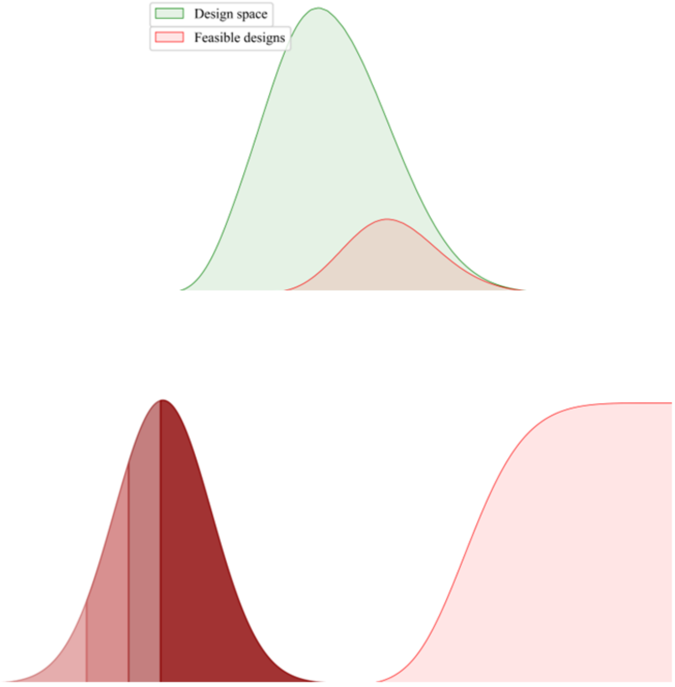

Set-Based Design: A Method for Improving Requirement Definition in the Bridge Procurement Process

How Set-Based Design Can Manage Uncertainty in the Preliminary Design Phase and Procurement of Frame Bridges

Master's thesis in Structural engineering and building technology,
Design and Construction Project Management

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

The Swedish Transport Administration (STA) has committed to achieving climate-neutral infrastructure by 2040, necessitating sustainable decisions early in public infrastructure projects. To strengthen decision-making in the preliminary design phase, managing uncertainty is crucial, and one approach is to implement Set-Based Design (SBD). This thesis investigates the application of SBD in the early stages of bridge design to address uncertainties and improve requirement-setting in procurement. A Python script was created to define the design space of bridge designs, which were presented as normal distributions of key variables: Material Cost, CO_2-eq emissions, and buildability. Interviews were conducted to identify how the information gathered by SBD can be used in decision-making during preliminary design and public procurement. Findings indicate that the normal distributions can help decision-makers early in infrastructure projects, particularly in public procurement. By providing distributions of key variables, SBD can assist the STA to include award criteria based on both emissions and price, rather than solely on price. The research highlights the potential of SBD to generate absolute threshold values in non-mandatory requirements and added values for evaluation criteria in tender documents to consider tenders' emissions in tender evaluation. The study's findings suggest that adopting SBD can lead to significant improvements in managing uncertainty, supporting better decision-making, and advancing sustainable infrastructure development.

Keywords: Set-Based Design, Infrastructure Projects, Bridge Design, Uncertainty Management, Sustainable Development, Public Procurement, Quality Procurement, Added-Value, Tender Evaluation

Set-baserad design: En metod för att förbättra kravdefinitionen i broupphandlingsprocessen
Hur set-based design kan hantera osäkerheter i den preliminära designfasen och i upphandling av rambroar

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Sammanfattning

Trafikverket har åtagit sig att uppnå en klimatneutral infrastruktur till 2040, vilket kräver hållbara beslut tidigt i offentliga infrastrukturprojekt. För att stärka beslutsfattandet i den preliminära designfasen är det viktigt att hantera osäkerhet, ett sätt är att implementera Set-Based Design (SBD). Detta examensarbete undersöker tillämpningen av SBD i den preliminära designfasen av brodesign för att hantera osäkerheter och förbättra upphandlingsdokument. En SBD-algoritm skapades för att kartlägga lösningsrymden av rambrodesigns, som presenterades i form av normalfördelningar av nyckelvariabler: Materialkostnad, CO_2-ekv-utsläpp och byggbarhet. Även intervjuer genomfördes för att identifiera hur den information som samlats in med SBD kan användas i beslutsfattandet under projektering och offentlig upphandling. Resultaten visar att normalfördelningarna kan hjälpa beslutsfattarna tidigt i processen, särskilt vid offentliga upphandlingar. Genom att tillhandahålla fördelningar av nyckelvariabler kan SBD hjälpa Trafikverket att inkludera tilldelningskriterier som baseras på både utsläpp och pris, snarare än enbart på pris. Studien visar att SBD har potential att generera objektiva siffror för börkrav och mervärde i upphandlingsdokument för att ta hänsyn till utsläpp i anbudsutvärdering. Studiens resultat tyder på att SBD kan leda till betydande förbättringar när det gäller att hantera osäkerhet, stödja bättre beslutsfattande och främja en hållbar infrastrukturutveckling.

Nyckelord: Set-Based Design, Infrastrukturprojekt, Brokonstruktion, Osäkerhetshantering, Hållbar utveckling, Offentlig upphandling, Kvalitetsupphandling, Mervärde, Anbudsutvärdering

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Lucas Hansson, Neo Tacking, Gothenburg 2024

List of Acronyms

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

ADD	Alteration, Addition, and Departure
DB	Design-Build
DBB	Design-Bid-Build
cc	Concrete Cover
CO_2-eq	Carbon dioxide equivalents
LM71	Load model 71
LOU	The Swedish Public Procurement Act
MBE	Model Based Engineering
PBD	Point based design
SBCE	Set-based concurrent engineering
SBD	Set-Based design
SBPD	Set-based parametric design
SLS	Serviceability Limit State
STA	Swedish traffic administration
ULS	Ultimate Limit State

Nomenclature

Below is the nomenclature of indices, greek letters, and other variables.

