrete which also is referred to as ordinary concrete. Cement combined with water takes the roll of a mixing gel and fills the gaps between aggregates to create a hard, versatile and durable material. Cement is the most important component in a concrete mixture due to its strict impact on the cost and durability of the final material.

Cement has many advantageous properties, some of them are described above but one major drawback is the relative high amount of carbon emissions during the production process (Glavind, 2009). The climate impact from different concrete classes is presented in Table 4.1.

The cement production tributes to about 8 percent of the world's total carbon emissions (Sivakrishna et al., 2020). Recent development, especially during the last decade, have resulted in many innovative alternatives to ordinary concrete and Sivakrishna et al. (2020) collectively referred to these alternatives as Green concrete. For further details of climate improved concrete and non-improved concrete, see Chapter 4. Green concrete is not necessarily defined as a concrete type but instead an informal classification of a concrete that has less embodied energy, less carbon emissions and optionally implements waste or reused materials. One of the main methods developed in recent years is partial replacement of the ordinary (Porter) cement with supplementary materials. The supplementary materials consist mostly of waste material collected from other industries. The most common supplementary materials are fly ash collected from coal burning and slag collected from the metal industry (Sivakrishna et al., 2020).

2.2 Steel in construction

The use of steel in construction has seen a stagnation over the latter half of the twentieth century and onwards. In the United States for example, steel is the thirteenth most used material by volume while concrete, cement and sand can be found at the top of the same list. Even though the use of steel in construction has stagnated compared to concrete which have tripled in used volume since the 1950's, it still accounts for 4.7 percent of the total carbon emissions in the EU (Horvath, 2004).

Steel production today is divided into two different production routes. The traditional route is to use natural resources in the form of iron ore and processed through energy demanding production to produce steel (Morfeldt et al., 2015). The production route includes treatment in blast furnace and refinement through oxygen furnace at high temperatures. The second production route uses steel scrap at the end of its life cycle and refine it once more through a less climate demanding process using an electric arc furnace. This route can in theory be close to net zero in $C0_2$-eq, dependent of what energy source is used to power the electric arc furnace.

The secondary route is advantageous when it comes to decreasing the $C0_2$ emissions of a structure with about 70 percent reduction of carbon emissions and 60 percent lower energy consumption (Morfeldt et al., 2015). Even though the advantages of the secondary production route are vast, the industry is still heavily dominated by the primary production route due to lacking availability of scrap metal. Even though this is thought to be improved, Morfeldt et al. (2015) states that 50 percent of steel production will still be produced using the primary production route by 2050.

In average, the steel manufacturers in the EU have a carbon emittance of 1000 kg CO_2-eq per ton (LCA phase A1, see Section 4.1) (Celsa Steel Service, 2021). This value is of course highly dependent of supplier and region. In northern Europe some of the leading manufacturers of reinforcement are Celsa steel service and BE-group which includes Kaunas metal and Serfas steel (WSP, 2021). Celsa Steel Service is Sweden's leading manufacturer and supplier of reinforcement in the construction industry who also produces their products from 100 percent scrap metal. Their reinforcement steel is produced using the secondary production route which results in an equivalent carbon emission of 413 kg CO_2-eq per ton steel (LCA phase A1-A3, see Section 4.1) (Celsa Steel Service, 2021).

Two other manufacturers and suppliers of reinforcement commonly used are Kaunas Metal and Serfas located in Lithuania. Both companies are distributed by BE Group Sweden. Kaunas Metal have an equivalent emission of 516 kg CO_2-eq per ton and Serfas have an equivalent emission of 780 kg CO_2-eq per ton (for LCA, A1-A3). The CO_2-eq per ton steel for different manufacturers are presented in Table 4.1. See Chapter 4 for further details of climate impact calculation of reinforcement.

2.3 Timber in modern construction

The interest in timber construction has risen and is thought to increase in the coming years due to the awareness of its potential when it comes to building sustainable (Woodard & Milner, 2016). The process of turning wood into timber products uses a relative low amount of energy compared to similar processes for other construction materials. As a renewable, recyclable and biodegradable material, Woodard & Milner (2016) describe timber as having the greatest potential of common building materials to be produced greenhouse positive.

Timber is used in many occasions when it comes to house construction. It can be used as flooring, facade elements and as structural elements. To become a structural element the material is refined by different processes. Commonly used refining methods include planning, profiling and gluing. After refining, the material can become structural elements in form of Laminated Veneer Lumber, beams or Glue Laminated Timber (Träguiden, 2017b).

The structural timber is labeled after the characteristic bending resistance. The most commonly used structural timber in Sweden is of capacity C14, C18, C24, C30 and C35 (Träguiden, 2017a). For the CLT used in this study the equivalent emissions are 0.12 kg CO_2-eq per ton (for LCA, A1-A3), see Chapter 4 for further details on climate calculation of timber elements.

3

Prefabricated Slab Elements

A slab is defined as a structural element distributing the load down to the foundation by nearby connected structural elements (Engström, 2011). A "one-way" slab is a slab supported on two supports on opposite sides and carries the load mainly in one direction. In cases when a slab has more than two supports on opposite sides the slab is called a "two-way" slab and carries the load in more than one direction.

"One-way" concrete slabs can be made as solid slabs and hollow core slabs. Filigree slab is a half-prefabricated variant of a solid slab whereas a solid slab is fully prefabricated. Even though the market is heavily dominated by concrete slab alternatives, the interest in CLT-options have increased and will be covered in this study (Hellberg, 2015).

To manage the sound level requirement of the slab there are several factors interesting to investigate in. The thickness of the slab and the different layers of sound reducing materials are two interesting factors. In a case study called "Impact sound insulation of floor systems with hollow brick slabs" it is presented how the impact of the several layers of different materials is giving a large benefit of the sound performance of the slab (Souza et al., 2020). However, in this study, the sound level requirement will not be considered.

The costs of elements are mainly retrieved from the calculation software Bidcon distributed by Elecosoft. Prices of materials were collected from the annual Building Masters Calculation tool. Both calculation tools contain costs of material, work performances and calculations of housing projects presented as net prices. The net prices are based on prices of materials excluding the assembly at site. The prices are derived from ideal project condition with no consideration of long transport distances, challenging foundations and multiple floor levels. For elements with varying concrete class the following cost seen in Table 3.1 has been used to calculate elements total cost.

Table 3.1: Cost of concrete (Svensk Byggtjänst, 2021).

Concrete class	Material cost
C28/35	1 743 SEK/m^3
C30/37	1 814 SEK/m^3
C32/40	1 884 SEK/m^3
C35/45	1 954 SEK/m^3
C40/50	2 024 SEK/m^3
C45/55	2 094 SEK/m^3

3.1 Hollow core slab

Hollow core slabs are prefabricated and prestressed concrete elements with longitudinal hollow cores in one direction which results in a large amount of weight being reduced (Al-Azzawi & Aziz, 2017). Hollow core slabs are most commonly used in roofs and intermediate floors of offices, schools and hospitals primarily but are also occasionally used in apartments and industrial facilities (Betongelementföreningen, 2010).

Figure 3.1: *Hollow core element (type HD/f-200) mounted by crane at construction site.*

3.1.1 Properties of hollow core slabs

The standard width for hollow core element is 1 200 mm, while the thickness and length are dependent on the chosen cross section (Betongelementföreningen, 2010). The elements are categorized by their cross section with a fixed thickness dependent on the chosen cross section. Industry standard thicknesses in mm are 200, 265, 320, 380, 400 and 500 (Skandinaviska Byggelement, 2021a). These standard thicknesses however can be adjusted marginally if needed during the casting without any additional cost but on the other hand an increase of weight and slight reduction of capacity (Betongelementföreningen, 2010). Elements can be manufactured in various lengths up to spans about 18 m (Skandinaviska Byggelement, 2021a). Elements are prestressed with strands varying from 4 up to 19 strands per element (Contiga AB, 2021). Hollow core slabs are usually covered with an additional 20-50 mm of concrete casted on site to get an even floor level and to reduce the sound transmittance (Svensk Betong, 2021c). Fire class R60 is fulfilled by every type of hollow core slab independent of thickness (Betongelementföreningen, 2010). R90 and R120 can be achieved for most element types by slight adjustment the cover thickness and element height. The cores can be used effectively to pass cables and pipes for electricity, heating, ventilation and air conditioning (Betongelementföreningen, 2010).

3.1.2 Net cost of hollow core materials

The cost of the hollow core unit is divided into two parts. The element cost is including the hollow core unit and smoothening using float and laser, see Table 3.2.

Table 3.2: *Cost of hollow core slab (Bidcon, 2021).*

Category	Material cost	Labor cost
Smoothening	-	8 SEK/m^2
Hollow core unit	3 279 SEK/m^3	126 SEK/m^3

3.2 Solid concrete slab

Solid reinforced concrete slab is an element, much like the hollow core, ready to be mounted when arriving to the site. The solid concrete slab is beneficial, especially in residential housing due to the relative low sound transmittance through the slab. Solid concrete slab can be reinforced and prestressed to manage large spans (Skandinaviska Byggelement, 2021).

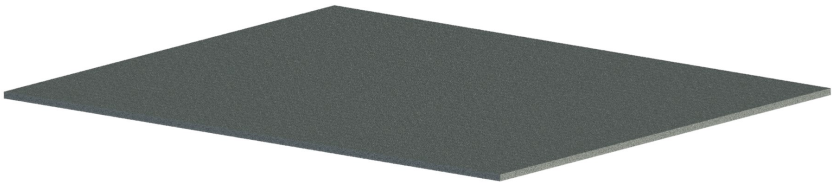

Figure 3.2: *Solid concrete slab model.*

3.2.1 Properties of solid concrete slab

A typical element is usually designed with a width up to 3.1 m and has a concrete casting of 20-40 mm on site to get an even floor level. Length and widths of the element is usually determined by transport demands where at least on side must be shorter than 4.2 m to be able to be transported on a trailer (Svensk Betong, 2021a). Installations and cast in materials are added during production of the element to have it ready to be mounted when arriving to the site and in this way improve the efficiency (Strängbetong, 2021).

Table 3.3: *Span for reinforced and prestressed solid slab (width 2.4 m) for residential houses (Svensk Betong, 2021a).*

Reinforced		Prestressed	
Thickness [mm]	Span [m]	Thickness [mm]	Span [m]
150	4.8	150	7
200	5.5	200	8

3.2.2 Net cost of solid concrete slab materials

The cost of the solid concrete slab is divided by different parts as formwork, smoothening, reinforcement, concrete and polishing. The cost is presented in Table 3.4.

Table 3.4: *Cost of concrete slab (Bidcon, 2021).*

Category	Material cost	Labor cost
Formwork	59 SEK/m^2	160 SEK/m^2
Smoothening	-	7 SEK/m^2
Reinforcement	12 SEK/kg	9 SEK/kg
Reinforcement mesh	43 SEK/m^2	18 SEK/m^2
Concrete	See Table 3.1	118 SEK/m^3
Polishing	6 SEK/m^2	36 SEK/m^2

3.3 Filigree slab

Filigree slab is mainly used for construction of residential buildings and prefabricated bridges. The filigree element can be either reinforced or prestressed. Filigree slab is prefabricated as a thin bottom plate which then is casted with a secondary layer of concrete on the construction site. When the reinforced plate arrives to the site, installations and reinforcement are added and the slab is casted with concrete to its full thickness. Compared to other prefabricated elements, the filigree slab is casted together with the walls instead of using steel connections. This results in a more connected structure (Skandinaviska Byggelement, 2021b). Filigree slab works as a mold for the installations and the rest of the slab casting that is made on site. In this type of element there are possibilities to add openings and recesses (Skandinaviska Byggelement, 2021b).

Figure 3.3: *Filigree elements mounted at construction site.*

3.3.1 Properties of filigree slab

The most common thickness used in residential buildings is 250 mm due to the sound level requirement and to have enough space for installations (Svensk Betong, 2021b). For the reinforced filigree the plate has a thickness of 45 mm respectively 70 mm for the prestressed plate. The slab is casted with a concrete of class between C30/37 - C40/50. For spans smaller than 6m the reinforcement of the plate can be used as lift for the slab and therefore minimize cost and use of material (Thomas Betong, 2021). The maximum width for the filigree slab is 2.4 m (Abetong, 2021). Reinforced filigree slab can be used for spans up to 10 m respectively 12 m for the prestressed version (Svensk Betong, 2021b).

Table 3.5: *Typical span length for various thicknesses of reinforced filigree slab for residential houses (Svensk Betong, 2021b).*

Thickness of slab [mm]	Typical span length [m]
200	4.9
220	5.3
250	5.7
300	6.6

3.3.2 Net cost of filigree materials

The cost of the filigree slab is divided by different parts as formwork, smoothening, reinforcement, reinforcement mesh, concrete and polishing. The cost of filgree slab is presented in Table 3.6 .

Table 3.6: *Cost of filigree slab (Bidcon, 2021).*

Category	Material cost	Labor cost
Smoothening	-	7 SEK/m^2
Concrete casted on site	See Table 3.1	109 SEK/m^2
Reinforcement	12 SEK/kg	9 SEK/kg
Filigree unit	403 SEK/m^2	81 SEK/m^2
Special reinforcement and shoring	27 SEK/m^2	52 SEK/m^2

3.4 CLT slab

CLT or Cross Laminated Timber is defined as a construction element consisting of a minimum of three layers of boards or planks glued together with each layer placed perpendicular to the previous layer. The simplest version of a CLT slab is a so-called Flat floor structure. A Flat floor structure is a solid panel with is simply determined by the number and thickness of layers. This type of CLT slab can be used in housing and offices with shorter spans. Some additional construction is usually needed to fulfill sound and fire requirements. (Borgström & Fröbel, 2019)

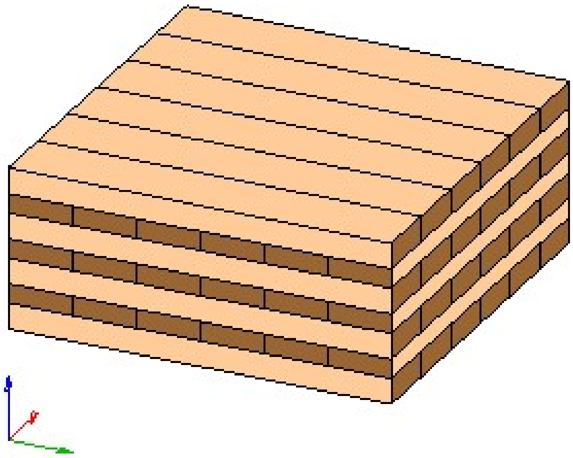

Figure 3.4: *Illustration of Cross laminated timber slab (Strusoft, 2021).*

3.4.1 Properties of CLT slab

Each board or plank usually has a thickness between 20 mm and 45 mm (but up to 60 mm is available). Width of each plank or board varies between 80 mm and 200 mm. Strength classes typically used are between C14 and C30 (Borgström & Fröbel, 2019).

3.4.2 Net cost of CLT unit

The cost of the CLT is only including the slab unit which is divided into material cost and labour cost, see Table 3.7.

Table 3.7: *Cost of CLT element (Bidcon, 2021).*

Category	Material cost	Labor cost
CLT unit	4 900 SEK/m^3	185 SEK/m^3

4

Climate Impact Analysis

4.1 Life cycle analysis

A Life Cycle Analysis (LCA) is a method used for calculating the environmental impact of a material or a product during its total lifespan (Boverket, 2019). With an LCA is it possible to analyze and understand during which period of the life cycle the largest impact can be found. The LCA gives an overall assessment of the environmental impact including climate impact, ground-level ozone, degradation of stratospheric ozone, acidification and more (Boverket, 2019).

In this study the focus will be on the climate impact. The most optimal way of handling an LCA is to be aware of the impact of the material choices and structural solutions early in the design phase of a building process. Life Cycle Analysis consists of four steps which are performed successively: Goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation (Pagnon et al., 2020). These four steps are illustrated in Figure 4.1 below.

Figure 4.1: *Stepwise methodology for performing a Life Cycle Analysis.*

A LCA of a building is divided into three main phases (Boverket, 2019). The building phase (A), the usage phase (B) and the final phase (C). In this study the focus will be on the product impact of the building phase (A). In this study A1-A3 are not studied separately instead they are presented as a unit. Each subphase in phase *A* can be seen in Figure 4.2 below.

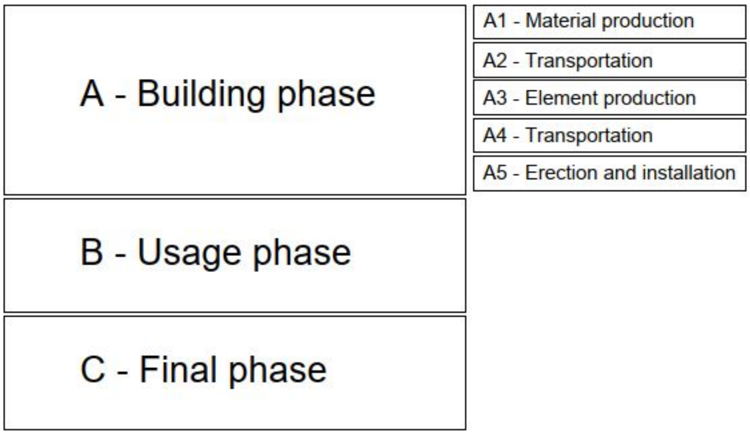

Figure 4.2: *The different phases of the LCA for a building.*

The Swedish government has proposed to settle a new law the 1 January 2022 about climate declarations of new buildings (Boverket, 2020a). To aid companies to perform climate declarations, databases are established both domestically by the National board of Housing, Building and Planning (Boverket) but also by private companies who has identified the demand of high-quality databases. Of the handful of European open-source databases available, Pagnon et al. (2020) imply that there are no database available today that contains all or enough data to be used exclusively in the construction sector. Pagnon et al. (2020) also state that even though data is scattered among several databases at this moment, there are current trends to collect all data under one unified format. This would provide a more detailed database which can be implemented for more fair and widespread use of LCA in the construction sector.