Indices

i	index of used characteristic variable load or index of used material
j	index of used characteristic permanent load

Greek letters

α	Adaptation factor
α_c	Expansion coefficient concrete
γ_b	Weight of ballast
γ_c	Concrete weight
$\gamma_{G,i}$	Partial factor regarding permanent loading
γ_{gs}	Unit weight for soil
γ_M	ULS partial factor in geotechnics
γ_p	Partial factor regarding prestressing
$\gamma_{Q,i}$	Partial factor regarding variable loads
ξ_j	Reduction factor for unfavourable actions of permanent loads
$\rho_{m,i}$	Unit price for each material
ρ_W	Unit labor cost
ϕ	Friction angle
ϕ_2	Dynamic factor
$\psi_{0,1}$	Partial factor regarding variable loads
$\psi_{0,i}$	Partial factor regarding variable loads
$\psi_{1,1}$	Partial factor regarding variable loads
$\psi_{2,i}$	Partial factor regarding variable loads

Other letters

C	Production cost
C_m	Cost of material

C_W	Cost of construction work
E	Elastic stiffness of the foundation
$G_{k,j}$	Characteristic value of permanent load
L	Bridge length
$Q_{k,i}$	Characteristic values of variable load
$Q_{m,i}$	Quantity of material
s_1	Spacing reinforcement layer 1
s_2	Spacing reinforcement layer 2
s'	Spacing reinforcement layer 3
T_0	Casting temperature
$T_{e,max}$	Maximum temperature
$T_{e,min}$	Minimum temperature
T_W	Time of Construction Works
t_1	Primary leg thickness
${}_t2$	Deck thickness in the center
t_3	Thickness of foundation slab
t_4	Secondary leg thickness
t_{bf}	Ballast thickness on foundation slab
t_{b1}	Ballast thickness underneath track
t_{b2}	Ballast thickness on the rest of bridge deck
t_f	Fill thickness underneath foundation
$t_{m,i}$	unit construction time for the activities related for each material
V_{Ed}	Design value of shear force
v_x	Shear force in the local x-direction
v_y	Shear force in the local y-direction
v_{sp}	vertical spacing
m_x	Negative bending moment force per unit width about the y-axis
m'_x	Positive bending moment force per unit width about the y-axis
m_{xr}	Negative design bending moment force per unit width about the y-axis
m'_{xr}	Positive design bending moment force per unit width about the y-axis
m_{xy}	Twisting moment force per unit width in the x–y plane
m_y	Negative bending moment force per unit width about the x-axis
m'_y	Positive bending moment force per unit width about the x-axis

m_{yr}	Negative design bending moment force per unit width about the x-axis
m'_{yr}	Positive design bending moment force per unit width about the x-axis
r	Radius of bridge deck
Ø	Size longitudinal reinforcement
$Ø_{shear}$	Size of shear reinforcement
$Ø_{trans}$	Size transversal reinforcement

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1 Introduction

This section introduces the thesis by presenting the background, purpose and objectives, and limitations of the thesis.

1.1 Background

The global temperature continues to rise as 2023 was the hottest year on record (WMO, 2024). In their 2023 report, WMO (2024) presented that the concentration of the main greenhouse carbon dioxide, methane, and nitrous oxide also continues to rise. More specifically, the CO_2 levels are 50% higher than the levels of the pre-industrial era. CO_2 traps heat in the atmosphere and has a long lifetime which means that the temperatures will continue to rise in the following years. To decelerate climate change, the UN and countries agreed in the Paris Agreement to set a goal to limit the long-term global average surface temperature to 1.5°(UN, 2015). To fulfill the Paris Agreement, Sweden has set a goal of net-zero emissions by the year 2045 (Naturvårdsverket, 2024). In accordance with Sweden's goal, the Swedish Transport Administration (STA) has committed to achieving climate-neutral infrastructure by 2040 (Trafikverket, 2022). To achieve this goal, the STA needs to be able to make decisions that lower the emissions of infrastructure projects.

In Sweden, frame bridges in infrastructure projects are publicly procured in which the STA acts as a *"Pure client"*. This means that the STA publicly procures functionality in terms of design and construction, and uses public procurement to drive long-term sustainable development in the construction industry (Eriksson, Kadefors, Gustavsson K, Lind, & Olander, 2014). However, the contracts for simple projects, such as frame bridges in infrastructure projects, are often design-build contracts (DB), and the award criterion is often the lowest price (Safi, Sundquist, & Karoumi, 2015). According to Safi et al. (2015), the reliance on the lowest bid is due to the "lack of other reliable, credible, and transparent award criteria". This means that cost is the sole award criterion for contracts in infrastructure. Notably, the lowest price award criterion for contractors does not take environmental sustainability into consideration, which hinders progress toward the goal of climate neutrality by 2040.

Before procurement, the STA develops tender documents in the so-called preliminary design phase, which describes the wanted function, identified requirements, and the award criteria for the procurement (Bengtsson, 2023). In creating these documents, the STA, in collaboration with consultants, creates initial designs, which include cost and emission calculations for the designs. However, the level of available information is limited in this phase (Bergenram, Ulander, & Rempling, 2023), inducing uncertainty in both design and cost estimates (Safi et al., 2015). This uncertainty reinforces the reliance on the lowest-price criterion for DB contracts. Therefore, to include additional award criteria, such as environmental impact, into the DB tendering process, these uncertainties must be managed. One way of managing uncertainty and strengthening decision-making in early design is to implement set-based design, rather than traditional point-based design (N. J. Shallcross, Parnell, Pohl, & Goerger, 2021).

The traditional method of construction design is based on point-based design (PBD) methodology (e.g., Rempling, Mathern, Tarazona Ramos, and Luis Fernández, 2019; K. D. Parrish, 2009). In PBD, an initial construction design that is deemed feasible — fulfills given design criteria — is chosen. Later, throughout the design process, the design is reiterated based on new information. The PBD-method is, therefore, a step-wise design procedure, where the decisions in the previous steps are dependent on the new iterations (Liker, Sobek, Ward, & Cristiano, 1996). If the decisions in a later design iteration do not align with the previous assumptions and decisions, the previous iterations must be adjusted and re-evaluated with the new assumptions and decisions. So, in the PBD methodology, a single design solution is iterated based on new information until a satisfactory design is created.

An alternative design methodology to PBD is set-based design (SBD). Set-based concurrent engineering (SBCE), also referred to as Set-based design (Ballard, 2000), is a design methodology in which a set of solutions — referred to as the "design space" (Ward, Liker, Cristiano, & Sobek, 1995) — is considered, selected, and narrowed down as the design process progresses, until a final solution remains (Ward et al., 1995; Sobek, Liker, & Ward, 1999). The PBD and SBD design methodologies then differ in the design process and the exploration of the design space. In PBD, the design process is the act of moving a design solution within the design space from point to point through iterations (Ward et al., 1995). Meanwhile, in SBD, the design process gradually narrows down the design space and the set of solutions. See Figure 1.1 for a side-by-side comparison of the methodologies.

SBD has been shown to outperform PBD in finding design solutions. It is argued by Ward et al. (1995) that SBD can potentially provide better design solutions than PBD by finding the globally optimal ones, meaning solutions that fulfill all stakeholder requirements to the highest degree, as well as avoiding "negative iterations" (See Ballard (2000)) that otherwise occur in PBD. In later research (Rempling et al. (2019); Bergenram et al. (2023)), SBD has been used to find design solutions for bridges that had significantly lower CO_2 emissions and costs than the ones created and built through a PBD approach. So, SBD holds promise as an alternative design methodology to PBD, both in finding solutions more effectively and of higher quality.

SBD also has the potential to be an asset in the early phases of the bridge design process (Bergenram et al., 2023). The main idea is that broadening the design space and finding all feasible solutions may provide better management of uncertainty in terms of cost, climate impact, and buildability of the bridge. Insufficient designs are rejected early in the design process, decreasing the variance of insufficient information early in the design phase. In essence, designers can prove, with the help of SBD

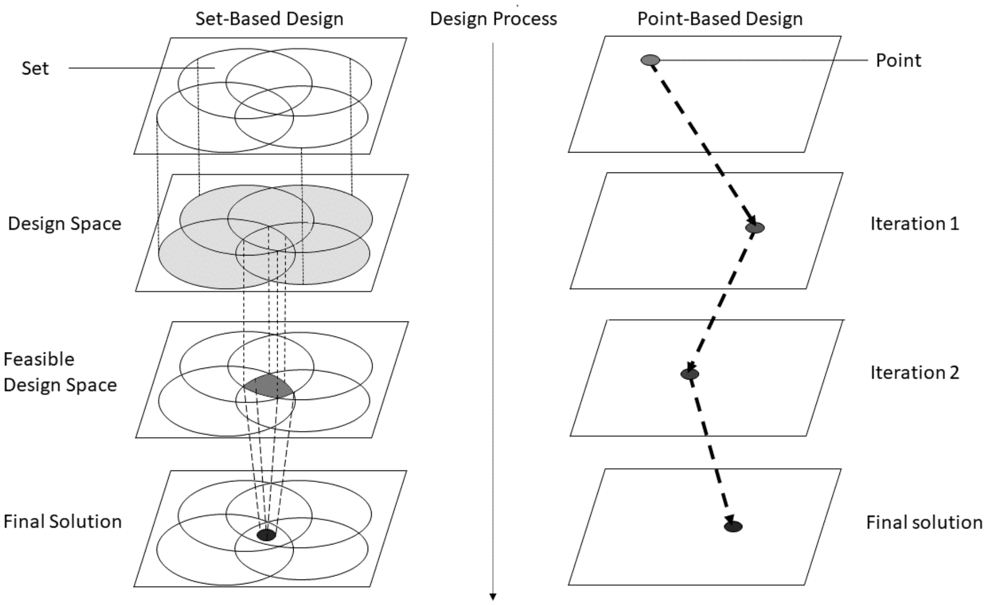


Figure 1.1: Conceptual overview of how design alternatives are generated as the design processes progresses with Set-Based Design and Point-Based Design. Inspired by and adapted from Ward et al. (1995); Bergenram and Ulander (2023)

and in the preliminary design phase, that there exists a certain amount of feasible designs within a specific set of criteria boundaries. Thus, SBD has the potential to gather information in the preliminary design phase, which otherwise would be obtained later in the design process. This, in turn, can potentially enable the STA to include evaluation criteria for environmental performance in tender documents in addition to price.

1.2 Purpose and objectives

This study aimed to examine how Set-based design could be used to reduce uncertainty in the preliminary design processes of frame bridges to facilitate tender evaluation based on CO_2-eq emissions.

- What is the added value of using SBD in the procurement process?
- How does set-based design provide relevant information and reduce uncertainties in the preliminary design phase regarding the buildability cost and CO_2-eq emissions?
- How can SBD be used to enhance the definition of requirements in the procurement process?

1.3 Limitations

General Limitations

- The thesis was conducted in a Swedish context, meaning only Swedish Laws concerning Procurement and the Swedish infrastructure process were considered.
- The thesis was limited to focusing primarily on the client's point of view in public procurement.
- The thesis only researches one public client (the STA) in infrastructure.
- Literature regarding tender evaluation based on emissions and quality has not been researched.
- The study's theory regarding public procurement and the project process was primarily based on the STA's document, which might entail biases.

Limitations in the Interview Study

- The interviews were highly exploratory, limiting a thorough cross-examination of answers.
- The interviewees were strategically selected, which might have resulted in biases in answers.
- Given the small number of interviews (7), the answers have not been saturated.
- The interviewees representing the contractor were employed at Sweden's largest contracting firms, which might have resulted in biases.
- The perspective of the consultant was limited to only 1 consultant.

Limitations in the SBD Algorithm

- The SBD algorithm focuses on the preliminary design of single-track frame bridges intended for railway traffic.
- The algorithm designs the bridge deck, the frame legs, and the foundation slab.
- The frame bridges are assumed to be straight.
- The structural analyses primarily include vertical loads, disregarding the effects of wind action.
- Structural checks in ULS and SLS are included.
- The function of the SBD algorithm is limited to defining the design space of the key variables: material cost, build cost, and CO_2-eq emissions.

1.4 Ethical and Environmental Considerations

The interviewees were kept anonymous in the thesis to convey what was said without complications. The answers and recordings from the interviews were also deleted when the study was complete. Lastly, the thesis aimed to provide conditions for the Swedish transport administration to achieve its goal of climate neutrality; thus, the environmental aspect was considered.

2 Methodology

This section presents the methodologies regarding the case study and the interviews.

2.1 Quantitative and qualitative studies

The research used a mixed-method approach to address the research questions, combining part of a qualitative interview study with a quantitative case study. To be able to compare and contextualize the results of the two "sub-studies", Morgan's (2007) pragmatic approach was used as the philosophical foundation for the thesis. Using the pragmatic approach with mixed methods, the two sub-studies were conducted in parallel with equal priority.

2.1.1 Case study

In the quantitative case study, an algorithm was created in accordance with the study's purpose. The specifics of this study are disclosed in Section 4.6. The study aimed to provide empirical material for general knowledge regarding SBD. The empirical material was then analyzed using an objective point-of-view to determine how SBD objectively can provide relevant information regarding cost, CO_2 emissions, and buildability. Thereafter, the empirical material gathered from the case study was contextualized based on the results gathered from the interview study.