4.2 Environmental product declaration

An Environmental Product Declaration (EPD) is an accounting of the environmental performance of a product. The declaration is based on calculations from an LCA. The EPD-report is presenting the phases of the LCA calculated and the amount of the environmental impact created by the product. The climate impact is one of the factors presented in an EPD and is represented with the unit kg CO_2-eq per m^2 or per kg. CO_2-eq, carbon dioxide equivalents, is a unit used when presenting the amount of greenhouse gas emissions. This unit is developed to include the fact that different gases impact the global warming in different magnitudes (Saint Gobain, 2021).

An EPD is an option to use when discussing and choosing material for a building in the early building process. To calculate the climate impact of a product the total amount of material is calculated and combined with the information given in the EPD for the product used (Saint Gobain, 2021).

An EPD is classified as specific data when used in climate declarations and is encouraged to be used from the National board of housing, building and planning. This information can be difficult to find and therefore can generic data from databases be used to replace the need of EPD (Boverket, 2021).

4.3 Generic climate data from the national board of housing, building and planning

The generic climate data from the National board of housing, building and planning became accessible in the beginning of 2021. The only generic data that will be allowed in 2022 to be used in climate declarations is from the National board of housing, building and planning database itself (Boverket, 2020b).

Therefore, data for this study was taken directly from the demo-version of their database that will be released officially 1st of June 2021. For a conservative calculation of A1-A3 a factor of 1.25 can be multiplied to the climate impact (Boverket, 2020a). Data collected from the database for this study includes concrete classes, hollow core, filigree, solid slab and CLT elements, see Table 4.1 and Table 4.2 for extracted data.

Table 4.1: *Climate impact, (kg (CO_2-eq/ton) dependent on concrete class from the National board of housing, building and planning (2021).*

Concrete class	kg CO_2-eq/ton	kg CO_2/ton (improved)
C28/35	0.1365	0.1024
C30/37	0.1446	0.1084
C32/40	0.1476	0.1108
C35/45	0.1630	0.1223
C40/50	0.1755	0.1316
C45/55	0.1420	0.1410

Table 4.2: *Climate impact, (kg CO_2-eq/kg) dependent on element type from the National board of housing, building and planning (2021).*

Element	A1-A3 [kg CO_2-eq/kg]	A4 [kg CO_2-eq/kg]	A5 [kg CO_2-eq/kg]
Hollow core	0.1700	0.045	0
Hollow core (improved)	0.1275	0.0324	0.01275
Solid concrete	-	0.045	0
Solid concrete (improved)	-	0.045	0
Filigree	-	0.045	0
Filigree (improved)	-	0.045	0
CLT – conifer	0.12	0.0345	0.006

4.4 Climate data from WSP Sweden

The National board of housing, building and planning climate database was used to as high extent as possible. When it came to data regarding reinforcement the information was considered inadequate. Therefore, data used by WSP and their manual calculation of slab climate impact was used to make the database more specific, see Table 4.3. Their data included the three manufacturers Celsa Steel Services, Kaunas Metal and Serfas Metal, see Section 2.2. These manufacturers where selected due to their common use in Sweden (WSP, 2021).

Table 4.3: *Climate impact (kg CO_2-eq/kg) of selected reinforcement manufacturers. (WSP, 2021)*

Manufacturer	kg CO_2-eq/ton
Celsa Steel Service	413
BE-group (Kaunas Metal)	516
BE-group (Serfas Metal)	780
Average manufacturer in the EU	1 000

4.5 Climate impact calculation of slab elements

For this study the climate data is retrieved from the climate database of the National board of housing, planning and building presented 2021. In Section 4.5.1-4.5.4 the calculation of the total climate impact, I is presented for each element type. The climate impact per phase, i is calculated by multiplying the general data factor per phase, k with the respective element mass, m.

4.5.1 Climate impact calculation of hollow core element

Calculation of hollow core climate impact was generalised to only depend on the total mass of the element. The general climate impact factors were taken directly from the National board of housing, planning and buildings database (2021). See Equations 4.1-4.4 below for calculation of climate impact from hollow core element.

$$i_{A1-A3} = k_{element.A1-A3} * m_{element} \tag{4.1}$$

$$i_{A4} = k_{element.A4} * m_{element} \tag{4.2}$$

$$i_{A5} = k_{element.A5} * m_{element} \tag{4.3}$$

$$I = i_{A1-A3} + i_{A4} + i_{A5} \tag{4.4}$$

4.5.2 Climate impact calculation of solid concrete element

Calculation of solid concrete element climate impact was generalised to only depend on the concrete mass and the reinforcement mass of the element. The general climate impact factors were taken directly from the National board of housing, planning and buildings database (2021). See Equations 4.5-4.8 below for calculation of climate impact from solid concrete element.

$$i_{A1-A3} = 1.25 * (k_{concrete.A1-A3} * m_{concrete} + k_{reinforcement.A1-A3} * m_{reinforcement}) \tag{4.5}$$

$$i_{A4} = k_{element.A4} * (m_{concrete} + m_{reinforcement}) \tag{4.6}$$

$$i_{A5} = k_{element.A5} * (m_{concrete} + m_{reinforcement}) \tag{4.7}$$

$$I = i_{A1-A3} + i_{A4} + i_{A5} \tag{4.8}$$

4.5.3 Climate impact calculation of filigree element

Calculation of filigree element climate impact was generalised to only depend on the concrete mass and the reinforcement mass of the element. The general climate impact factors were taken directly from the National board of housing, planning and buildings database (2021). See Equations 4.9-4.12 below for calculation of climate impact from filigree element.

$$i_{A1-A3} = 1.25 * (k_{concrete.A1-A3} * m_{concrete} + k_{reinforcement.A1-A3} * m_{reinforcement}) \tag{4.9}$$

$$i_{A4} = k_{element.A4} * (m_{concrete} + m_{reinforcement}) \tag{4.10}$$

$$i_{A5} = k_{element.A5} * (m_{concrete} + m_{reinforcement}) \tag{4.11}$$

$$I = i_{A1-A3} + i_{A4} + i_{A5} \tag{4.12}$$

4.5.4 Climate impact calculation of CLT element

Calculation of CLT element climate impact was generalised to only depend on the total mass of the element. The general climate impact factors were taken directly from the National board of housing, planning and buildings database (2021). See Equations 4.13-4.16 below for calculation of climate impact from CLT element.

$$i_{A1-A3} = k_{element.A1-A3} * m_{element} \tag{4.13}$$

$$i_{A4} = k_{element.A4} * m_{element} \tag{4.14}$$

$$i_{A5} = k_{element.A5} * m_{element} \tag{4.15}$$

$$I = i_{A1-A3} + i_{A4} + i_{A5} \tag{4.16}$$

5

Methods Used for Structural Optimization

Per definition, structural optimization means making an assemblage of materials sustain loads in the best way (Christensen & Klarbring, 2009). The term “best” however can be highly debatable. Christensen & Klarbring (2009) suggest definitions of the “best” structure could be for example the lightest structure, the stiffest structure or the structure most insensitive to instability. By minimizing or maximizing the structures ability to withstand load in a predefined “best way”, an optimal solution can be derived. To achieve a well-defined solution to the optimization problem, constraints or limitations are needed (Christensen & Klarbring, 2009).

The term optimal can also be used freely in common terms with subjective interpretations of what truly is an “optimal” solution. Optimality will be presented in this chapter from a mathematical point of view. This report is limited to optimize the design of prefabricated slab elements. The optimization is categorized as *size optimization* which is presented more extensively in Section 5.1 in combination with Full Factorial Design presented in Section 5.4.

A structure can be optimized on a system level including optimization on the manufacturing process, transportation and assembly at site. Another option is to optimize each structural element on a component level to ensure that the design is optimal according to specified demands (Christensen & Klarbring, 2009). This study is focused on optimizing structures on an element level but the aspects of optimizing on a system level is acknowledged by the authors of this study. The overall impact of optimization on a system level will not be presented or discussed further in this study.

When it comes to slab elements, one approach to climate optimization is discussed by Sehlström & Nyström (2020) on optimization of slabs in the form of vault or arched structures. Sehlström & Nyström (2020) discuss recent development of modern vault structures able to minimize the amount of material needed and thereby reducing the climate impact of the structure. One project mentioned in their article was originally developed at ETH in Zurich by Block Research Group (BRG). This project studied prefabricated concrete shell structures with minimized material use, see Figure 5.1. This project is minimizing by altering the geometry in multiple ways. The two most prominent geometry parameters are the arch geometry and the amount of material replaced by voids which later is filled with lightweight concrete (Sehlström & Nyström, 2020). Both changes to the geometry compared to a standard flat and solid slab element can be described as examples of shape optimization (or topology optimization arguably) which will be discussed in the next section regarding the homogenization approach.

Figure 5.1: *Climate optimized concrete "vault" structure developed by BRG (BRG, 2020).*

Another approach to slab optimization is to use a voided biaxial slab. This method uses hollow plastic containers placed inside the element before casting, see Figure 5.2. This leads to a heavily reduced concrete volume. Similar to the prefabricated hollow core element, the voided biaxial slab can by its reduced weight be used for longer spans. One major disadvantage with having large voids in the element is the reduced shear resistance which is strictly connected to the concrete volume (Churakov, 2014).

Figure 5.2: *Voided biaxial slab (Mortensen, 2016).*

Voided biaxial slab is yet another example that may be defined as topology optimization, see Section 5.1.

5.1 The homogenization approach

One prominent method used for optimization is the homogenization approach also referred to as the homogenization method (Bendsøe, 1995). This method is used to find the optimal layout of linear elastic structure. The term layout represents information of the structure which can be categorized into topology, shape or sizing information. The method can be used to optimize the structural layout in its entirety or of a certain selected category.

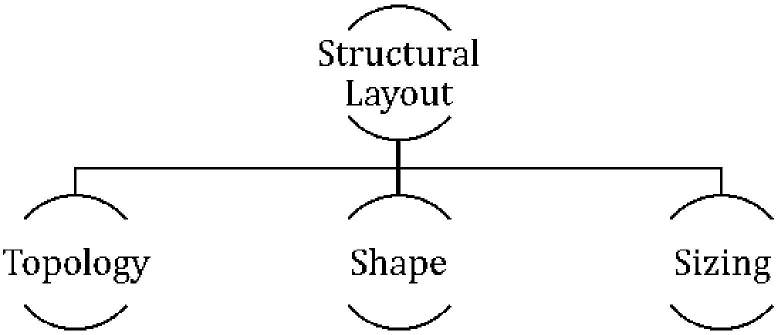

Figure 5.3: *Illustration of the hierarchy and categories of information included in the structural layout.*

Shape optimization is typically used to create a contour of the structural domain (Christensen & Klarbring, 2009). This can be used for example to find the optimal function to describe the shape or curvature of a load bearing structure. The problem is limited by a fixed number of nodal points as boundary conditions.

Figure 5.4: *Illustration of shape optimization performed on a hollow core slab (Bendsøe & Sigmund, 2003).*

Topology optimization is used to allow members or design variables to take the value zero which in practice would mean removal of structural member or creation of voids in a material (Christensen and Klarbring, 2009). Topology optimization can be either pure binary where the optimal thickness is either 1 or 0, i.e. material exists in the node or not. It can also be altered by a density function which can vary the density ranging from 1 to 0 of each node to find the optimal solution (Christensen & Klarbring, 2009).

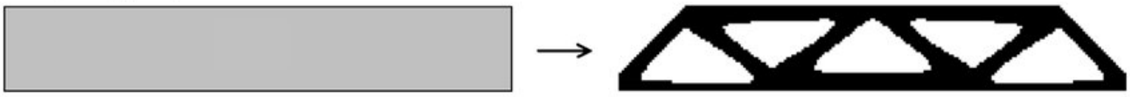

Figure 5.5: *Illustration of topology optimization on a solid material region (Bendsøe & Sigmund, 2003).*

Size optimization is implemented on selected parameters of the structure (Christensen & Klarbring, 2009). Each parameter has a specified size which can be a length, diameter, area or classification which will be varied within certain limits to find the optimum solution (Christensen & Klarbring, 2009). Within the limit of this study, examples of size parameters would for example be slab thickness, reinforcement diameter or span length.

Figure 5.6: *Illustration of size optimization where line thickness represents bar dimension (Bendsøe & Sigmund, 2003).*

5.2 Structural optimization problem formulation

When a structure's layout has been defined and on what categories the optimization will be performed on, a problem formulation and specification of parameters can be defined (Bendsøe, 1995). It is also during the problem formulation that limitations and fixed data are presented as known quantities. Examples of fixed data could be applied loads, support conditions and prescribed design conditions (Bendsøe, 1995).

From a mathematical perspective an optimization problem always consists of the following functions and variables (Christensen & Klarbring, 2009). The objective function (f) is used to classify the performance of the design. The objective function usually returns a number where a “good” result is represented by small value for f. The design variable (x) can be a function or vector that represent geometry, material dimensions i.e. thickness, diameters, and material properties. The state variable (y) is a function or variable that represents the response which in this case would mean response in the form of displacement, stress, strain, or force. The structural optimization then takes the general form of Equation 5.1 (Christensen & Klarbring, 2009):

$$\begin{cases} minimize.f(x,y) \\ subject.to \begin{cases} behavioral.constraints \\ design.constraints \\ equilibrium.constraint \end{cases} \end{cases} \tag{5.1}$$

5.3 Multi-objective optimization

The general form of structural optimization problem is used to solve a single objective optimization. This formulation can also be expanded upon to cover multiple objective optimization. The general formulation of the multi-objective optimization problem is then presented in Equation 5.2 (Christensen & Klarbring, 2009):

$$\begin{cases} minimize.f_1(x,y), f_2(x,y)...f_l(x,y), \\ subject.to \begin{cases} behavioral.constraints \\ design.constraints \\ equilibrium.constraint \end{cases} \end{cases} \tag{5.2}$$

Where l denotes the total number of objective functions. Minimization of all objective functions using the same design variable x and state variable y is not very often able to be achieved. A solution to treat multiobjective optimization is to use *Pareto Optimality.*

Pareto Optimality is used to find a satisfying solution when an overall optimal design for all objective functions exists (Christensen & Klarbring, 2009). This solution denoted with variables x^* and y^* will be determined as the Pareto Optimal design. The Pareto Optimal solution will satisfy the objective functions according to Equation 5.3 and 5.4 (Christensen & Klarbring, 2009):

$$f_i(x,y) <= f_i(x^*,y^*).for.all.i = 1,...,l, \tag{5.3}$$

$$f_i(x,y) < f_i(x^*,y^*).for.at.least.one.i = 1,\ldots,l. \tag{5.4}$$

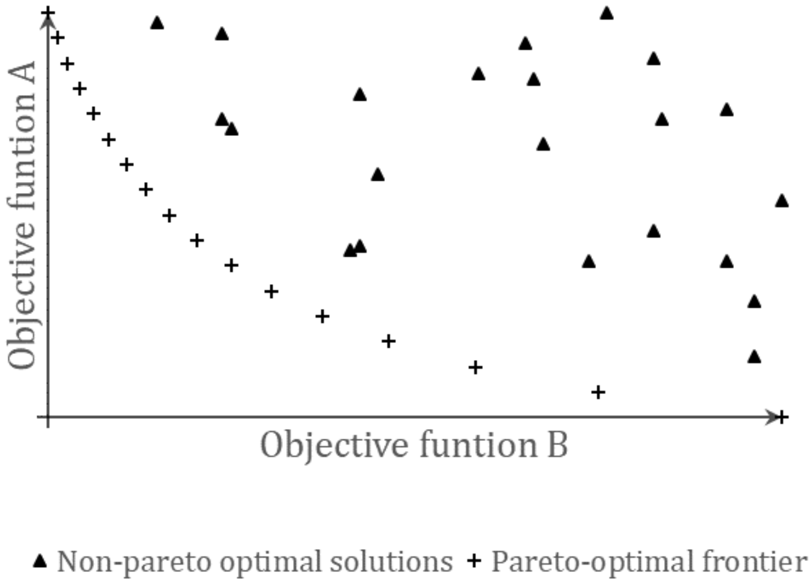

Figure 5.7: *Illustration of Pareto Optimality.*

The implementation of *Pareto Optimality* to solve the multi-objective optimization problem is used by introducing objective specific weight factors w (Christensen & Klarbring, 2009). Weight factors can be ranked by the performer of the optimization through a point system where a high numeric value I represents high importance. For example the scale could be: somewhat important=1; important=2; very important=3 (Ek et al., 2019). The weight factor w is then calculated according to Equation 5.5:

$$w_k = \frac{I_k}{\sum I_k} \tag{5.5}$$

5.4 Full-factorial Design (FFD)

For a Full-Factorial Design (FFD) experimental points are created based on all possible combinations and the factors of all different levels. A FFD, with n factors and with each factor having m different levels, the total amount of experimental points will be m^n (Sahoo & Barman, 2012).

FFD is a technique used for solving general problems where all possible solutions are generated (Mahoor et al., 2017). The possible solutions are checked to fulfill the statements for the problem. This approach is easy to implement and use since there are not any sophisticated intelligent methods needed. This algorithm is a possible method to use when looking for an element among many combinations. It is suitable to use this algorithm when there is a limited problem size (Mahoor et al., 2017).

JMP (2020) argues that using FFD as optimization method is conservative and expensive. When the number of factors increases the number of experimental points grows exponentially. Although for a custom design with limitations JMP (2020) believes this method can be cost-effective and efficient.

5.5 Decision Tree Model

A machine learning problem can be categorized into one of three groups. The first problem group is regression problems where numeric values are to be predicted, the second one is clustering problems where data needs to be sorted into groups to find certain patterns and trends. The final category is so called classification problems where logical statements with yes or no, true or false answers helps with solving the problem. A Decision Tree Model is used to solve the last-mentioned group, classification problems (Simplilearn, 2018).

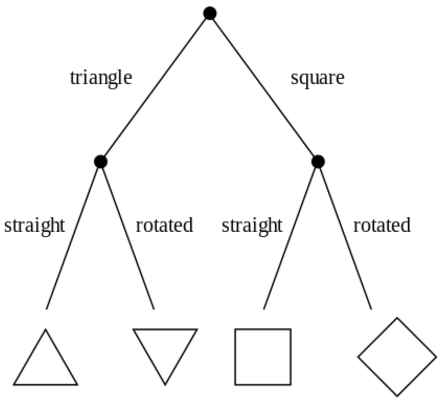

Figure 5.8: *Basic example of Decision Tree Model (Bach, 2013).*

The Decision Tree Model is a method used for extracting and presenting information in an easy and interpretable way. This method is not only suitable for large databases but can also predict results from historical data. A Decision Tree Model consists of nodes and branches where steps as splitting, pruning and stopping are used. The nodes represent decisions, possibility and final result of a combination. The branches represent paths of occurrences where each path is a classification decision rule. The nodes are then split into two or more categories. With a complex model it can be difficult to predict future results. Stopping rules are applied to prevent a model from becoming too complex. Pruning is used when the tree is grown into a large size and then customized to an optimal size by removing parts that contribute with less additional information (Song & Lu, 2015).