2.1.2 Interview study

The interview study aimed to identify how information gathered by SBD can be used in decision-making during preliminary design, public procurement, and tendering. Specifically, the study aimed to investigate the potential and limitations of SBD in preliminary design. Furthermore, cost and climate impact calculations in the preliminary design were investigated. Lastly, price and quality evaluation in public procurement and preliminary design were investigated. The results from the interview study, with the theoretical framework, were later used to contextualize the results from the case study.

The interview study was conducted qualitatively. The interview respondents were strategically selected, in which the respondents were representatives of consultants, contractors, or clients. The interviews were conducted semi-structurally, given that the knowledge of an SBD implementation in the infrastructure project process is limited. The interviews were then used to investigate and contextualize SBD in the process. The question formulation aligned with the study's purpose and the semi-structured aim; thus, an interview guide was created per Bell et al. (2019, p.439-440). Both the empirical material from the interviews and the case study shaped the gathered theory, and vice versa, during the research process.

The interview data was managed and analyzed in the following way. Firstly, the audio was transcribed using Microsoft Word's transcription tool. Secondly, the transcribed data was cleaned, removing the non-usable or irrelevant data. After the data cleaning, initial themes in the answers from the first interview were extrapolated. The themes were iterated until the themes were saturated, meaning each answer could be categorized into a theme. The final themes are presented in Table 2.1. The themes were then used to categorize the data from the interviews. After the categorization, documents for each theme were created, and the categorized data from each interview was put into their respective documents. Each document was structured based on the chronological order of the interviewees. To clarify, each document represented a theme and included everything the interviewees said concerning the theme. The data under each theme from each interviewee was then analyzed and summarized based on keywords and phrases in the documents. The summarized data was later included in an Excel spreadsheet containing each theme, interviewee, and corresponding summary. In creating the spreadsheet, "meta-themes" — themes of the themes — were identified. Following this, each summary, theme, and meta-theme were translated using Deepl's AI translate software from Swedish to English. Lastly, a document to facilitate cross-analyses between the interviewees' answers was created, containing all translated summaries and structured according to the meta-themes and themes. The analyzes was later presented in Section 6.

Lastly, the results from the qualitative and quantitative studies were contextualized with the theoretical framework in the discussion (Section 7) to provide answers to the research questions.

Table 2.1: The found themes in the interviews

Background on the interviewee
Understanding of SBD
Opportunities with SBD implementation
Preconditions for SBD to be implemented
Limitations of SBD
Description of the road-railway plan
Price and quality in contracts
Trafikverket's limitations in calculations
Variance between preliminary design and final product
SBD as a database
Design process of bridges in road-railway plans
Design calculations
Implementation of normal distributions of solutions in procurement documents
Requirements, bonuses & evaluation criteria

3 Theoretical Framework

This section presents a literature overview of SBD, the public tendering process, the infrastructure project process, and decision-making under uncertainty.

3.1 Set-based design: an overview

As mentioned in 1.1, SBD is a design methodology that considers sets of solutions that are gradually narrowed down as the design process progresses. Ward et al. (1995) & Sobek et al. (1999) presented the steps and principles that constitutes SBD (referred to as Set-Based Concurrent Engineering (SBCE)). First, designers should map the design space for a given system by establishing the total sets of solutions applicable to the system. This means that designers define the design constraints — allowable ranges — for each design parameter in the system to establish the feasible regions for the parameters. After defining the feasible region for each parameter, the regions are intersected and overlapping regions are found, resulting in all feasible sets of solutions for the given system (See Figure 3.1). Lastly, when the design space has been established, and the sets have been integrated through the intersection, the sets are gradually narrowed down, ultimately converging toward a single set of solutions. In essence, SBD is a design methodology that considers all possible design options and gradually narrows them down as the design process progresses.

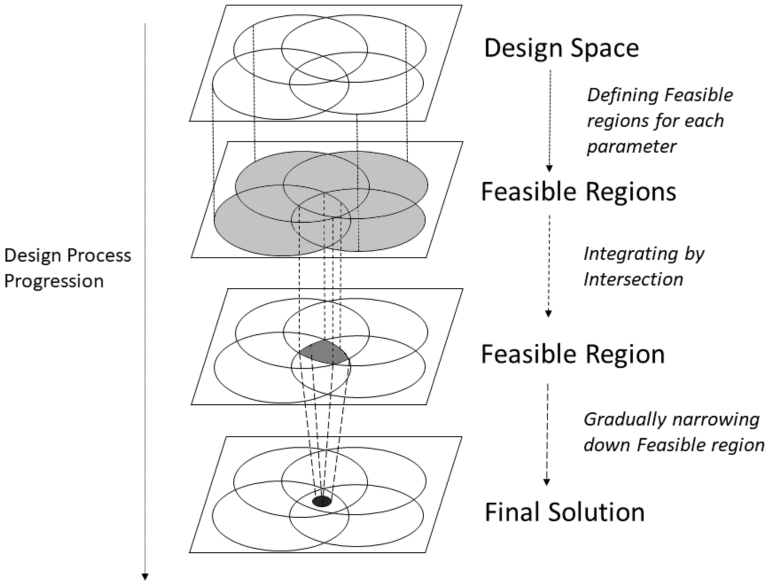


Figure 3.1: Conceptualization of the steps constituting Set-Based Design, from creating design space to a final solution. Inspired by and adapted from Ward et al. (1995); Sobek et al. (1999); Bergenram and Ulander (2023)

3.1.1 The Emergence of Set-Based Design

In Toche et al. (2020), SBD's main point of emergence is credited to Ward et al.'s paper "The Second Toyota Paradox" (1995). In their comprehensive literature review of SBD, Toche et al. (2020) found that the research of SBD was limited before Ward et al. (1995)'s paper. (Toche et al., 2020) split their review into pre- and post-reviews of the Second Toyota Paradox paper due to it being a large contributor to SBD's rise in relevancy. Following Ward et al.'s (1995) paper, another paper from Sobek et al. (1999) was presented, where a more in-depth exploration of SBD and its application in the design phase was conducted. In Toche et al. (2020), it is stated that the papers succeeding Ward et al. (1995) accept SBCE's philosophy and focus rather on developing the SBD theory and its implementations. Therefore, SBD emergence as a general design theory is contributed largely to Ward et al..

Although Toche et al. (2020) provides a thorough overview of SBD's emergence as a field of research, it does not provide an overview of SBD in specific areas, such as the construction industry. Toche et al. briefly mention the papers Tommelein et al. (1992), K. Parrish et al. (2008), and K. D. Parrish (2009), all of which are focused on SBD implementation within a structural engineering context.

3.1.2 Rise in Construction Academia

In Tommelein et al. (1992), a model was created, SightPlan, which generates layouts of temporary construction facilities on a building site. The model generates sets of solutions, or "sets of alternative positions" as Tommelein et al. refer to them, and gradually narrows them down using different constraints until satisfactory layouts are found. Although not explicitly stating or referring to SBD in their paper, their design process is largely similar to the later defined process of SBCE by Ward et al. (1995).

Later papers from Ballard and others Ballard (2000); Ballard and Zabelle (2000); Ballard (2008) all studied SBD in a construction context and referred explicitly to "SBD". In his paper, *"Positive vs Negative Iteration in Design"*(Ballard, 2000), referred to SBCE as Set-based design (SBD), which was the first time in the construction literature. The paper also presented the notion of negative iteration in design and presented preventative techniques for the notion, the implementation of SBD being one of them. Negative iteration is when designs are made outside the set of possible solutions for all subsystems within the design space and must be reworked to fulfill other stakeholders' requirements. It is argued that SBD can be used to avoid negative iterations in design by coordinating among stakeholders, considering their various requirements, and creating a solution space based on these requirements. This generates design solutions that fulfill every stakeholder's requirement, thus avoiding negative iterations.

Following the initial design and construction papers (Ballard, 2000; Ballard &

Zabelle, 2000; Ballard, 2008), Parrish et al. conducted and presented research on SBD in a structural engineering context in the literature (K. Parrish, Tommelein, Wong, & Stojadinovic, 2007; K. Parrish et al., 2008; K. D. Parrish, 2009). K. Parrish et al. (2007) argues that SBD may be superior to PBD due to PBD's limitations in communication leading to reworks in design, i.e., negative iterations as defined by Ballard (2000). K. Parrish et al. then applied and modified the three suggested SBCE principles presented in (Sobek et al., 1999). The modified principles were the following: Map the design space, find compatible combinations, make commitment. The authors then applied the modified principles in a fictitious case of reinforcing a concrete beam-column joint in a reinforced concrete frame. The design space was described, in a structural design context, as *"A design space may compromise sets of design options that can be continuous or enumerated as discrete design options depending on the level of abstraction"* - (K. Parrish et al., 2007). Therefore, the authors argue that, when formulating the design space, computers could define the total designs required to define the feasible design space completely. K. Parrish et al. also introduces the notions of hard and soft constraints, where hard constraints are code requirements, such as Eurocode, and soft constraints are design preferences. The articles by K. Parrish et al. thus provide modified principles and a step-by-step breakdown of applying them in a structural engineering context.

Following the case of K. Parrish et al. (2007), Parrish et al. provided real-life case studies of SBD implementation in structural engineering (K. Parrish et al., 2008; K. D. Parrish, 2009). In the study, SBD helped create a design that met the project's target costs. This design used an otherwise overlooked solution for certain elements of the building and fulfilled not only the structural requirements but also other stakeholder requirements.

In her PhD thesis, K. D. Parrish (2009) provided proof of concept for SBD and further documentation of SBD usage in structural engineering. K. D. Parrish also contextualizes SBD terms and definitions for structural engineering and concertizes the correlation between the level of detail and design space. For set-based rebar design, relevant stakeholders to be included are the suppliers of materials, designers, and contractors. Furthermore, a set was defined as *"a group of design alternatives at some level of detail, that can be defined either as discrete (specific rebar configurations) or continuous (a 24 in. Deep beam+-1 in.)"*-(K. D. Parrish, 2009) p.79. Lastly, the thesis presented the notion that the level of detail is inversely correlated with the design space size in the design process. Figure 3.2 illustrates this correlation. The thesis, along with the other papers K. Parrish et al. (2007, 2008) co-authored by Parrish, provides a theoretical foundation for SBD in the structural engineering design process by presenting proof-of-concept and contextualizing SBD principles in structural engineering.

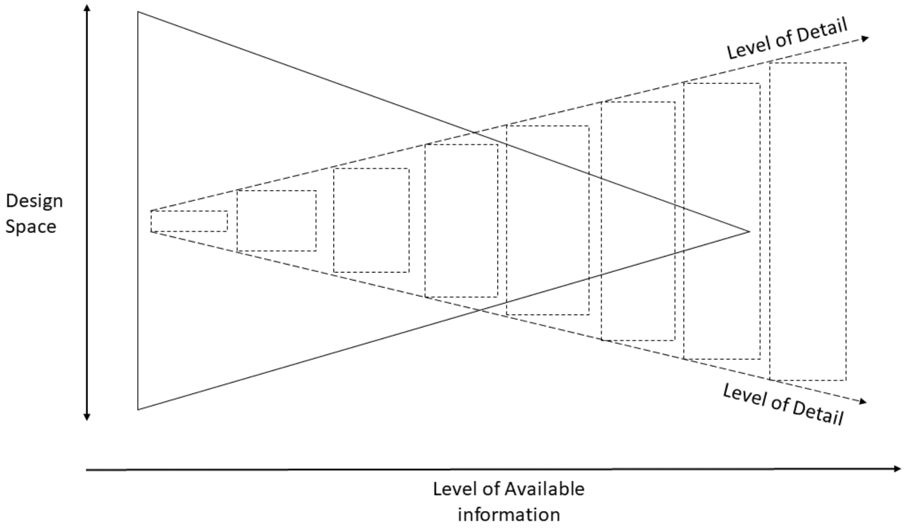


Figure 3.2: The inverse correlation between design space and the level of detail as the level of available information increases, inspired by and adapted from K. D. Parrish (2009).

3.1.3 Set-Based Design in Bridge Design

The article Rempling et al. (2019), master thesis Löfgren (2020), and proceedings Bergenram et al. (2023) are some of the first academic efforts to investigate SBD's applicability in structural bridge design. In their article, Rempling et al.(2019) studied the potential of the method of Set-based parametric design (SBPD) — a combination of the set-based design methodology and parametric modeling technique (Nahm & Ishikawa, 2006) — in the preliminary design phase of bridges. The specific method used (and suggested) for generating bridge designs is built around developing an algorithm that utilizes parametric design in an SBD fashion. Using the method, i.e., creating the algorithm and applying it to bridge designs, the authors generated design solutions for three already-built bridges with substantially smaller material costs and CO_2 equivalent emissions. Thus, Rempling et al.'s article provides proof-of-concept and a theoretical footing for SBD in a bridge design context.