6

Implementation

The Full Factorial Design approach chosen for this study was implemented by using an external Python script, ran and written in Microsoft Visual Studio. The script acts as an access point to already established calculation models in FEM-design (3D finite element software). FEM-design was chosen as the base program due to its common use in the industry, but also due to its Application Programming Interface (API) functionality. An API is a computing interface which enables interaction between two or more programs through the universal XML-file format (StruSoft, 2021). This functionality enables the user to either create a file from scratch directly in Python or changing parameters in an already predefined file in the struXML format.

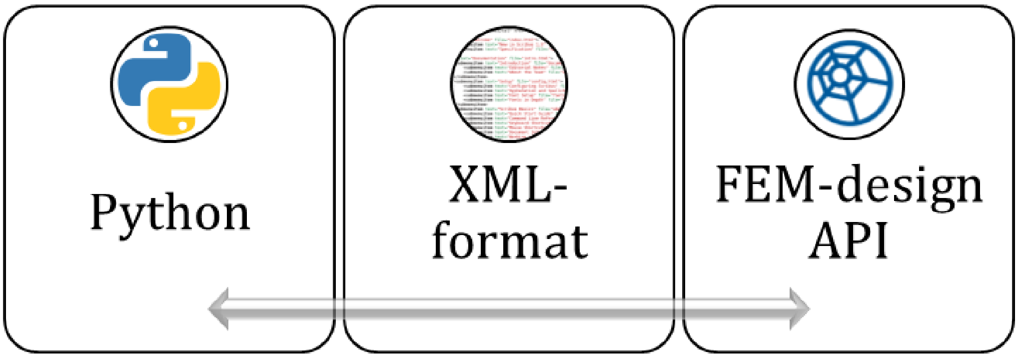

Figure 6.1: *Illustration of the interaction of the Optimization script with FEM-software.*

6.1 Reference project

This study is based on a construction project from WSP called Kv Apelsinen Etapp 1 built in 2011, see Figure 6.2. The project is a residential building of two floors located in Solna, Stockholm.

Figure 6.2: *Reference project (Kv Apelsinen Etapp 1) before and after picture (Eksta Bostads AB, 2015).*

The area consisted of multiple building with identical designs, as illustrated in Figure 6.3, hence it was found suitable to perform an analysis on. Each floor consists of three seperate slab regions with an area of 7.7 x 7.7 m. The total effective slab area is calculated to 356 m^2. The slab element of this project was chosen as a pre-stressed filigree slab with a thickness of 280 mm.

Figure 6.3: *Areal photograph of the reference project (TomTom, 2017).*

The original calculations, model and drawings of the project from WSP were used in this study to confirm that models in Section 6.2 and Section 6.3 below were established with correct results. The model was originally designed by WSP in

FEM Design (Figure 6.4) and therefore the natural choice was to recreate models for this study using FEM Design as well, see Section 6.2-6.3 for information on the establishment of FE models.

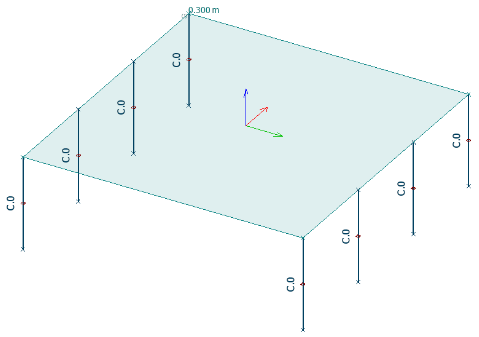

Figure 6.4: *Original model used by WSP in the reference project.*

6.2 Establishment of solid slab and filigree in FEM design

The design approach of these two element types are identical in the design phase but with the difference being prestressing of the filigree slab and needed casting on site. The differences will however not be significant in the design phase and are therefore controlled according to Eurocode with the same controls. Both elements were design in FEM design (3D structure).

6.2.1 Geometry used in solid slab and filigree design

The slab was designed as a single shell (plane plate) element with length and width according to Section 6.1. Slab thickness was set arbitrary to 200 mm as a starting parameter. The alignment was set to centre, and eccentricity was not considered. Support structures were modelled as load bearing walls with a thickness of 200 mm, this dimension will however be fixed during the whole optimization process. The height of load bearing walls was set to 3 m according to the reference project.

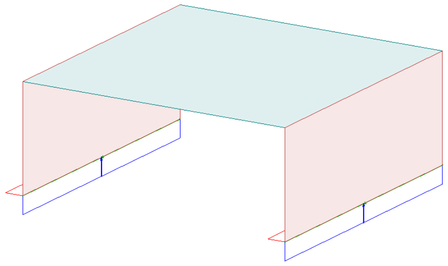

Figure 6.5: *Concrete element model geometry in FEM Design.*

6.2.2 Support conditions used in solid slab and filigree design

The slab was modelled as a one way with hinged connections on the supporting walls. Additionally, line supports were created to support the load bearing walls (see Figure 6.5).

6.2.3 Loads used in solid slab and filigree design

Loads considered in the design included dead weight, permanent loads, creep and shrinkage. No variable was needed to be defined or other special loads due to the rather simple project. The service load was set according to Eurocode to 2.5 kN/m^2 for residential housing and dead weight was calculated automatically in the FEM design software.

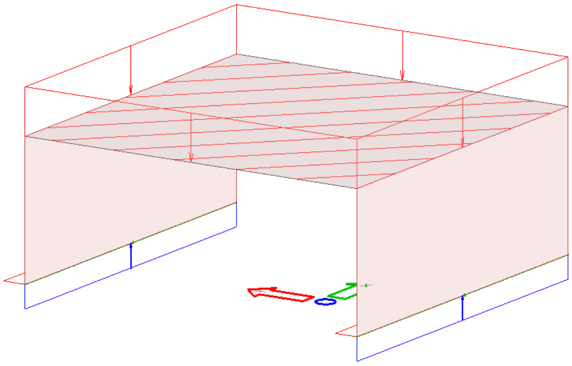

Figure 6.6: *Applied loads on concrete element model geometry in FEM Design.*

Loads were combined into load combinations, ULS (Ultimate Limit State) and SLS (Service Limit State) with the respective weight factors presented in Table 6.1.

Table 6.1: *Load combinations and weight factors used in Solid and Filigree design.*

Load Combination	Dead weight load factor	Permanent load factor
ULS 6.10b	0.89*1.35 = 1.20	1.50
SLS (Quasi permanent)	1.0	1.0
SLS (Characteristic)	1.0	1.0

6.2.4 Material models and FE-mesh used in solid slab and filigree design

The slab was designed using linear static analysis calculation with a FE mesh consisting of 9-noded rectangular elements. The mesh was only controlled for convergence initially since the optimization will not vary the boundary geometry and therefore the same mesh size can be used for all generated results. The final mesh can be seen in Figure 6.7.

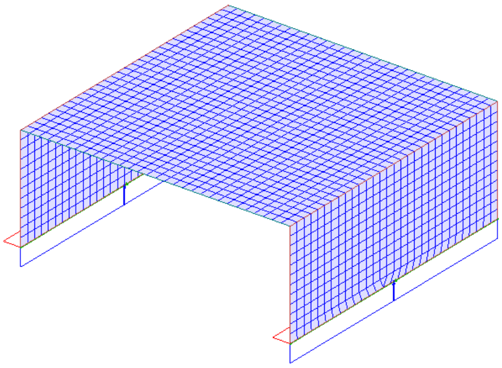

Figure 6.7: *Generated FE mesh on concrete element model geometry in FEM Design.*

6.2.5 Material models and FE-mesh used in solid slab and filigree design

FEM design allows the user to either create reinforcement layers by manual design where reinforcement is created in bottom, mid or top layer in either x- or y-direction. Alternatively, can the tool “Auto design” be used to generate a reinforcement alternative. This study used the Auto design tool to generate a reinforcement arrangement and thereafter validated the regions positioning and controlled the reinforcement mass per meter was logical. The reinforcement configuration chosen as a starting point for the optimization is presented in Figure 6.8, Figure 6.9, Table 6.2 and Table 6.3.

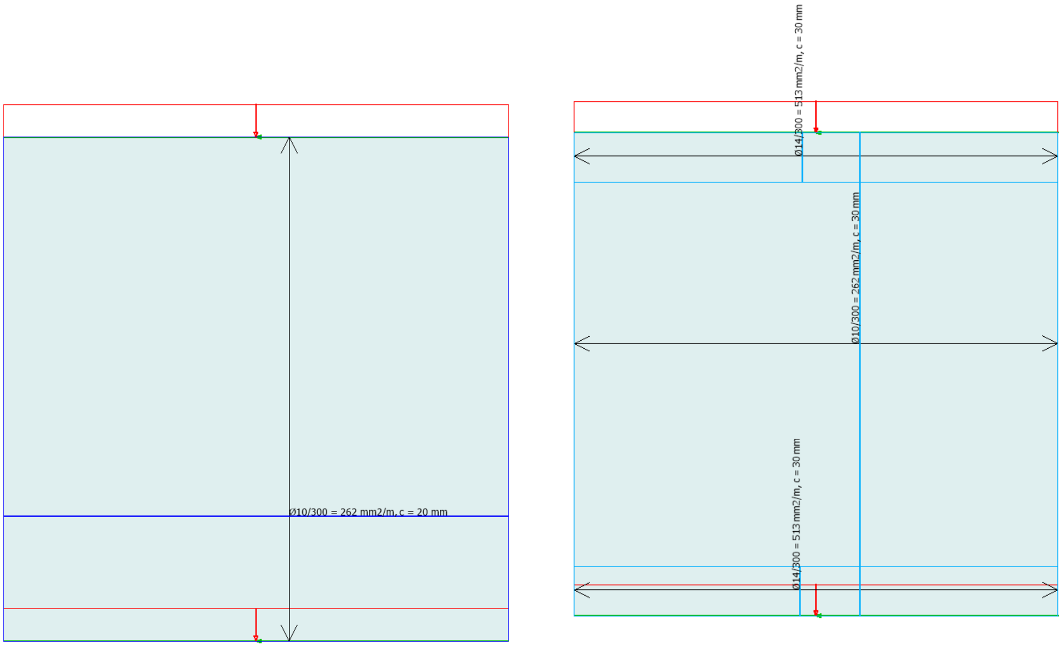

Figure 6.8: *Top reinforcement X-direction (left) and Y-direction (right) initial design.*

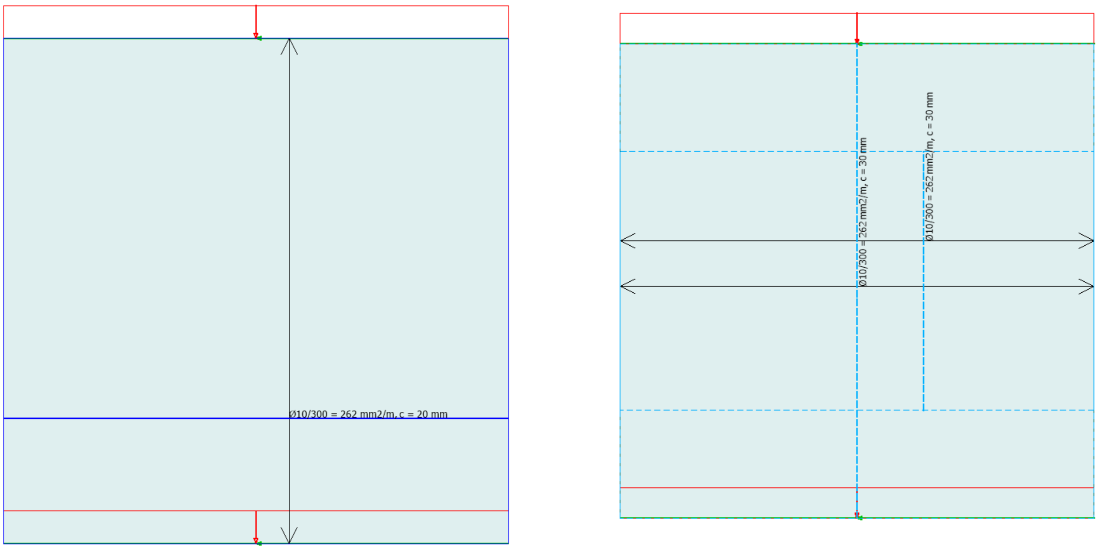

Figure 6.9: *Bottom reinforcement X-direction (left) and Y-direction (right) initial design.*

Table 6.2: *Top reinforcement configuration used as reference/starting point for optimization.*

	Primary X.dir	Primary Y.dir	Secondary X.dir	Secondary Y.dir
Quality	K500C	K500C	-	K500C
Cover [mm]	30	30	-	30
Bar diameter [mm]	10	10	-	14
Bar space [mm]	300	300	-	300

Table 6.3: *Bottom reinforcement configuration used as reference/starting point for optimization.*

	Primary X.dir	Primary Y.dir	Secondary X.dir	Secondary Y.dir
Quality	K500C	K500C	-	K500C
Cover [mm]	30	30	-	30
Bar diameter [mm]	10	10	-	10
Bar space [mm]	300	300	-	300

6.2.6 Results and analysis of initial sold slab and filigree design

After the analysis of the model was performed, results were generated into a csv-file which then was imported back to the Python-script. The Python-script generated five different csv-files two of them where related to deflection in the form of maximum characteristic deflection and maximum quasi-permanent deflection. These deflections were sent back to the script and checked according to Eurocode 2. One of the files included results in the form of utilization percentages from design checks according to Eurocode 2. The design checks made in this file are presented in Table 6.4. The final two files included material quantity data, where one generated concrete volume and the other generated steel reinforcement mass.

Table 6.4: *Design checks included in FEM-design output.*

Name of control	Acronym
Utilization of bottom reinforcement, x-dir.	RBX
Utilization of bottom reinforcement, y-dir.	RBY
Utilization of top reinforcement, x-dir.	RTX
Utilization of top reinforcement, y-dir.	RTY
Utilization for crack width on the bottom face	CWB
Utilization for crack width on the top face	CWT

6.3 Establishment of CLT elements in FEM design

One of the newest updates to FEM design is the addition of timber design where timber plates can be designed as orthotropic shell, cross laminated timber (CLT) or general laminated composite. This made the decision of including CLT elements in the study easy to make since majority of the algorithm was able to be implemented without changes.

6.3.1 Geometry used in CLT design

The slab was designed as a single shell (timber plate PTM) element with length and width according to Section 6.1. Slab thickness was set arbitrary to 250 mm using a predefined profile (see Figure 6.11) as a starting parameter. The alignment was to centre, and eccentricity was not considered. The physical model was set to panel with widths of 1.5 m while the analytical model was set to continuous. Support structures were modelled as load bearing walls with a thickness of 200 mm. This dimension is however fixed during the optimization process. The height of load bearing walls was set to 3 m according to the reference project.

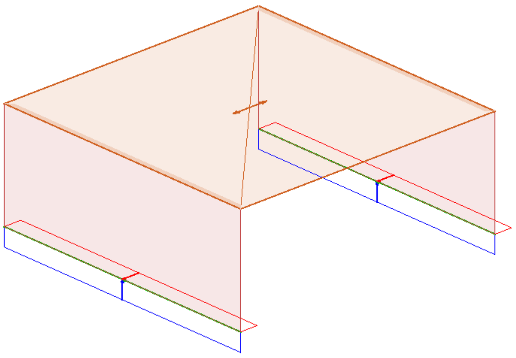

Figure 6.10: *CLT element model geometry in FEM Design.*

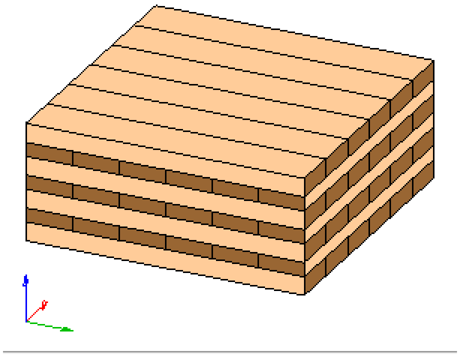

Figure 6.11: *Standard profile CLT250 L7s from Södra AB's product library.*

6.3.2 Support Conditions used in CLT design

Support conditions used for the CLT design were identical to those already presented in Section 6.2.2.

6.3.3 Loads used in CLT design

Loads considered in the design included dead weight, permanent loads, creep and shrinkage. No variable load was needed to be defined or other special loads due to the rather simple project. The permanent load was set according to Eurocode to 2.5 kN/m^2 for residential housing and dead weight was calculated automatically in the FEM design software.

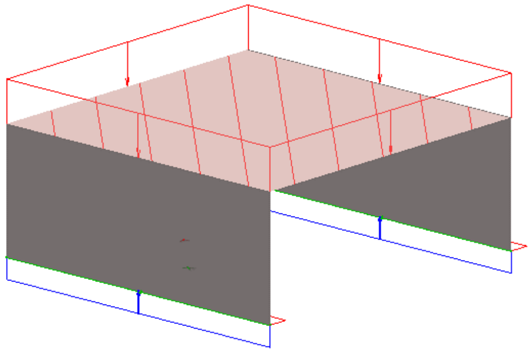

Figure 6.12: *Applied loads on CLT element model geometry.*

Loads were combined into two load combinations, ULS (Ultimate Limit State) and SLS (Service Limit State) with the respective weight factors presented in Table 6.1.

6.3.4 Material models and FE-mesh used in CLT design

The CLT slab was designed using linear static analysis calculation with a FE mesh consisting of 9-noded rectangular elements. The mesh was only controlled for convergence initially since the optimization did not vary the boundary geometry and therefore the same mesh size could be used for all generated results. The final mesh can be seen in Figure 6.13.