Löfgren (2020) developed further on the SBD approach of Rempling et al. (2019). In his master thesis, Löfgren(2020) also investigated an implementation of SBD in the preliminary phase of bridge design. Similarly to Rempling et al. (2019), Löfgren analyzed the potential of SBD by incorporating material cost and CO_2 equivalent emissions into the algorithm as a criterion. However, the author also attempted to include a buildability criterion in the algorithm, but the criterion was deemed too hard to quantify.

Bergenram et al.(2023) continued Löfgren (2020)'s research by conducting a study that also studied the potential of implementing SBD and included sustainability evaluation criteria. However, these authors also successfully implemented a buildability criterion. The buildability criterion was quantified as economic costs from longer production processes incurred by material properties, geometrical complexity, and reinforcement. The authors found that SBD could substantially decrease the environmental impact of designs with a minor increase in costs compared to their case designs. These academic works then provide proof-of-concept for including buildability in the algorithm. Thus, the latest research provides a theoretical footing for developing an SBD algorithm for generating bridges in the preliminary design phase that considers material cost, buildability, and environmental impact criteria.

3.2 Public Procurement for the STA

The Swedish Transport Administration (STA) is a governmental administration tasked with long-term transport planning in Sweden and is a client in large infrastructure projects in Sweden (Aldin, 2023). They are also responsible for building, operating, and maintaining state roads and railways. The STA is a state-governed entity that acts as the client in public procurement. In Sweden, the majority of public procurements are conducted under *"The Public Procurement Act"* (LOU) (Upphandlingsmyndigheten, n.d.). The National Agency for Public Procurement (Upphandlingsmyndigheten in Swedish) establishes general procurement principles and processes and apply to all public procurements. The principles state that public procurement organizations must be objective and neutral to all stakeholders who want to become suppliers. Furthermore, the procurement process must be conducted in a way that is identified as transparent and proportional.

As mentioned, the STA is a client in the public procurement process for infrastructure projects. This is because the state-governed entities take on the role of clients in projects to drive the development of markets and create favorable conditions for private actors in the market (Aldin, 2023). STA then embraces the role as a pure client, that is, publicly procuring functionality instead of ready-made technical solutions, to drive the construction industry's market, productivity, and rate of innovation (Eriksson et al., 2014). How the STA executes its role as a pure client and its aim to drive development in the construction industry is disclosed in its procurement strategy document (Aldin, 2023). The procurement strategy includes using public procurement to drive long-term sustainable development in the construction industry.

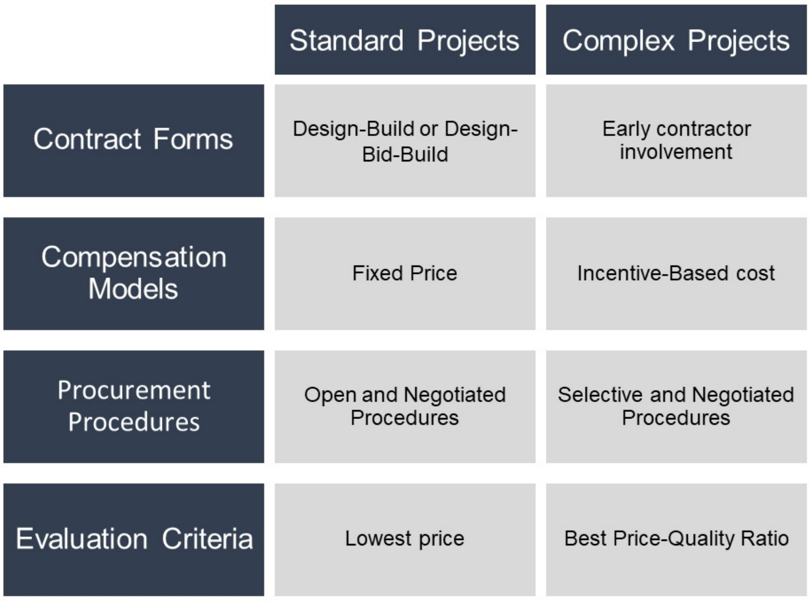
3.2.1 Planning Procurement

The STA begins the procurement process by assessing and specifying transport needs in Sweden, as well as identifying supply measures and market development conditions in the construction industry (Aldin, 2023). The conditions for market development include demands of innovation, life-cycle perspective, and goals for market development. The conditions are explored and defined through dialogue with relevant actors in the construction market and the procurement process, such as contractors and consultants. Furthermore, the transport demands refer to different transport-related problems highlighted by the government either at the local, regional, and/or national level (Trafikverket, 2015). The STA plans what measures to take to supply these demands in what they call *"Strategic Choice of Measures"* (Aldin, 2023) p.5. The result of this is final outcome objectives for procurements (Aldin, 2023). So, the STA conducts analyses of demands, potential solutions for the demands, and conditions for market development to finalize outcome objectives for procurements.

Following the formulation of outcome objectives, STA chooses the type of business form they want to procure (Aldin, 2023). This includes choosing the type of contract or the type of assignment based on the outcome objectives, degree of freedom, the complexity of the project, and uncertainties connected to the procurement and project. After selecting the type of business form, STA specifies which contract, compensation, and cooperation form to use in the project (Trafikverket, 2019) (This is disclosed in detail in Section 3.2.2). After this selection, the contract is announced and is open for tendering.

3.2.2 Tender documents

As previously mentioned, the STA chooses the type of business form based on different characteristics and challenges of the procured project. To reiterate, STA analyses and later determines the connected outcome objectives, degree of freedom, complexity, and uncertainty of the project when selecting business forms (Aldin, 2023). Using this analysis, STA determines the contract form, compensation model, procurement procedure, and evaluation criteria to include in the tender documents (See Figure 3.3 for clarification). For projects with low degrees of complexity, uncertainty, and freedom — referred to as simple projects — the contract type is either Design-Build (DB) or Design-Bid-Build (DBB) as shown in Figure 3.3. The compensation form for simple projects is fixed price, with or without quantity regulation, and focuses on promoting competition rather than collaboration. Therefore, the basis of evaluation for simple projects is based on the lowest price rather than quality and price.



	Standard Projects	Complex Projects
Contract Forms	Design-Build or Design-Bid-Build	Early contractor involvement
Compensation Models	Fixed Price	Incentive-Based cost
Procurement Procedures	Open and Negotiated Procedures	Selective and Negotiated Procedures
Evaluation Criteria	Lowest price	Best Price-Quality Ratio

Figure 3.3: Overview of components included in tender documents, inspired by and adapted from Aldin (2023)

Figure 3.3 presents what is generally included in the tender documents based on the level of complexity of the projects. The STA has the following considerations for each component in the tender documents.

- **Functional Requirements and Life-Cycle Perspective**: The STA aims to set functional requirements and standards based on a life-cycle perspective of the infrastructure to ensure long-term sustainability and performance.
- **Contract Forms**: Based on outcome objectives, project goals, needs, risks, and opportunities, the STA selects appropriate contract forms. This includes early market dialogue, negotiated procedures, and collaboration to enhance project outcomes.
- **Compensation models**: The STA uses bonuses and other incentives to motivate suppliers to deliver beyond the basic requirement levels to foster innovation and superior performance.
- **Procurement Procedure**: The procurement procedure is planned and executed to ensure transparency, fairness, and the achievement of desired outcomes.
- **Evaluation Criteria**: The evaluation criteria are designed to ensure that the quality offered by suppliers exceeds the basic requirements. Through what is referred to as added value, tenders' quality can be considered, and their sum be reduced by a ratio. This ratio is relative to price and is pre-simulated — determined before the procurement — to find an optimal level that achieves the intended effect. Typically, this ratio is aimed at a maximum of 30% of the expected bid amount, though in special cases, it can go up to 50%.

To summarize, the STA considers and includes different procurement-specific details in the tender documents to meet Sweden's infrastructure needs and promote long-term market development and innovation.

3.3 Project process

In public construction projects, where the STA acts as the client, the process involves identifying needs, developing concepts, and designing solutions to meet those needs through in-house efforts and external procurement. Cost and environmental impact estimations are conducted throughout the creation of designs and concepts. An overview of the project process is presented in Figure 3.4. The overview presents the process' design space, level of available information and detail, different actors' involvement, sub-phases, time of cost and environmental impact estimations chronologically. The project process is split into 7 sub-phases: Business development, Action Study, Pre-design, Preliminary design, Detail design, construction and delivery, and Asset Management (see Figure 3.4), all of which are further explained in the following sections.

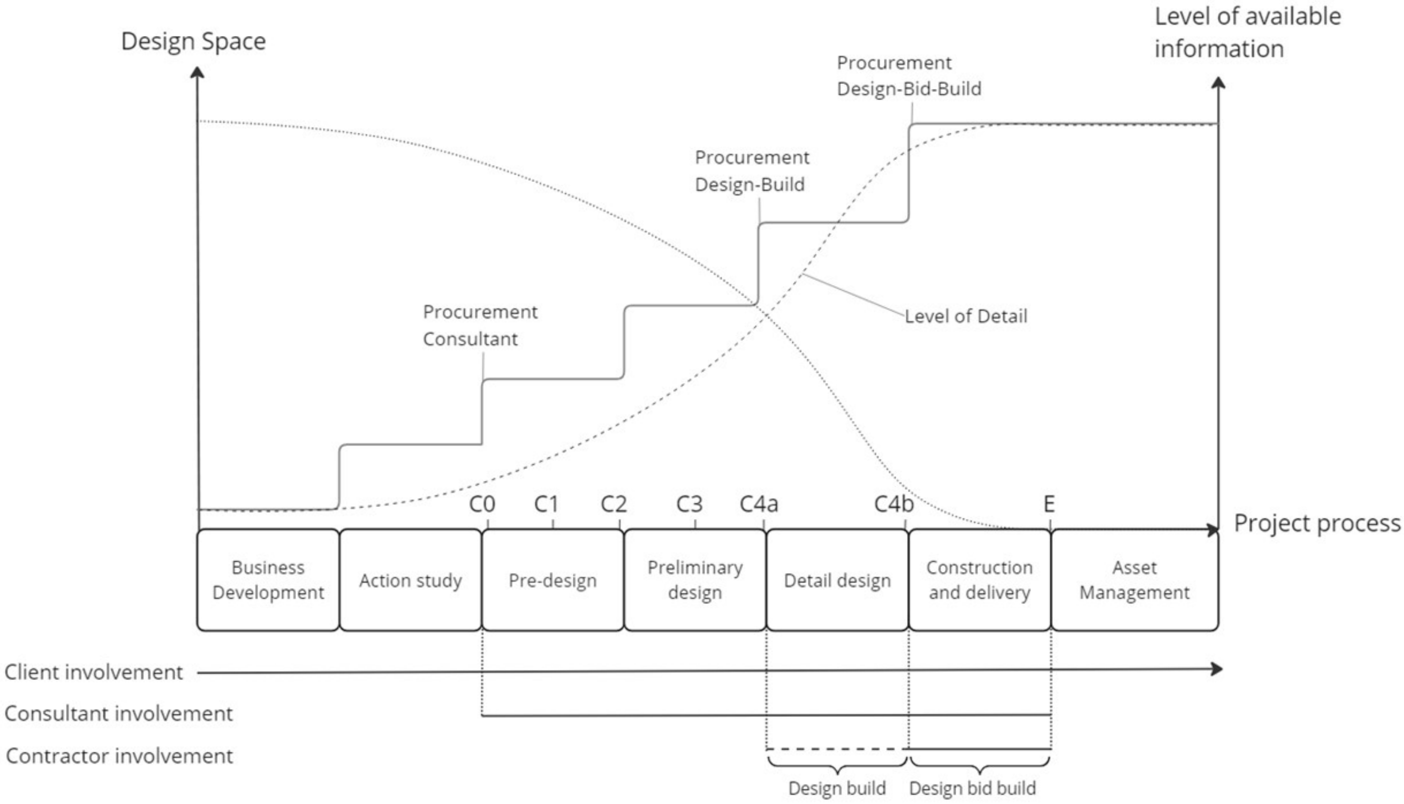


Figure 3.4: Overview of the project process. Inspired and adapted from (Bengtsson, 2023; Bergenram & Ulander, 2023; Lagerkvist, 2023; Antonsson, Lindvall, Lagerkvist, & Rempling, 2022; Miliutenko, 2022; Karlsson, Rempling, Gylltoft, & Plos, 2017; Dht, Walker, & Lloyd-Walker, 2012; K. D. Parrish, 2009)

3.3.1 Business development & Action study

The phase *Business Development* refers to the long-term planning and strategy for the STA. In this phase, as described when initiating procurements processes in Section 3.2.1, the STA maps out the different transport needs in Sweden (Aldin, 2023).