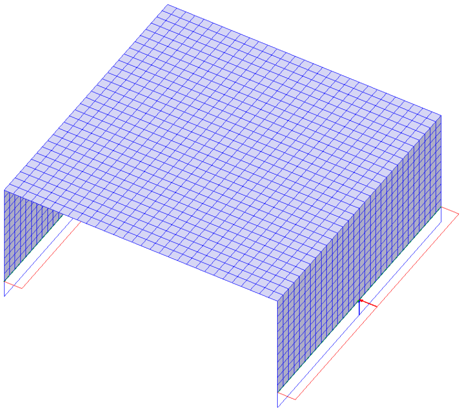

Figure 6.13: *Generated FE mesh on CLT element model geometry.*

6.3.5 Results and analysis of initial CLT design

Similar to Section 6.2.6 the output from FEM Design was generated into csv-files. The Python-script generated four different csv-files where two of these were related to deflection in the form of maximum characteristic deflection and maximum quasi-permanent deflection. These deflections were sent back to the script and checked according to Eurocode 5. One of the files included the result of design checks according to Eurocode 5. The design checks performed in this file are presented in Table 6.5. The last file included material quantity data of the CLT.

Table 6.5: *CLT design checks included in FEM-design output.*

Name of control	Acronym
Utilization for x-directional tension	Sx+
Utilization for y-directional tension	Sy+
Utilization for x-directional compression	Sx-
Utilization for y-directional compression	Sy-
Utilization for shear xy	Txy
Utilization for shear xz/yz	Tx/Ty

6.4 Design of Algorithm

Due to the vast amount of data that had to be generated and sorted a Python algorithm was the natural choice. The design of an effective and stable algorithm is of high importance when it comes to generating a database with thousands of individual entries for each possible configuration. The main script was written in Python, but a secondary script written directly in FEM design was also used to: establish the link between the main script, initiate the FE analysis as well as export design checks results for each loop. Packages used in Python included the subprocess, xml.etree.ElementTree, csv, time and pandas libraries to construct the algorithm.

The main script tasks for each iterative loop included:

- Choosing individual input parameters for the data entry
- Accessing the base file and replace said input parameters in the original models (presented in Section 6.2 and 6.3)
- Activating the secondary script (i.e. initiating FE analysis)
- Collect and filter the output results from the secondary script
- Calculate climate impact
- Calculate net cost
- Generate individual labels for each configuration
- Sort all results into a single row entry
- Send row with data to the database

Since the script was only linked to one of the two original models another script was designed to retrieve data entries from the concrete and CLT model as well. Both scripts had the same tasks but had to be designed differently due to slight differences in how the model was structured in its code. The main difference between the two scripts where that the concrete model was able to be altered by simply varying numerical values or material classes. CLT elements on the other hand needed to replace whole sections of the script since each standardized profile had their certain capacity and individual settings in FEM design. The script and its functions are visualized in Figure 6.14.

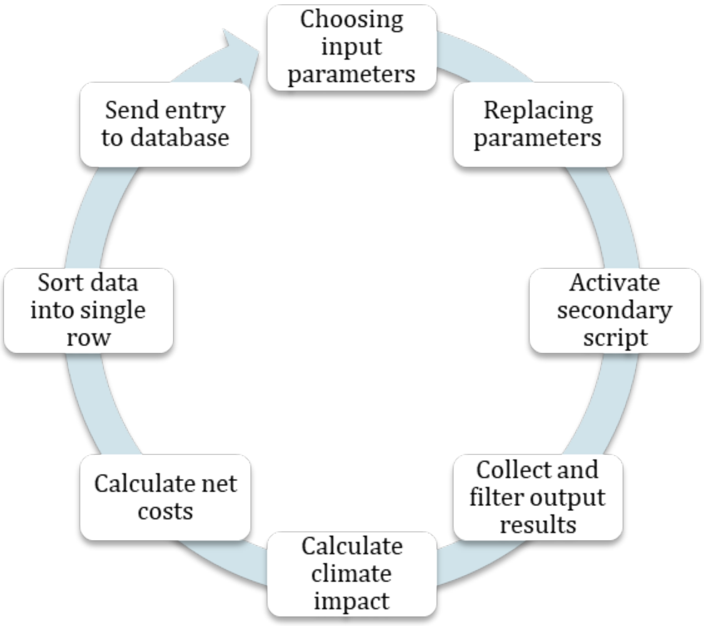

Figure 6.14: *Visualization of the tasks performed for each iterative loop of the script.*

Even though one full loop of the script only performed one FE analysis was a total of 12 entries to the database able to be produced per loop. This was made possible by switching parameters connected to costs and climate impact which did not affect the structural performance. One example is that the same FE analysis could be used as results for an entry with climate improved as well as non-improved concrete.

6.5 Variation of parameters

This section presents the parameters used for each element type and what values the parameter could take. For all element types, the applied load was varied in the algorithm between 1.5 to 5.0 kN/m^2 with 0.5 kN/m^2 intervals.

The span length of solid and filigree elements was varied between 5.0 m up to 12.0 m with 1 m intervals. The concrete class of solid and filigree elements was varied according to concrete classes presented in Table 4.1. The thickness of solid and filigree elements was varied between 200 mm up to 400 mm with 50 mm intervals. The climate impact from A1-A3 from reinforcement was varied according to the different steel manufacturers presented in Table 4.3. The solid and filigree element could be designed with climate improved concrete or non-climate improved concrete.

The span length of hollow core elements was varied between 4.0 m up to 18.0 m with 1 m intervals. The concrete class of hollow core elements was fixed as concrete class C45/55. The thickness of varied between 200 mm up to 400 mm including intermediate thicknesses according to Section 3.1.1. The number of prestressing strands was varied between 4 and 19 strands dependent on the profile and needed capacity. The hollow core element could be designed with climate improved concrete or non-climate improved concrete.

The span length of CLT elements was varied between 4.0 m up to 7.0 m with 1 m intervals. The profile of the CLT elements could be varied to all available profiles included in FEM Design but due to repetitiveness, the profile library was limited to 56 profiles included in the Södra AB (CLT manufacturer) product library.

6.6 Establishment of database and post-processing in R

Each of the two scripts had their separate database as an output where all data points were saved in a csv-file with the individual entries (i.e. slab configurations) as rows with parameters as columns. The two files share the same structure and was then able to be combined into a single database. Each entry was given a label with individual information specific to each entry to give a quick understanding of the configuration used. An example how the database looks when opened can be seen in Table 6.6.

Table 6.6: *Example of how the database was structured with individual labels and parameters as columns. Actual database includes a more extensive number of rows and columns.*

Id-nr	Label	Element type	Concrete quality
1	RD-200-6.0-C28/35-yes-Celsa-5.0-96	RD	C28/35
2	Filigree-200-6.0-C28/35-yes-Celsa-5.0-96	Filigree	C28/35
3	RD-200-6.0-C28/35-yes-Kaunas-5.0-96	RD	C28/35
4	Filigree-200-6.0-C28/35-yes-Kaunas-5.0-96	Filigree	C28/35
5	RD-200-6.0-C28/35-yes-Serfas-5.0-96	RD	C28/35
6	Filigree-200-6.0-C28/35-yes-Serfas-5.0-96	Filigree	C28/35

The generated and final database was imported into RStudio. RStudio is a development environment for the statistical programming language R. In this environment the data was cleaned through filtering, sorting and established as data frames. The necessary packages needed for the analysis included:

- farver
- ggplot2
- ggthemes
- dplyr
- plotly
- dplyr

The most important data related to this study was then normalized by dividing each parameter with known minimum value of said parameter. Several scatterplots were generated reflecting the CO_2-eq impact against cost. Three-dimensional plots were used to include the z-axis representing the utilization, see Chapter 7 for generated plots. The database was then analyzed through a fundamental machine learning technique called Decision Tree Model which splits the data and presents trends as well as key decisions of parameters and their effect on the optimality, see Section 7.4.

7

Results

Results presented in this chapter contain: an overview of the database including statistical information; relation between elements' climate impact and costs in two-dimensional scatter plots; relation between elements' climate impact, cost and utilization in three-dimensional scatter plots and categorical Decision Tree Models of the data.

Section 7.1 gives an overview of the database. Table 7.1 and Table 7.2 present key statistical values. Figure 7.1 - 7.3 illustrate the same values in box plots but also additional information in the form of first and third quartile values and overall spread of outliers in the data. Figure 7.4 - 7.6 present the frequency of values for the three specified output parameters (climate impact, cost and maximum utilization). Section 7.2 presents how data can be presented in normalized scatter plots and how optimal solutions can be found by filtering the data on both design and behavioral constraints. Section 7.3 presents plots similar to those in Section 7.2 but with the additional axis representing maximum utilization. Section 7.4 presents the Decision Tree Models generated for the outgoing parameters climate impact, cost and maximum utilization.

7.1 Overview of the database

The generated database from the second part of the study resulted in a database with 29 230 individual element designs with 56 parameters each. The total number of entries in the database per element type is presented in Table 7.1 below. The minimum and maximum values of the three output parameters (climate impact, cost and maximum utilization) are presented in Table 7.2.

Table 7.1: *Number of individual entries in the database per element type.*

Element type	Number of individual entries
Hollow core	3 742
Solid concrete	11 880
Fligree	11 880
CLT	1 728

Table 7.2: *Maximum, minimum and average values for selected output parameters in the database.*

	Climate impact [CO_2-eq/m^2]	Cost [SEK/m^2]	Max. Utilization [%]
Maximum	262	1961	2537
Minimum	5	305	5
Average	133	1389	85

Information in Table 7.2 as well as other statistical measurements of data are also visualized in Boxplots in Figure 7.1 - 7.3 below.

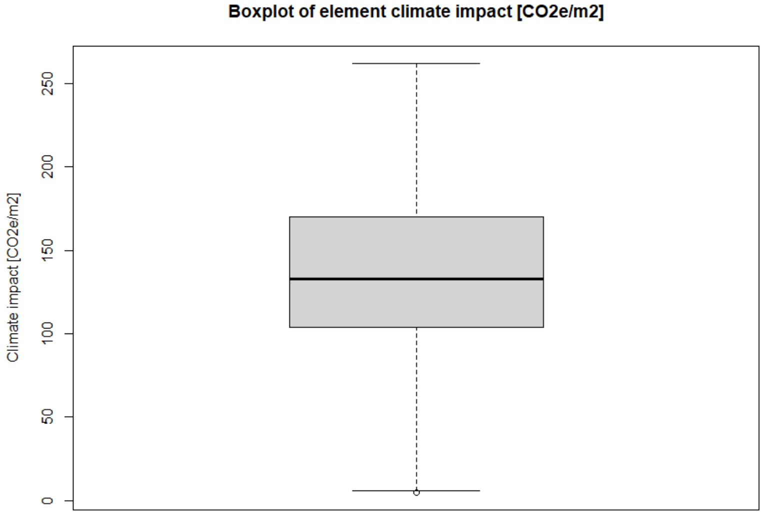

Figure 7.1: *Boxplot of element climate impact.*

Figure 7.1 presents statistical information regarding the values of output parameter climate impact. The median of the climate impact parameter is 133 (CO_2-eq/m^2).The interquartile range of the climate impact is 66 (CO_2-eq/m^2). Number of outliers in the data is relatively small and can only be seen towards smaller values in Figure 7.1.

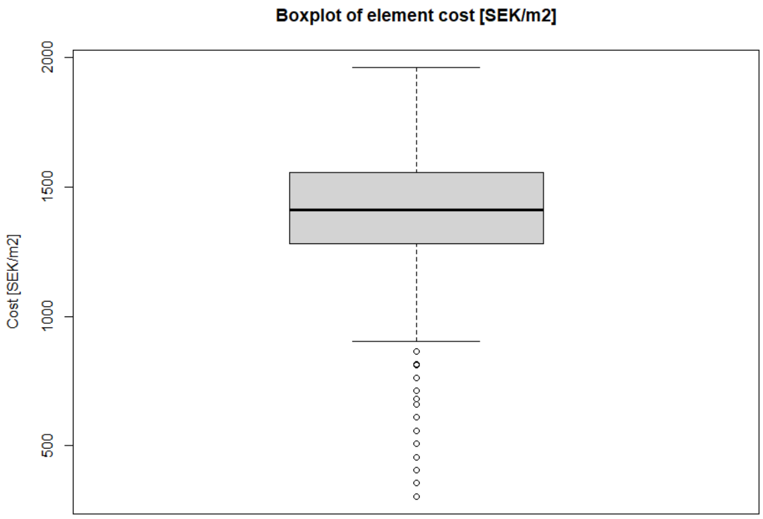

Figure 7.2: *Boxplot of element cost.*

Figure 7.2 presents statistical information regarding the values of output parameter cost. The median of the cost parameter is 1 411 (SEK/m^2). The interquartile range of the cost is 275 (SEK/m^2). Number of outliers in the data is relatively high and can be seen towards the smaller values in Figure 7.2.

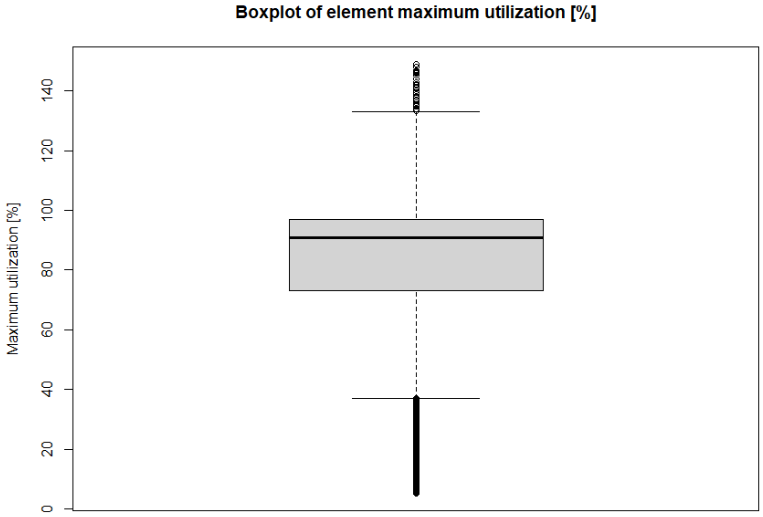

Figure 7.3: *Boxplot of element maximum utilization.*

Figure 7.3 presents statistical information regarding the values of output parameter maximum utilization. The median of the maximum utilization parameter is 91 (%). The interquartile range of the maximum utilization is 23 (%). Number of outliers in the data is high and can be seen both towards the smaller and bigger values in Figure 7.3.

The frequency of a parameter's value is another measurement of the database that can be useful to understand the generated database in detail. The histograms in Figure 7.4 -7.6 present the frequency of datapoints in a certain span of values. Each figure gives a specific view of where the database is overrepresented or in what range the database lacks information.

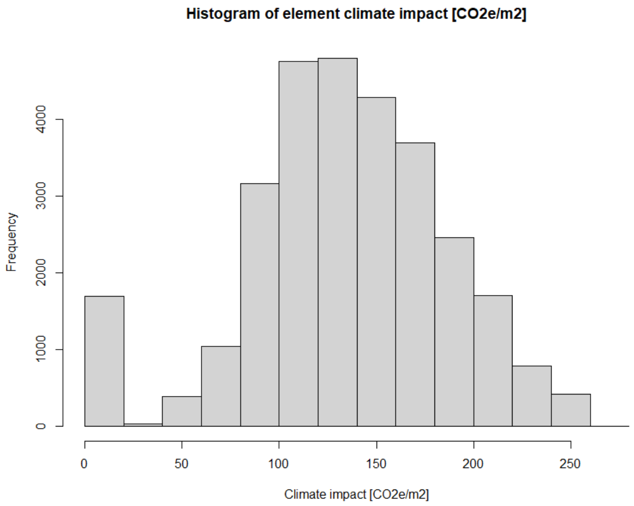

Figure 7.4: *Histogram presenting the frequency of climate impact data in the generated database.*

The presented frequency of climate impact in Figure 7.4 shows that the highest occurrences are located around 120 CO_2-eq/m^2. The frequency above this value can be estimated to be fairly normal distributed. The spread below 120 CO_2-eq/m^2 drops fast with low frequency within the range of 30-80 CO_2-eq/m^2. Although a high frequency can be found among the smallest value of climate impact.

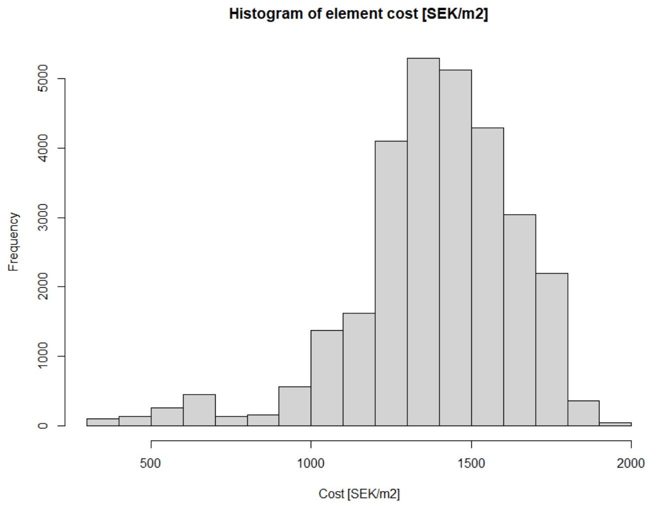

Figure 7.5: *Histogram presenting the frequency of cost data in the generated database.*

The presented frequency of cost in Figure 7.5 shows that the highest occurrences are located around 1 400 SEK/m^2. The frequency by this value is considered normally distributed. Below 1 200 SEK/m^2 a low frequency can be seen.

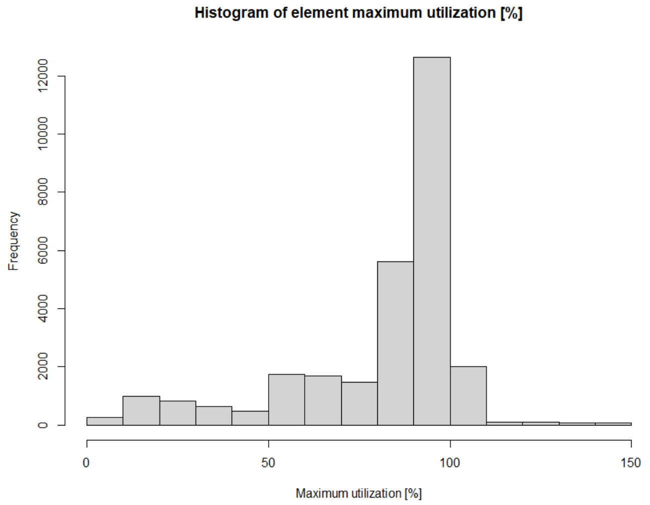

Figure 7.6: *Histogram presenting the frequency of maximum utilization data in the generated database.*

Most of the values in Figure 7.6 are in close proximity of 100 percent of the maximum utilization. The frequency below the limit of 100 percent is significantly higher than the frequency above said limit.

7.2 Relation between element climate impact and cost

The database was filtered and sorted in R, additionally the output parameters climate impact (CO_2-eq/m^2) and cost (SEK/m^2) were normalized by dividing each of these columns by their respective minimum value. The normalized data of climate impact (CO_2-eq/m^2) and cost (SEK/m^2) for the entire database with a total of 29 230 datapoints each is visualized in Figure 7.7. The data in Figure 7.7 is not meant to be used to get specific values of the two parameters but rather represent the relative position of each “data cloud” for each element. Solid slab elements and filigree elements are included in the same data cloud with a high amount of overlapping between the elements. These two element types have the highest number of varying parameters which results in less linear data compared to hollow core and CLT elements. Hollow core elements have a lower number of varying parameters. This element type has a fixed concrete type, variation of length and thickness and was determined by the available data in tables with limited amount of data. CLT elements are strictly linear in Figure 7.7 which is a result of both calculation of climate impact and element cost being exclusively dependent on volume. Another reason for the strictly linear data is the limited number of parameters that can be changed for this element type.

As presented in Section 5.3 the optimality is measured as a minimization of the two objective functions, which in this case are the output parameters climate impact and cost. This can be seen in Figure 7.7 as the bottom left node. Finding the bottom left datapoint however is not a good measure of optimality since maximum utilization is not represented in Figure 7.7 and thus it can lead to false solutions where the utilization is not fulfilled.

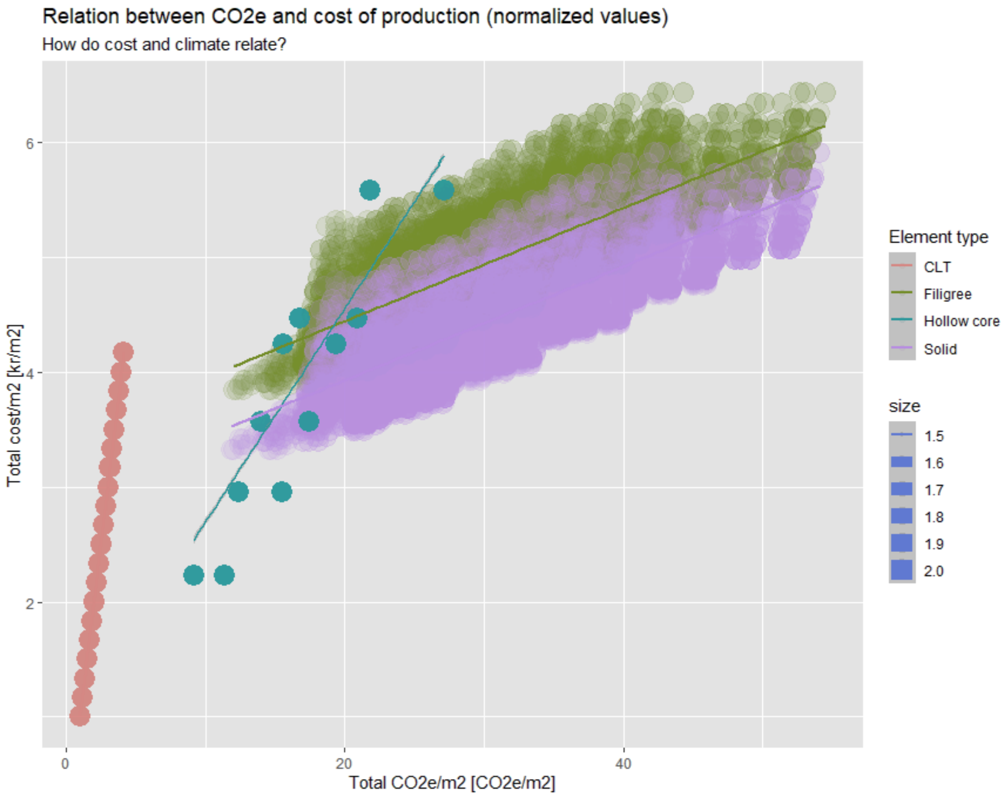

Figure 7.7: *Relation between CO_2-eq and cost of the full database. Database includes varying applied loads and span lengths. Data has not been filtered on utilization, hence data presented is not necessarily viable solutions.*

With a high amount of data needed to be visualized, the use of a single plot can easily be crowded which can lead to data being disregarded in comparisons. To aid the understanding of what regions are heavily dense with data, the density of the data was studied. The density of the data presented in Figure 7.8 shows that the overlapping region of filigree and solid slab options is about four times as dense with data as the CLT and hollow core data. The most heavily dense region within the data is the overlapping region towards the bottom left of the largest data region. This region is also shown in Figure 7.7 as the intersection point of the hollow core and filigree elements regression lines.

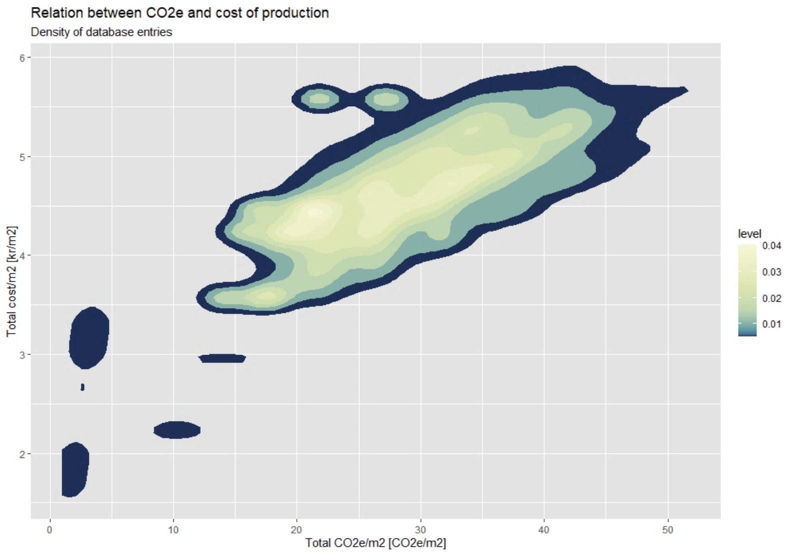

Figure 7.8: *Relation between CO_2-eq and cost of the full database (Visualization of density in the data).*

With acquired information of where data is positioned in the plot and where data is heavily dense, the database can be filtered in R to create more specific plots dependent on the needs of information. For example, the plot can be filtered according to the span and load conditions of the reference project in Section 6.1. The filtered database is presented in Figure 7.9 below. This is an example of introducing design constraints (x) according to the structural optimization problem formulation presented in Section 5.2.

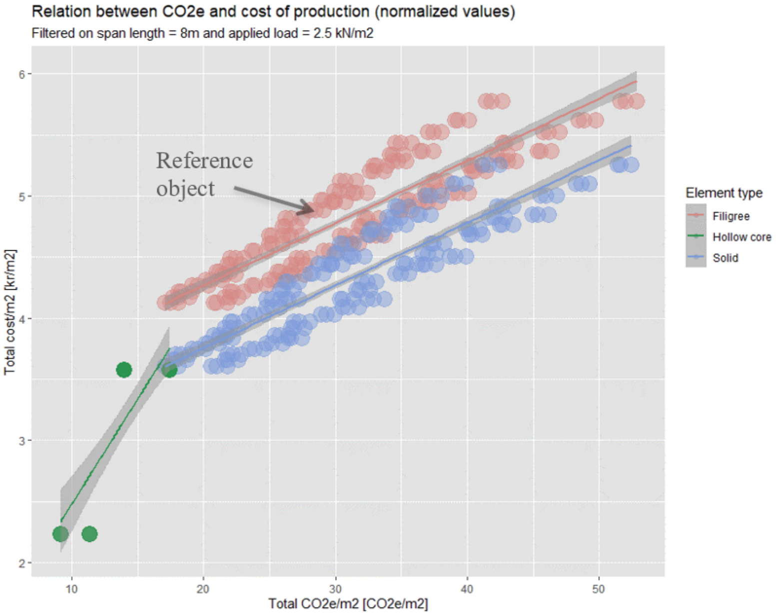

Figure 7.9: *Relation between CO_2-eq and cost of the filtered database (8m, 2.5 kN/m^2). Annotation represent the reference project position in the database.*

The reference project used a filigree element with a thickness of 280 mm which has been annotated in Figure 7.9 with its position in the filtered database. The reference project is positioned centered which indicate that an improved element design may be found by investigating elements closer to the bottom left corner. At this stage it can also be reasonable to introduce the behavioral constraint (y) which is part of the structural optimization problem formulation presented in Section 5.2. In this study the maximum utilization acts as a behavioral constraint with an upper limit of maximum hundred percent utilization. Figure 7.10 was created by removing elements with a utilization higher than hundred percent and a bottom limit of fifty percent utilization from the database in order to represent a more specific database.

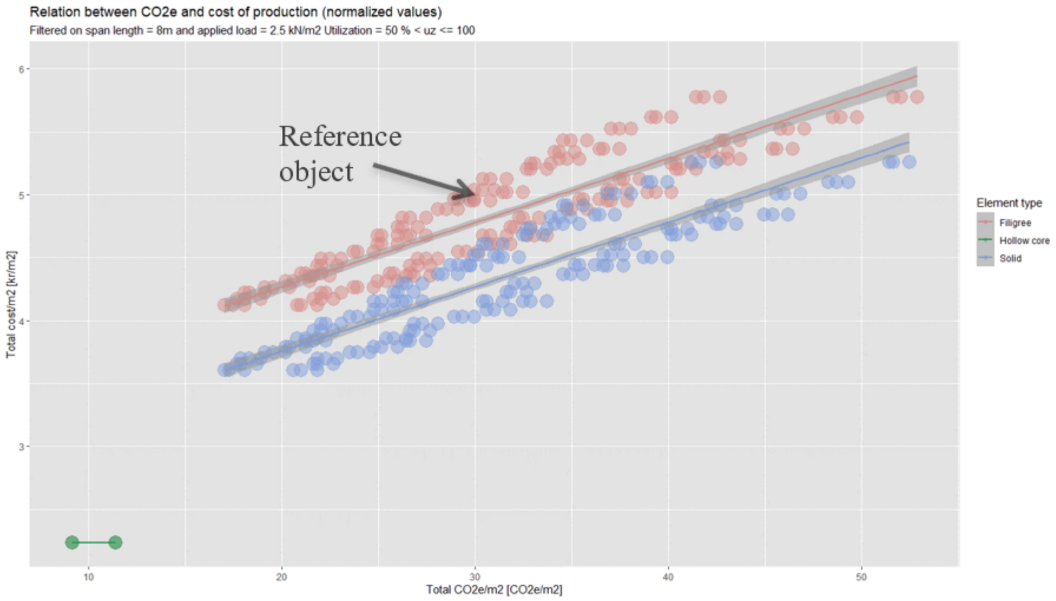

Figure 7.10: *Relation between CO_2-eq and cost of the filtered database (8m, 2.5kN/m^2 50%<max.utilization<=100%)*

The final step to create a visual representation of the optional element designs is to implement Pareto Optimality. Section 5.3 presents a point system for evaluating parameters from somewhat important to important and finally very important. The point system is of course subjective but for this study two example plots have been produced where one of the parameters is ranked somewhat important and the other parameter as highly important. The weight factors multiplied with the normalized parameters can be seen below in Equation 7.1 and 7.2.

$$w_1 = \frac{1}{\sum w_k} = 0.25 \tag{7.1}$$

$$w_2 = \frac{3}{\sum w_k} = 0.75 \tag{7.2}$$

The effect of multiplying weight factors with the normalized data can be seen in Figure 7.11 and 7.12 below where the difference between the figures is which parameter is prioritized higher.

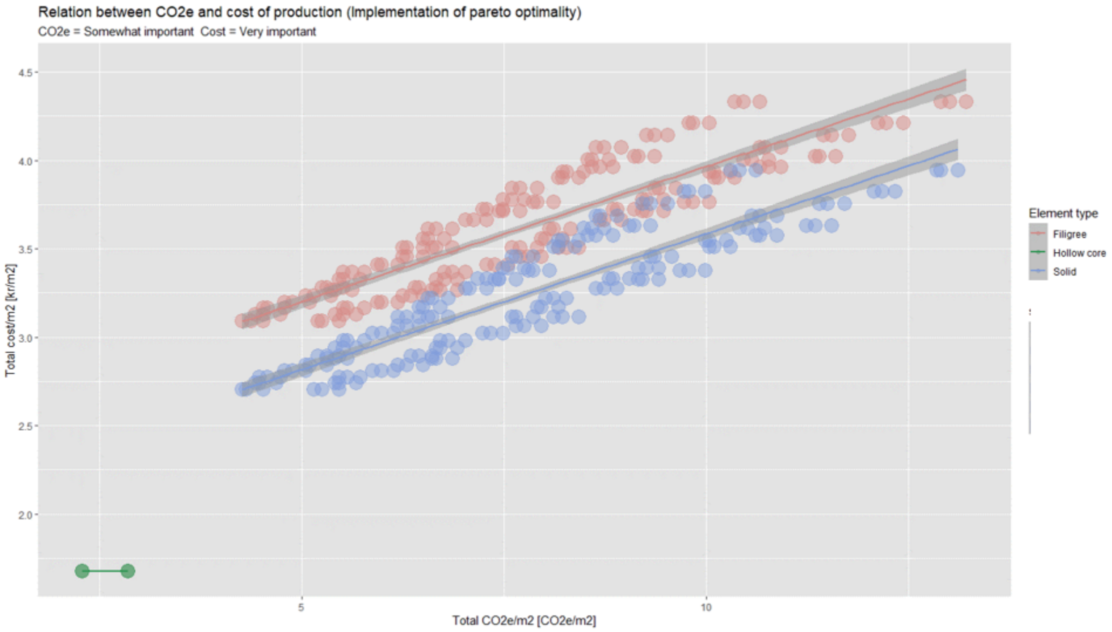

Figure 7.11: *Relation between CO_2-eq and cost of the filtered database (8m, 2.5 kN/m^2 50%<max.utilization<=100%). Pareto optimal values with climate impact ranked as somewhat important and cost ranked as very important*

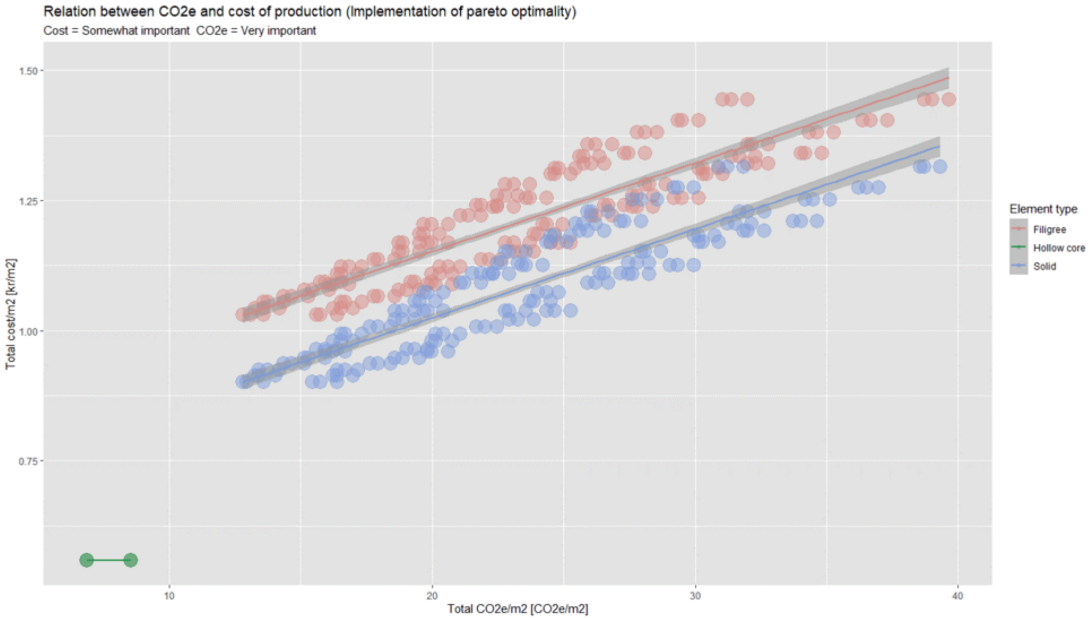

Figure 7.12: *Relation between CO_2-eq and cost of the filtered database (8m, 2.5 kN/m^2 50%<max.utilization<=100%). Pareto Optimal values with climate impact ranked as very important and cost ranked as somewhat important*

7.3 Relation between element cost, climate impact and maximum utilization

In addition to the figures presented in Section 7.2 the same plots were created in three dimensional scatter plots where the maximum utilization is presented on the z-axis instead of only being used as a filter. Generation of the full database in three dimensions (climate impact, cost and maximum utilization) is presented in Figure 7.13. Figures in Section 7.3 were generated as interactive plots which have the advantage of being able to be rotated, zoomed and scaled by the user in real time. Judging an element's optimality is done by comparing the distance of the element's data coordinate to the origin.

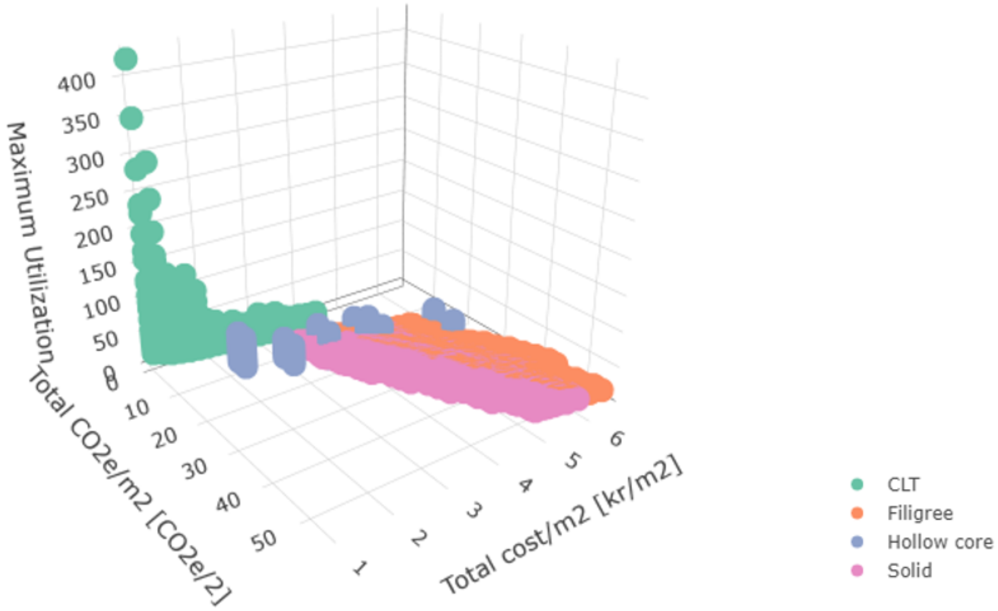

Figure 7.13: *Relation between CO_2-eq, cost and maximum utilization of the full database. The database includes varying applied loads and span lengths. Data has not been filtered on utilization, hence data presented is not necessarily viable solutions.*

Interactive labels were added to the figures in Section 7.3 to further improve the amount of information collected in one single plot. The interactive label included the normalized values of the three output parameters climate impact, cost and maximum utilization. The label also included the label generated from the Python script which labeled each element according to the following template:

element type-thickness-length-concrete quality or CLT profile-use of climate improved concrete-steel manufacturer-applied load-maximum utilization.

An example of this interactive label can be seen in Table 7.3.

Table 7.3: *Example of information included in the interactive label while hovering over data in Figure 7.13.*

Category	Value
Normalized CO_2-eq/m^2	16.70
Normalized Cost/m^2	0.88
Normalized Maximum utilization	16.33
Label	Solid-200-7.0-C30/37-no-Serfas-2.0-98

The data presented in Figure 7.13 has improved visibility of individual data points compared to data in Section 7.2. The addition of filtration of the data is implemented in Figure 7.14 below to present data specific for the load and span of the reference project.

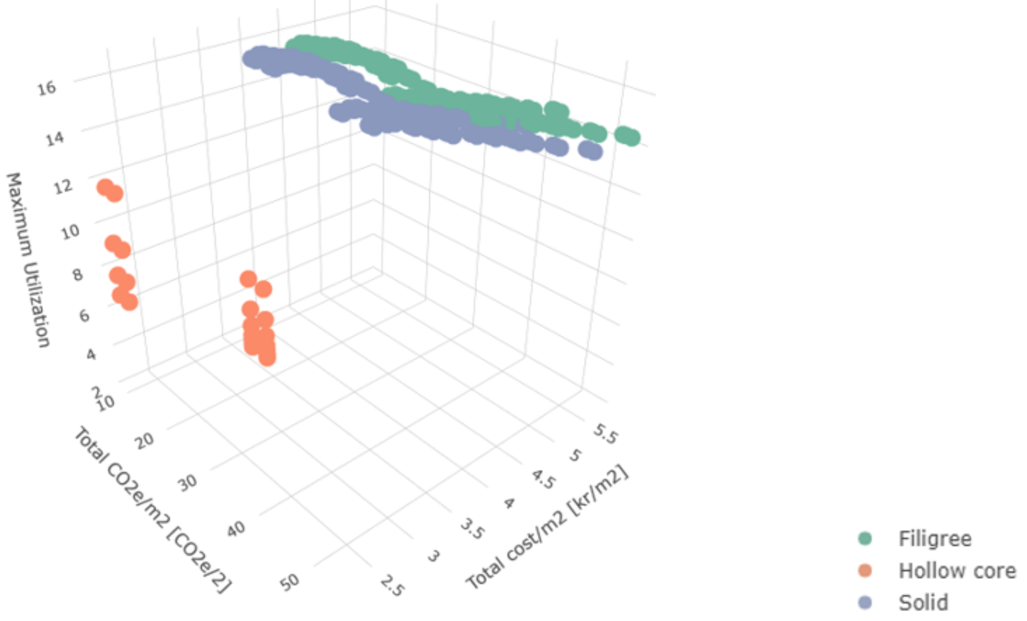

Figure 7.14: *Relation between CO_2-eq, cost and maximum utilization of the filtered database (8m 2.5 kN/m^2).*

The behavioral constraints identical to those in Section 7.2 were implemented to the data and the results are presented in Figure 7.15.

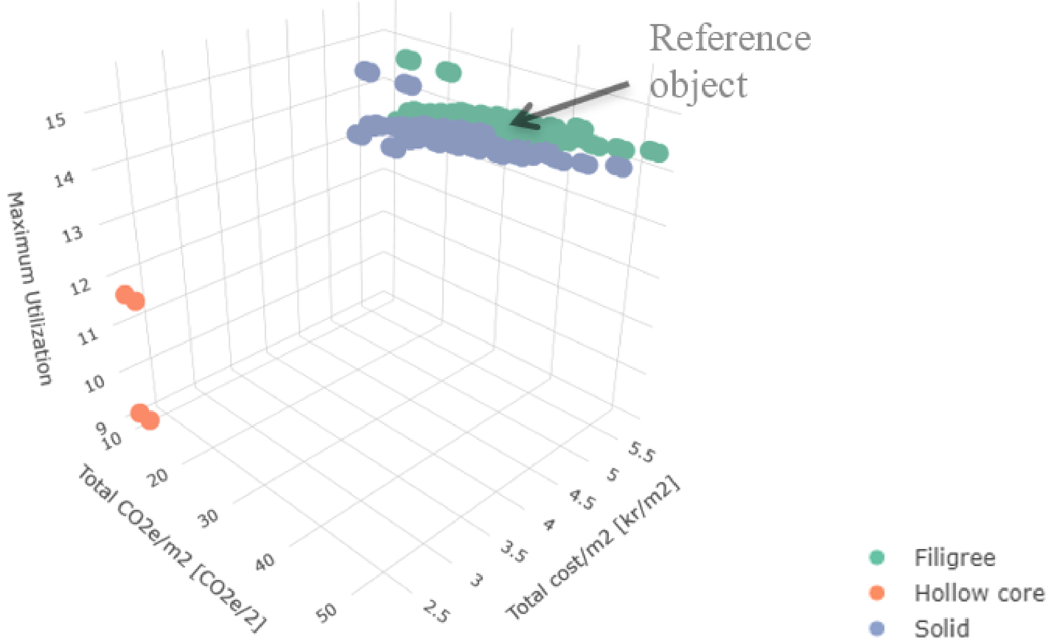

Figure 7.15: *Relation between CO_2-eq, cost and maximum utilization of the filtered database (8m, 2.5 kN/m^2 50%<max.utilization<=100%).*

The final step to generate a scatter plot which can be used to judge optimality is to apply weight factors to rank the parameters importance. The three weight factors used are presented in Equations 7.3-7.5 below.

$$w_1 = \frac{1}{\sum w_k} = 0.17 \tag{7.3}$$

$$w_2 = \frac{2}{\sum w_k} = 0.33 \tag{7.4}$$

$$w_3 = \frac{3}{\sum w_k} = 0.5 \tag{7.5}$$

The weight factors were added to each respective column as an example with climate impact ranked as very important, maximum utilization as important and cost as somewhat important. The results of introducing Pareto Optimality through weight factors can be seen in Figure 7.16.

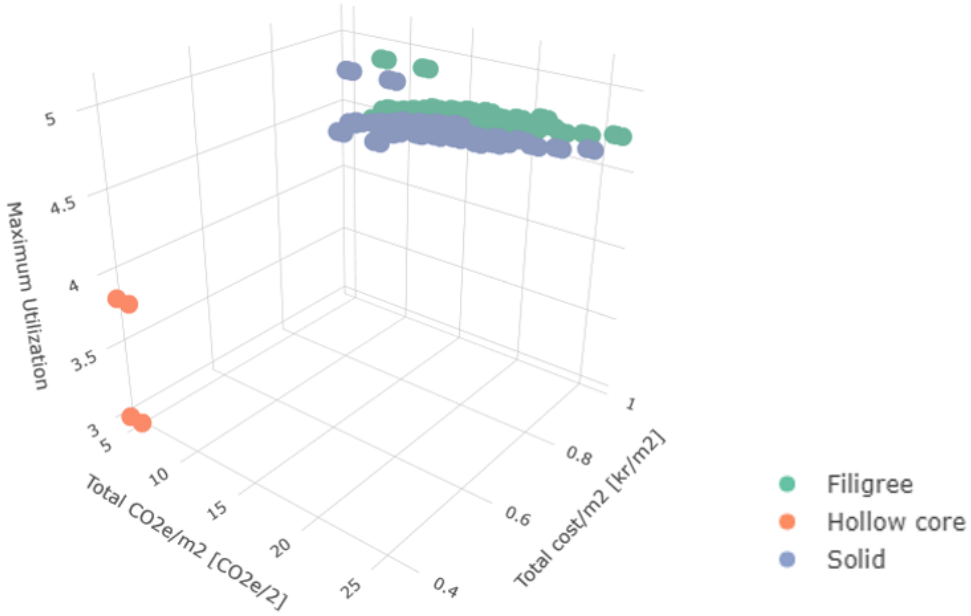

Figure 7.16: *Relation between CO_2-eq, cost and maximum utilization of the filtered database (8m, 2.5 kN/m^2 50%<max.utilization<=100%). Pareto optimal values with climate impact ranked as very important, maximum utilization ranked as important and cost ranked as somewhat important*

7.4 Decision Tree Models of database

The use of interactive scatter plots has the advantage of containing a big amount of information in one single graph, especially with the use of interactive labels. However, an engineer's time is valuable and studying each specific data entry is not an efficient way to use that time. The results in Section 7.3 were therefore analyzed by sending the data through a decision tree algorithm with the purpose of splitting the data into categories and determine the most influential parameters.

Decision Tree Models are with ease able to be produced in R with the help of the *rpart* and *rpart.plot* function library. Decision trees were created for the three main output parameters (climate impact, cost and maximum utilization). An overview of the output from the Decision Tree Models can be seen in Figure 7.17 - 7.19. For a more detailed view of information found in each node see Appendix A.

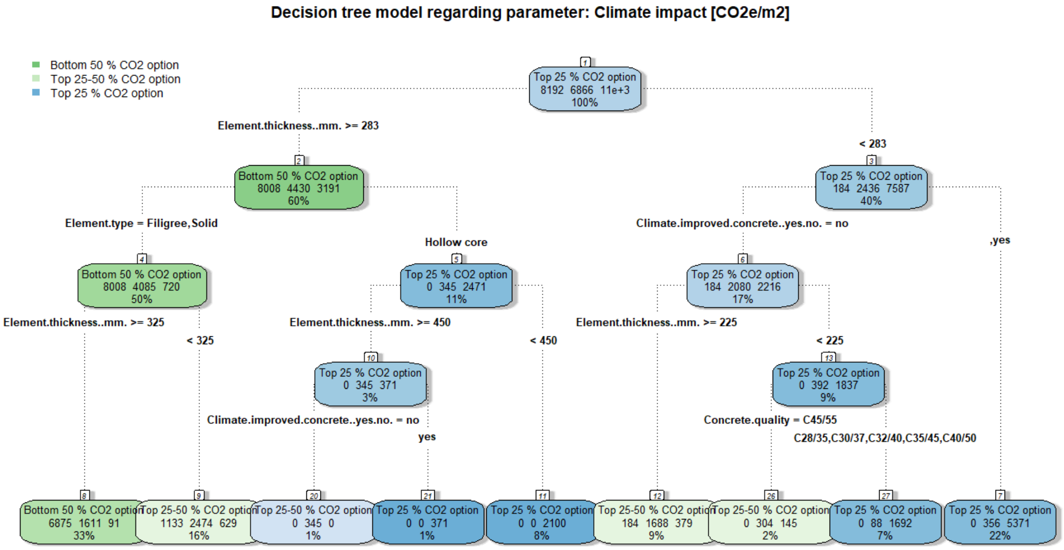

Figure 7.17: *Decision Tree Model regarding climate impact.*

The data seen in Figure 7.17 above has been categorized to be one of three categories. A top performing element is sorted into the top 25 percent element designs with the lowest climate impact. The second category is the element designs with climate impact lower than the median element but greater climate impact than the first category. The final category included elements with a climate impact greater than the median element. As seen in Figure 7.17 the top node (node 1) holds the entire database. Right below node 1, the first split of the tree model has been performed on element thickness. The algorithm has determined that a value of element thickness over or under 283 mm is a key parameter for sorting the data into one of the three predetermined categories. This split in the tree sends majority of the elements of bottom 50 percent category to the left in the tree (8 008 elements of the original 8 192 elements). The top performing elements have been distributed more evenly with 3 191 elements in the top performing category sorted into the left and 7 587 to the right. Continuing down the tree, the model splits the data on the most important variables to determine the classification.

The rpart library in R allows the user to analyze the ranking of a parameter's importance. The most important ingoing parameters in the Decision Tree Model are scored with a high value while low important parameters are scored lower. Table 7.4 presents the most important parameters and their relative importance scoring.

Table 7.4: *Parameter importance ranked in Decision Tree Model (Climate impact).*

Parameter	Relative Importance (Value)
Element thickness	45
Element type	21
Use of climate improved concrete	15
Concrete quality	9
Span Length	8
Total weight	1
Reinforcement manufacturer	1

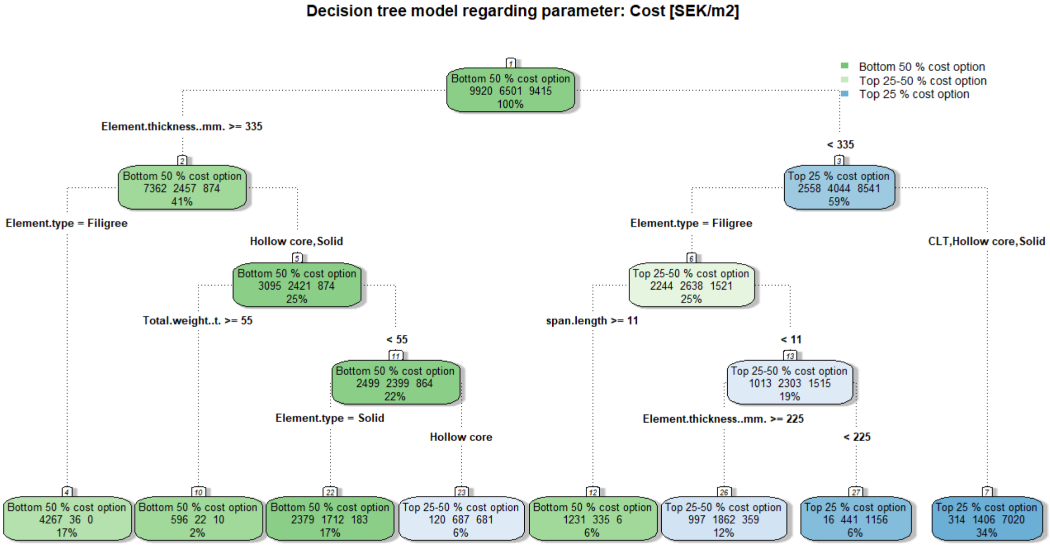

Figure 7.18: *Decision Tree Model regarding element cost.*

Figure 7.18 presents the Decision Tree Model determining element cost classification. Same as for Figure 7.17, the data has been categorized to be one of three categories. A top performing element is sorted into the top 25 percent element designs with the lowest cost. The second category is the element designs with cost lower than the median element but greater cost than the first category. The final category included elements with a cost greater than the median element. The first split of the data divides the data dependent on element thickness higher or lower than 335 mm. This split in the tree sends majority of the elements of bottom 50 percent category to the left in the tree (7 362 elements of the original 9 920 elements). Majority of top performing elements has been sorted to the right side of the tree with 8 541 of the original 9 415. Continuing down the tree, the model splits the data on the most important variables used to determine the classification. Table 7.5 presents the most important parameters and their relative importance scoring for this model.

Table 7.5: *Parameter importance ranked in Decision Tree Model (Cost).*

Parameter	Relative Importance (Value)
Element thickness	42
Element type	37
Span length	13
Total weight	5
Concrete quality	3

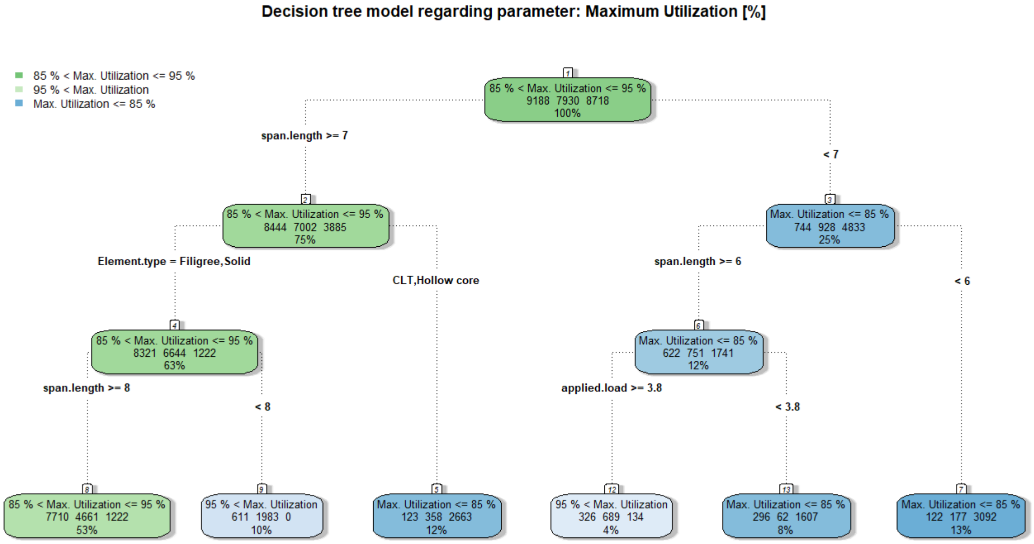

Figure 7.19: *Decision Tree Model regarding maximum utilization.*

Figure 7.19 presents the decision tree model determining maximum utilization classification. The data has been categorized to be one of three categories. The categorization of elements is performed differently in this model than in the previous two models. The optimal category is deemed to be defined as having a maximum utilization within the range of 85 to 95 percent. The two remaining categories are grouped dependent if they are higher or lower than the optimal range of 85 to 95 percent. The first split of the data divides the data dependent on span length longer or shorter than 7 m. This split in the tree sends the majority of the elements of the optimal category to the left in the tree (8 444 out of 9 188 elements). Elements with maximum utilization greater than 95 percent are mainly sent to the left branch (7 002 out of 7 930 elements). Elements with maximum utilization lower than 85 percent are more evenly distributed on both branches in the initial split (3 885 elements on the left branch and 4 833 on the right branch). Continuing down the tree, the model splits the data on the most important variables used to determine the classification. Table 7.6 presents the most important parameters and their relative importance scoring for this model.

Table 7.6: *Parameter importance ranked in Decision Tree Model (Maximum utilization).*

Parameter	Relative Importance (Value)
Span length	44
Element type	30
Element thickness	8
Applied load	7
Concrete quality	6
Use of climate improved concrete	6

Another aspect of establishing a Decision Tree Model is to predict the category of elements that are not part of the original database. To test the database and the model's capabilities the original database was split into two databases, one for training the algorithm and one to be used for testing the algorithms prediction capabilities. The training data is first used to establish models similar to those presented in Figure 7.17 - 7.19. After the algorithm is trained, the test data goes through the same algorithm which analyze the data and returns probability of each elements chance of being sorted to each category. Table 7.7 presents a handful example predictions of the test data using the prediction on climate impact. Each column represents the individual element's probability of being sorted into that column's category.

Table 7.7: *Prediction of element categorization probability performed by Decision Tree Model (Climate impact).*

Element ID	Bottom 50%	Top 25-50%	Top 25%
83	7.8%	75.2%	16.9%
128	7.8%	75.2%	16.9%
158	26.5%	58.4%	15.1%
330	80.0%	18.8%	1.2%
542	26.5%	58.4%	15.1%

The elements in Table 7.7 were checked using the original model to validate if the algorithm had been trained properly and if the predictions matched the correct results. In Table 7.8 the predicted class and the correct class are presented next to each other.

Table 7.8: *Comparison between the trained algorithm predictions on classification of climate category compared to the correct class.*

Element ID	Prediction model	Correct result
83	Top 25-50%	Top 25-50%
128	Top 25-50%	Top 25-50%
158	Top 25-50%	Top 25-50%
330	Bottom 50%	Bottom 50%
542	Top 25-50%	Top 25-50%

The classification was able to be predicted in the handful of example data entries in Table 7.8. This comparison is merely an example of the algorithm ability to perform predictions on elements. This is just a proof of concept since the algorithm must be evaluated extensively to ensure the quality of predictions. This will be further discussed in Chapter 8.

8

Discussion

This chapter will discuss the implementation of the method presented in Chapter 6 and the results from the generated database presented in Chapter 7. This discussion has been divided into discussion about the general methodology, the use of generic data, parameter importance and different aspects regarding optimality.

8.1 Discussion about the general methodology

This study has tested to combine several separate methods into a workflow including traditional FEM design, Full factorial Design and Decision Tree Modelling. Combining these three separate methods to one single workflow was challenging due to a lot of planning and design of a structured process. This workflow had to be able to analyse in FEM, generate additional data in Python and create a database able to be imported and exported in and out of several programs.

Creation of the script in Python and R demanded an intermediate knowledge of programming. The authors of this study spent a lot of time in the beginning of the study to learn multiple programming techniques. These techniques included for example how data can be extracted from a FE software (FEM Design), how a Python script can control other software, how data in the form of csv-files can be imported into a database and updated through looping.

Fortunately, the early studies on programming was worth the time and effort since the method was successful and each step of the process was able to be performed as intended or even better. The amount of data resulted in 29 230 data entries (or element designs) including multiple span lengths and applied load. The initial goal was to only generate data specific to the span length and load of the reference project which would have resulted in a drastically smaller database of 2 180 entries.

One advantage to the Full Factorial design is that with vast amount of data and design generated, the structural engineer can choose to analyse this data with preferred method of choice. Multiple engineers with varying knowledge of programming, statistics and computer science can use the exact same data but in very different ways. If the structural engineer wants to find a known entry in the database and the specific data connected to this design can this simply be checked by opening the database in excel or similar program and search for the design. If another engineer prefers to analyse the data through programming can vast amount of data be processed and studied using scatter plots and regression lines be used to find trends in the data and thus improve the understanding of each parameters influence on optimality. Yet another engineer can use the same data and establish a simple machine learning problem and use the data to predict optimality of elements that was not generated in the first place. Each one of the three examples above are examples of the versatility of having large and specific databases with precise information at hand.

One of the biggest advantages of having a database compared to tradition analysis is of course the time saving aspect which mostly comes from removing the need of running a FE analysis every single time an analysis must be performed for simple load cases and spans. Instead all checks and controls including utilization of reinforcement, deflection checks and crack widths are gathered in a single file that can be accessed instantaneously.

One improvement to the workflow that could be implemented would be to include FEM analysis and multiple controls of hollow core elements. All element types were able to be analyzed through FEM Design except for hollow core elements which cannot be controlled in said software. The company behind FEM Design, Strusoft have developed a separate FE-software called Pre-stress that can perform analysis of hollow core elements. Unfortunately, Pre-stress does not have the same API functionality presented in Chapter 6. Without API functionality the results from the analysis would not have been able to be imported back to the Python script and therefore hollow core utilization was retrieved from basic and unspecific tabular data. If this API functionality would have been available, it would both improved the validity of the database but also enable the script to generate a bigger total number of data entries.

Another aspect of the tested method is its capability to be reproduced. The climate impact data used as input is free and open access while cost is retrieved from Bidcon that needs a paid license. Another license that was needed was for FEM Design but since this software usually is standard this would not affect the capability of reproducing the results in any way. The remaining two software's used in this method, Visual Studio and R-studio used for writing code in python an R respectively is free and can be downloaded by anyone. This is yet another advantage of the method since most of the method except the gathering of cost data can be reproduced by any structural engineer at any company or university without any cost or budget restricting the use of the method.

8.2 Discussion about the use of generic data

Probably the most integral part of this study was to gather and implement the generic data found on both climate impact analysis and cost. Without up to date and detailed data the comparison would have become unspecific and the analysis would have been affected negatively.

Climate data was almost exclusively gathered from the National board of housing, building and planning. This data is certainly deemed to be up to date and applicable since this is the only database that will be allowed to use in climate declaration of buildings starting 2022. Data was able to be gathered both on element level with climate impact from A1 to A5 and material level for varying concrete qualities in A1 to A3. The database also specified the difference between climate improved and normal hollow core, solid and filigree elements which further improved the detail of the calculated database.

The National board of housing, building and planning's database with generic data was deemed to be acceptable to be used to perform conservative calculations of climate impact. Although for use in complex and highly detailed comparisons of structural elements there is still a lot of room for improvement.

The generic database is specifically meant to be used by developers reactively to calculate structures climate impact for elements without EPD. The National board of housing, building and planning wants the developers to mainly rely on detailed EPDs for their climate declarations and use the generic database in those occasions when an EPD of an element is not available. This study predicts the climate impact proactively without any specified project limitations or information to base the calculation on which gives the study a degree of uncertainty.

Another aspect to discuss regarding the generic database is that the data is exclusively dependent on volume and mass. For climate impact from A4 and A5 a more extensive database with the inclusion of project parameters (transportation, assembly and project size) would have been preferred in order to further improve the detail level of the analysis of this study. Another desired data category missing from The National board of housing, building and planning's database was climate impact from reinforcement with or without recycled scrap metal. This was instead added externally from WSP's calculation tools for climate impact which is based on EPD's from industry leading manufacturers. Using EPD's is of course allowed as stated previously but for this study it would have been preferred to use data from the National board of housing, building and planning's database exclusively.

The second big database used for the study was Bidcon where element costs were collected and implemented into the script. The database included cost data for all element types needed but the detail level of the calculation was varying between the element types.

As presented in Chapter 3 the calculation of solid and filigree element cost included multiple process and labor costs while hollow core only included the cost of the element and smoothening. The calculation of CLT element was simply calculated dependent on the element weight which resulted in the perfectly linear results presented in Section 7.2. The fairness of comparing elements with varying levels of detail can be questionable. The gap between the CLT elements and the remaining concrete elements position in Figure 7.7 might have been shortened with an increase of overlapping data. An alternative calculation method would have been to request procurements directly from manufacturers on the reference project. This option of method was discussed in the beginning of the study, but the use of generic cost data was preferred in order to keep the study general without being dependent on a handful of manufacturers and their prices which may or may not be a good representation of the overall market.

Another aspect of the cost data that could have been studied is how a project's scale affects the final cost. This is an example of a project parameter that could have been introduced. This will be further discussed in Section 8.5 below.

8.3 Discussion about parameters importance and decision order ranking

Section 7.4 presented the results from the Tree Decision Model including the estimated measurement of ingoing parameters importance. The point scale represents the parameter relative importance in the sorting of the elements. Selected points in Table 7.4 are discussed further below.

Comparing the two most important parameters for affecting the climate impact, the study shows that the decision on element thickness (relative importance equal to 45) is more than two times as important then the decision on element type (relative importance equal to 21).

The Decision Tree Model presents the relative importance by placing a parameter close to the root node and therefore affecting the split of the branches below it. In the decision tree model regarding climate impact (Figure 7.17) the key decision to categorize an element in the database is to choose an element thickness lower or higher than 283 mm. Choosing a lower thickness than 283 mm leads to a much higher probability of reaching the best performing alternatives while the opposite can be said about elements thicker than 283 mm. Worth mentioning is the fact that all CLT elements have a thickness lower than 283 mm. That means that all CLT elements have been sorted together in the first and most important split. The split also means that hollow core elements with a maximum thickness of 265 mm is preferred to reach the top 25 percent best performing category.

Continuing down the branch with element thickness lower than 283 mm, the next decision is the use of climate improved concrete. The split is dependent if the parameter is set to yes, no or “blank”. A blank value represents the CLT elements where the parameter is left empty since the element does not contain concrete. If the parameter is set to either yes or “blank” the elements are sorted into node 7 which is a leaf (end) node with a total of 5 727 elements with a high probability of being a top 25 percent performing element. Node seven contains 22 percent of the original data which is the second biggest leaf node except for node 8 that contains 33 percent of the original database. The difference between node 7 and 8 is that node 8 contains a majority of the worst performing elements while node 7 contains in majority elements in the top performing category. If a non-climate improved element would have been chosen instead, the branch would have continued into node 6 instead. Node 6 splits the data once again on thickness and defines that an element thinner or thicker than 225 mm is important for deciding the category. Choosing a thickness lower than 225 mm in node 6 leads to the highest probability of reaching the top performing category. A small possibility still exist for elements with thickness over 225 mm as can be seen in leaf node 12 where 379 high performing elements have been sorted. But the probability is relatively low compared to the less performing majority of elements that are sorted into node 12.

Another interesting comparison is to compare the importance of using climate improved concrete to choosing concrete quality in order to lower the climate impact. Table 7.4 shows that the use of climate improved concrete (relative importance equal to 15) is about 50 percent more important than the choice of concrete quality (relative importance equal to 9).

An unexpected low importance to the climate impact was the choice of reinforcement manufacturer which only scored a relative importance equal to 1. This was not expected since each supplier presented in Table 4.3 has a big variation of the climate impact. The importance of steel manufacturer may have been ranked higher if the database contained solid and filigree elements exclusively since the other two element types are not affected at all by changing the reinforcement manufacturer.

Comparing the most important parameters for affecting the cost, the study shows that the decision on element thickness (relative importance equal to 42) and element type (relative importance equal to 37) is more equal than each parameter respective importance in the decision tree regarding climate impact. The third most important parameter is the span length (relative importance equal to 13). The reason for span lengths relative high importance is that cost data presented in Chapter 3 is partially dependent on the area rather than the element weight or volume.

In the decision tree model regarding cost, the key decision to categorize an element in the database is to choose an element thickness lower or higher than 335 mm. Choosing a lower thickness than 335 mm leads to a much higher probability of reaching the best performing alternatives while the opposite can be said about elements thicker than 335 mm.

Continuing down the branch with element thickness lower than 335 mm, the next decision is the element type. The split sends the filigree elements further down the tree while the remaining element types (hollow core, solid and CLT) are sorted into a leaf node with high probability of being categorized as a top 25 percent best performing element in node 7, see Figure 7.18. Node 7 is a leaf (end) node with a total of 7 020 elements with a high probability of being a top 25 percent performing element. Node seven contains 34 percent of the original data which is the biggest leaf node.

Studying the branch originated from the leaf node with element thickness bigger than 335 mm the possibility of reaching a top performing design is less likely. The only leaf node on the left side with high probability of performing better than the median cost is in node 23. Node 23 includes hollow core elements with a total weight less than 55 tons on the area established in the reference project with a thickness of either 200, 265 or 320 mm.

8.4 Discussion about the methodology's capability of presenting optimality

Section 7.2 - 7.4 presents different alternative approaches to show elements optimality. Depending on the occasion and for what purpose optimality is needed to be evaluated can one of these alternatives be more or less useful in its context.

Section 7.2 presents the simplest alternative to evaluate optimality through two-dimensional plots. This alternative is preferred when optimality needs to be proven in text or without explanation for someone not familiar with this study and the tested method. The plots are limited in the amount of information that can be extracted from them, but they are at the same time intuitive and focused on the comparison of two selected parameters. The data is both normalized and weight scored which lead to values in the figures without any real application. This is not necessary a disadvantage as long as it is clear in figure and text that values are used exclusively to compare optimality and not for extracting climate impact and cost data from.

Section 7.3 is a continuation of the methodology from Section 7.2 where the same results are recreated in three dimensions instead of two. This was implemented since Figure 7.8 proved that data is crowded and stacked upon each other but with varying degree of utilization. Section 7.3 benefitted the analysis of CLT and hollow core elements which were difficult to distinguish in two dimensional plots. An example of these improvement is presented in Figure 8.1 and Figure 8.2 below where the same data is presented in two-dimensional and three-dimensional plots.

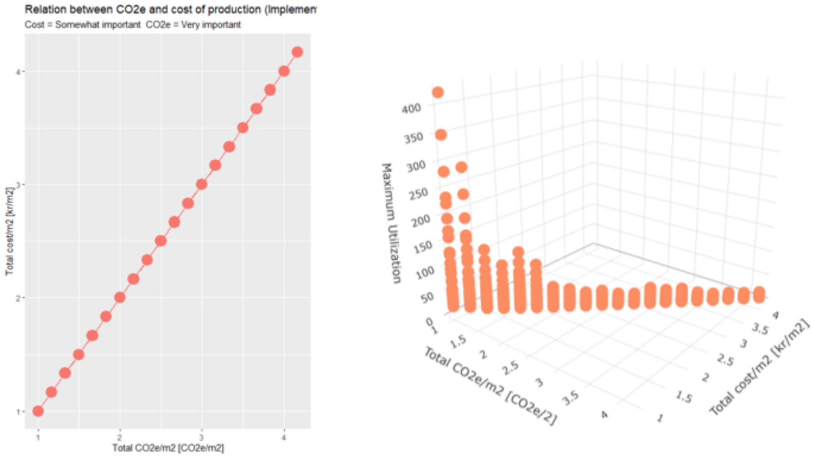

Figure 8.1: *Comparison of CLT elements representation in two-dimensional vs three-dimensional scatter plots*

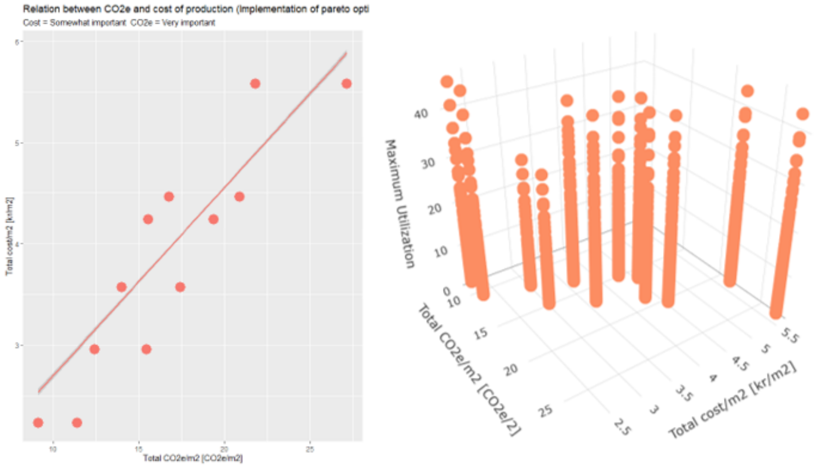

Figure 8.2: *Comparison of Hollow core elements representation in two-dimensional vs three-dimensional scatter plots*

The increased visibility of data in three-dimensional plots however is a worse fit for presentation in report or in other printed format.

Overall the Decision Tree Models in Section 7.4 were found the best way to represent the data. The results were discussed with structural engineers at WSP and the tree decisions models were found to be the most intuitive and comprehendible without needing to read the study in its entirety. The models are also the best option when it comes to inclusion in reports and presentations compared to the other presented options.

The categories for each Decision Tree Model were taken subjectively as the top 25 percent best performing designs, 25 to 50 percent best performing designs and 50 percent worst performing designs.

Studying the boxplots seen in Figure 7.1 and Figure 7.2, the chosen elements for the top performing category would be valued lower than the interquartile range's bottom boundary. Studying the lower boundary of the interquartile range in Figure 7.1 the climate impact defining the top performing category is about 100 CO_2-eq/m^2. Studying this limit for the top performing category in the histogram in Figure 7.4 the amount of data is unevenly spread in this region with a high frequency in the lower and upper limits and very low frequency in-between these limits, see green region in Figure 8.3 below. Depending on what percentage chosen for the top performing category will influence how the Decision Tree Model chooses to split the data. The top performing category is heavily dominated by CLT elements where most elements can be found in the column closest to the origin. If the top performing category would have been chosen as lower percentage, i.e. lowering the threshold of being classified as a top performing element, the splitting in decision would be more influenced by parameters effecting CLT elements. The 25 percent limit however includes elements of all types where concrete elements can be found closer to the upper limit but are still classified as top performing.

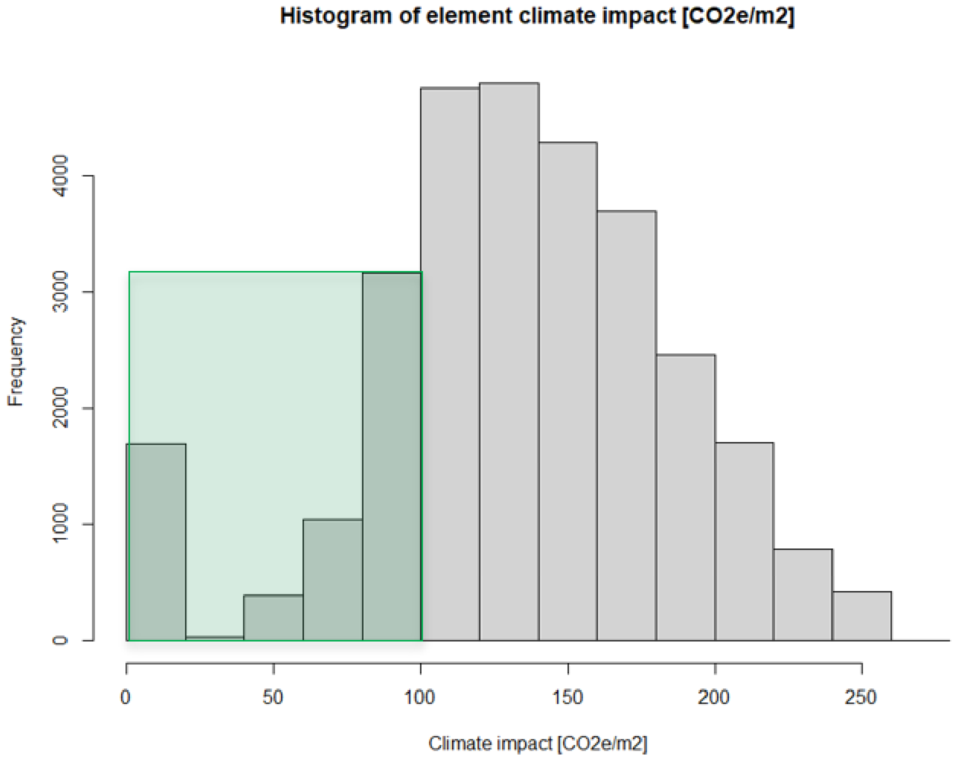

Figure 8.3: *Histogram presenting the frequency in the top 25 percent best performing elements frequency (highlighted in green) of climate impact data in the generated database.*

8.5 Discussion about the methodology's definition of optimality

Although this thesis has proven that optimality can be both measured and presented effectively through tested methods the defined measurement of optimality in this study will not always lead to a design being chosen or considered further.

This study is first and foremost a study in the methodology that can be applied in early decisions of a slab design. To simplify the process of generating data and presenting a study with a clear focus were several aspects influencing the final choice of slab element disregarded. Some of these aspects include controls of eigenfrequency, fire class and sound class. The inclusion of these controls is especially relevant for the timber alternatives. These three examples are all examples on additional behavioral constraints (y) that could be implemented into the objective function (f), see Section 5.2. In the same way as span length and load magnitude are possible to filtrate among the alternatives (as seen in Section 7.2), sound class and fire class are also relevant parameters to navigate through and would lead to resulting graphs with even higher precision of optimality and detail level.

An important aspect to have in mind is that this thesis does not consider the parameters affected by optimizing large projects and on structural system level. When the scale of the project increase, the amount of element and material increase. This however affects the parameters of climate impact and cost in interesting ways. The production cost can be lowered for larger projects by the profit of mass production and replication whereas the climate impact will give another response.

In addition to behavioral constraints the method could have been improved by implementing more design constraints (x). These design constraints could be practical limitations due to the type of building that is being constructed. One example of what types of design constraints that could have been implemented is presented in Section 3.3. Section 3.3 presents the filigree slab element and that the thickness is usually set to a minimum of 250 mm. This is due to practical reasons as having enough room for installations inside the element.

Another aspect to discuss regarding the definition of optimality is that data generated also need reflect or compensate for the competences of the expected users of the method. Dependent on the competences within a team or company the database should be reduced to only include those elements exclusively. The need for this exclusion would be especially needed if a company or group does not have experience of CLT elements. The top performing categories in each Decision Tree Model is heavily influenced by the CLT elements and if they would be disregard due to lack of competence, the data needs to reflect reality.

9

Conclusion

This study aimed to contribute to the reduction of climate impact in the design process by presenting a method to choose and compare optimality of prefabricated slab elements with respect to climate, element costs and structural performance. By using a workflow including FEM Design analysis, Full Factorial Design and Decision Tree Models it can be concluded that:

(i) *FEM Design* can be used to generate a high number of element designs including solid, filigree and CLT elements with output including design checks according to Eurocode and quantity estimations of mass and volume. A method able to analyze and generate hollow core elements data in FEM Design was not achieved. The data used as input from the National board of housing, building and planning's database was found to include good variation on the data on element level for each element type. However, data regarding variations dependent on concrete type, reinforcement type and project specific impact in phase A4 and A5 were found to be limited for use in this study.

(ii) *Full Factorial Design* can be used to generate a database with close to 30 000 individual element designs with 56 parameters each. However, an intermediate level of programming knowledge is required for generating the database. When a database like this is completed, multiple engineers with varying knowledge of programming and machine learning may use the data in their preferred way to compare optimality.

(iii) The study indicates that the use of *Decision Tree Models* may create intuitive illustrations of the generated data. The Decision Tree Models can be used as guidance to reach top performing elements. With additional testing the models used in this study may be able to be used to predict optimality of element designs not included in the original database.

Some of the prominent findings from comparing the data in the generated database are: the use of an element thickness lower than 285 mm gives the design a high probability of being categorized among the top performing element designs when it comes to climate impact, regardless of element type; the relative importance of parameters importance indicates that the choice of climate improved concrete is about 50 percent more important than the choice of concrete class; elements with a thickness lower than 335 mm has a high probability of being classified as a top 25 percent performing element when it comes to cost.

The study indicates that possible designs could have been used instead of the reference project's original design to minimize the three output parameters. The possible element design needs additional design and behavioral constraints to further improve the comparison of elements.

9.1 Further Studies

The study has discussed the following interesting aspects that could be included in further studies:

- Inclusion of additional design constraints dependent that limit the different element types parameters
- Inclusion of additional behavioral constraints including control of eigenfrequency, fire class and sound class
- Inclusion of the influence of a project scale and how its effects climate impact and cost
- Testing and validation of presented concept regarding prediction capability of Tree Decision Models

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A

Decision Tree Models in detail

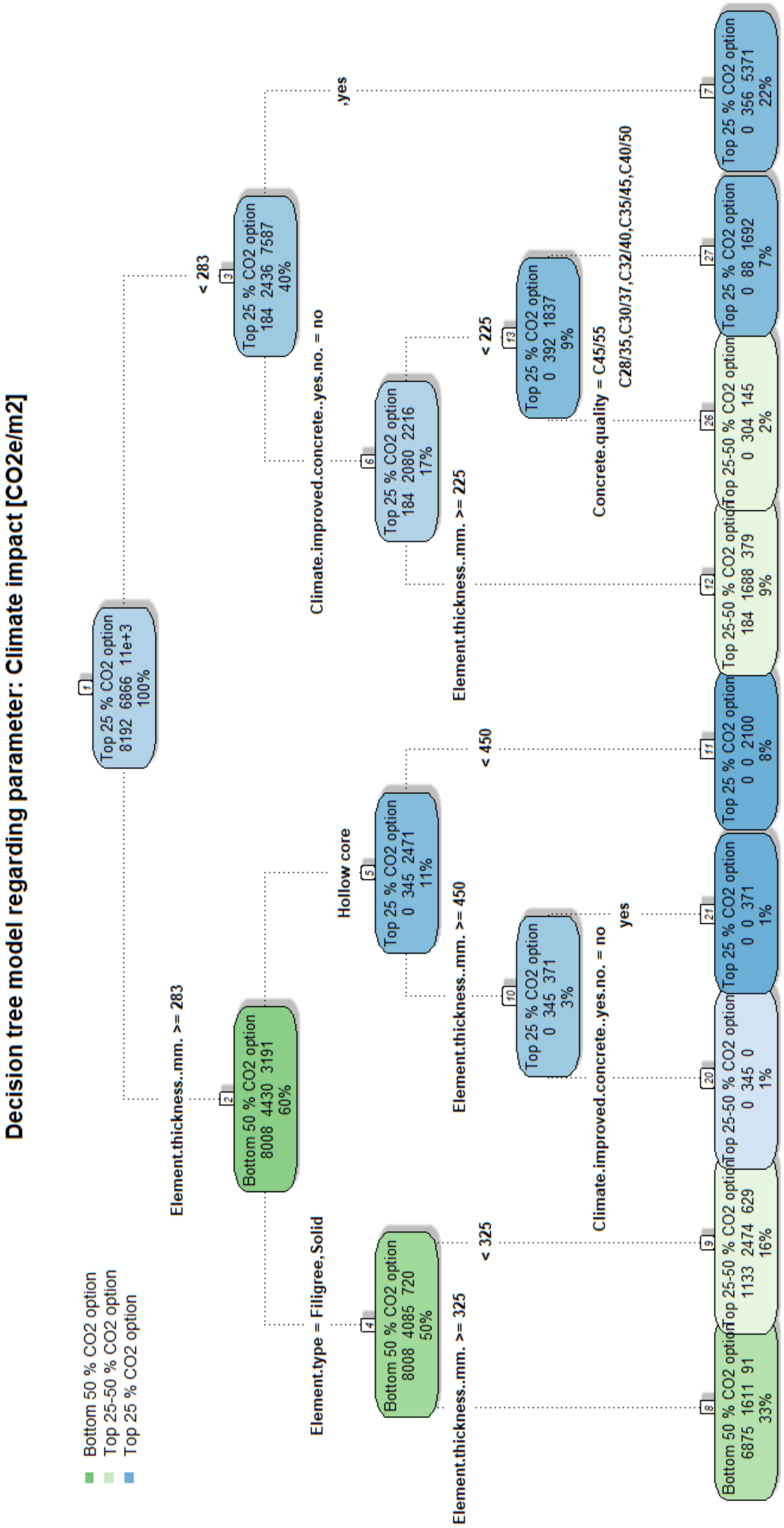

Figure A.1: *Decision tree model regarding climate impact.*

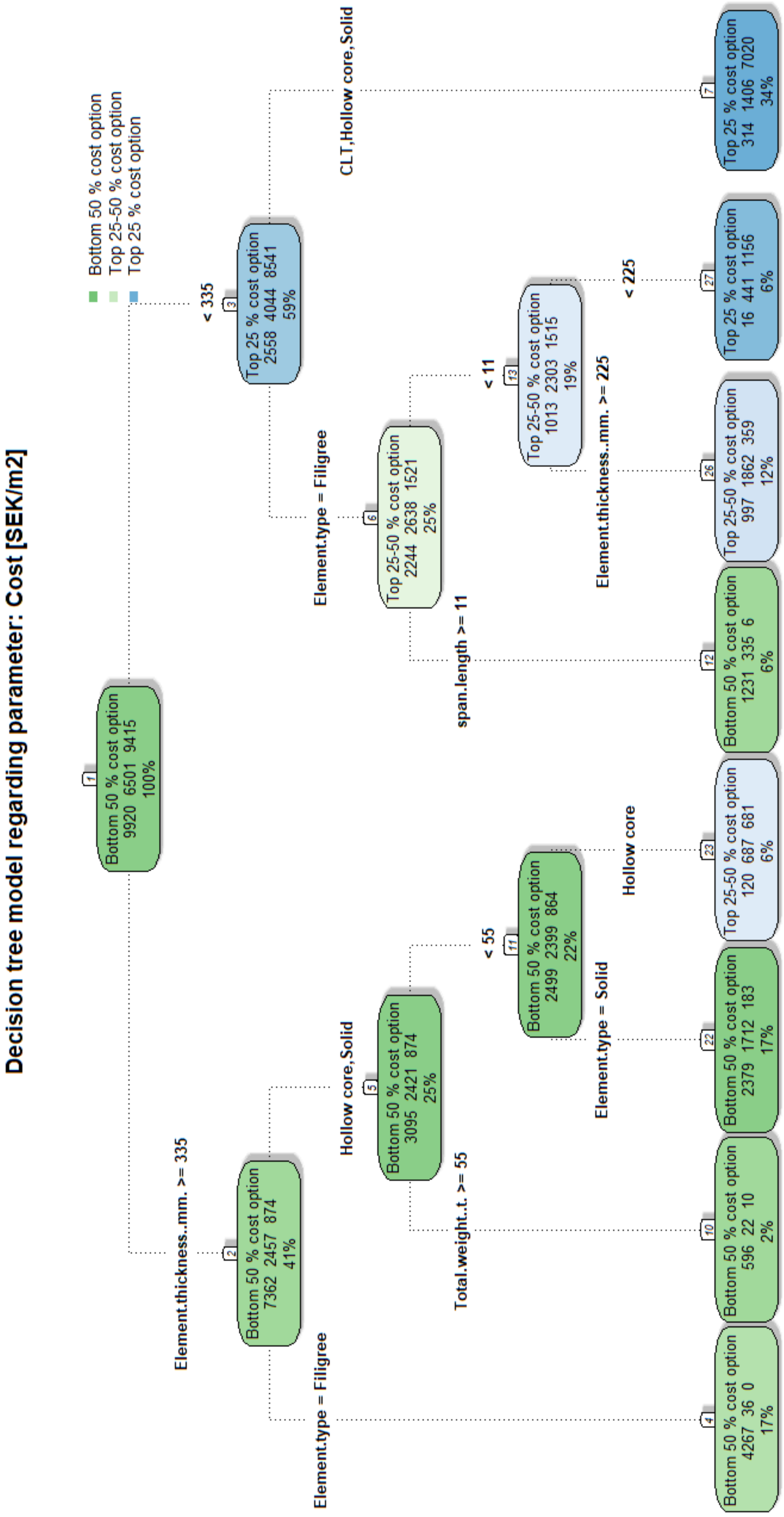

Figure A.2: *Decision tree model regarding cost.*

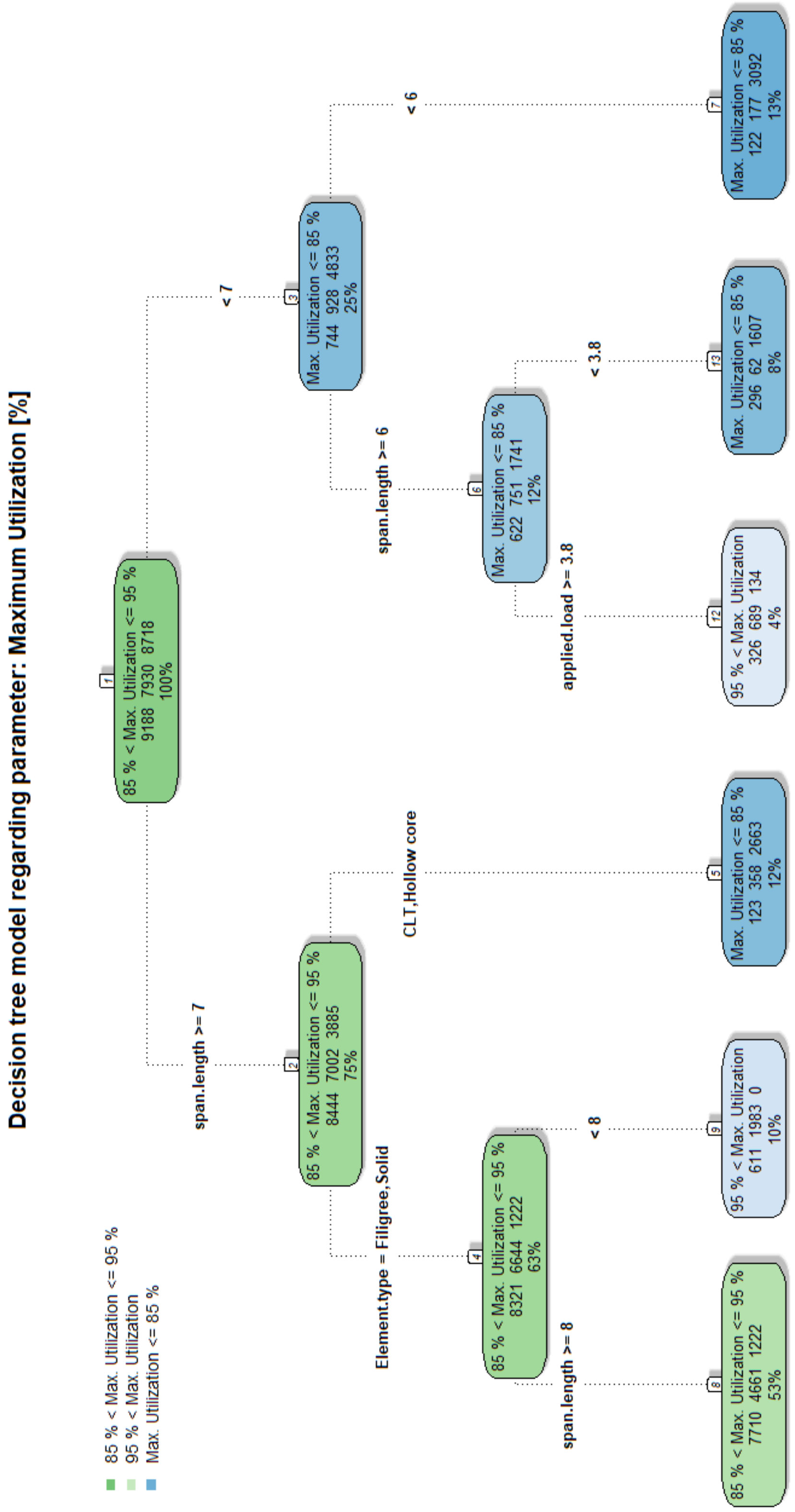

Figure A.3: *Decision tree model regarding maximum utilization.*

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