After identifying the needs, the STA initiates the phase *Action Study.* This phase includes conducting "action studies" that analyze and produce potential and feasible future actions for the identified needs (Trafikverket, 2015). The action studies also include market development needs in the construction market, resulting in action proposals stored for further use. In the studies, STA includes rough estimates of financial costs and emissions of the actions — C0 in Figure 3.4 (Miliutenko, 2022). The emission estimations lay the grounds for the climate requirements for the consultants during the project planning process. The result of this phase is thus potential projects that might satisfy the established needs. Furthermore, the action proposal constitutes possible solutions for the identified problems. In essence, by identifying problems, establishing needs, and conducting action studies to create action proposals for the needs, the STA creates possible solutions for the problems.

3.3.2 Pre-design

In the following phase, *Pre-design*, the action proposals act as the basis for formulating more specific action descriptions in project planning. The planning process for road and railways is initiated when the action proposals include either building or changing roads or railways, and actors (e.g., the STA) decide to follow through with the proposals (Sandberg, 2014). When initiating the planning process, the client states the project's purpose, which is connected to the found needs in the business development phase. Following this, the client sets specific project goals to fulfill the project's purpose. The goals encompass the qualities and functions needed to fulfill the project's purpose. The client then initiates the Pre-design phase by starting the planning process for the project, which includes defining the project by stating its purpose and specific goals.

After defining the project, the client procures further planning of the project by consultants, which will continue with the Pre-Design phase and the planning process of the project (Sandberg, 2014). The consultants are tasked with starting the physical planning for the project, that is the design and layout of the construction site. This plan aims to determine the degree of the project's environmental impact. Moreover, this plan includes a reiteration of the construction cost and carbon footprint estimations from the action studies — C1 (Miliutenko, 2022). In cases where the project's degree of environmental impact is significant, alternative designs and layouts of construction sites need to be studied (Sandberg, 2014). The alternatives' construction cost and carbon footprint must also be estimated — C2 (Miliutenko, 2022). After consulting with relevant stakeholders and consultants, the client decides what alternative to continue with (Sandberg, 2014). This concludes the "Pre-design" phase. In short, in the "Pre-design" phase, initiated by the client, action proposals form the basis for specific action descriptions in the planning process, which includes defining the project's purpose, setting goals, and initiating physical planning by consultants, resulting in the selection of alternative designs and layouts based on environmental impact assessments.

3.3.3 Preliminary design

Following the selection of alternatives in the "Pre-design" phase, the "Preliminary design" phase commences. This phase includes formulation, review, and approval of the road or railway plan, i.e., the project plan (Sandberg, 2014). When formulating the project plan, designers produce designs of how the road or railway will be built.

Throughout the design process, information regarding the project is gathered from continuous checks, surveys, and stakeholder feedback. The designs are then iterated based on the influx of new information as the process progresses. Moreover, cost and carbon footprint estimations — C3 in Figure 3.4 — are made of the designs when they are deemed finished. Lastly, the project plan is deemed finished and ready for review when the project "profile" (e.g., background, goals, environmental assessments, preconditions, location, design, effects, land usage, ongoing work, implementation, and financing) is established.

The finished project plan is later announced for review, and feedback on the project is gathered (Sandberg, 2014). The client is responsible for responding to each point of feedback. The feedback can result in changes in the project plan. When the feedback prompts changes in the plan, changes and notes are introduced. Following the review, the county administrative board states whether they approve of the project plan or not. If the plan is not approved, the project plan needs further revision. After receiving the statement from the county administrative board and potentially changing the project, an approval document is assembled and sent to the STA headquarters. The STA then assesses the project plan and either approves or denies it based on the assessment.

If and when the project is approved, reduction requirements for emissions in the construction documents produced in the *Detailed design* phase are formulated (Bengtsson, 2023). The basis of these reduction requirements is dependent on whether the project is intended to be a Design-Build (DB) contract or a Design-Bid-Build (DBB) contract. The basis for the requirements in the construction documents for DBB contracts is based on the carbon estimates from C3 in figure 3.4. These requirements are put on the consultants who will carry out the detailed design. However, in the case of DB contracts, the tender documents are formulated after the project is approved. These documents include a reiteration of the cost and carbon footprint estimations, referred to as C4a in Figure 3.4. Then, based on the estimations, the reduction requirement for a design-build contract is formulated. To summarize, after getting the approval for the project, formulating the tender documents for DB contracts, or establishing the emission requirements for the consultants responsible for the detailed design phase, the *Preliminary design* phase is finished, and the *Detail design* phase is ready to start.

3.3.4 Detailed design

The *Detail design* phase entails the production of construction documents for the project. This phase differs depending on whether the contract will be DB or DBB (Bengtsson, 2023). In the case of DB, the contractor is tasked with, excluding the construction and delivery, producing the detailed design — that is, the construction documents — for the project (Miliutenko, 2022). These documents are based on requirements in the tender documents developed in the preliminary design.

However, in the case of DBB contracts, the client's design consultant(s) is tasked with the detailed design instead (Sandberg, 2014). Other than producing the construction documents for the project, the consultant(s) is tasked with reiterating the cost and emission estimates in C3 in Figure 3.4, resulting in estimates based on the construction documents (C4b in Figure 3.4). After establishing the emission estimates, reduction requirements are formulated for the construction phase (Bengtsson, 2023). Next, procurement of the DBB contract occurs. The construction documents, cost and emission estimates, and emission reduction requirements then make up the tender documents for the contract. In essence, the detailed design phase produces more specific designs —construction documents— to enable the following construction phase.

3.3.5 Construction, Delivery, & Asset management

In the *Construction and delivery* phase, the contractor(s) executes the tasks specified in the construction documents with supervision by the client and consultant (Karlsson et al., 2017). When the construction is finished, the actual economic cost and emissions for constructing the project are calculated (Miliutenko, 2022), referred to as E in Figure 3.4. Moreover, if changes need to be added to the contract, alteration, addition, and departure (AAD) works are implemented into the contract. The client is responsible for the added costs of the AAD works (Trafikverket, n.d.). Following this, the road or railway is delivered and handed over to the client by the contractor. After handing over the project, the contractor leaves the project, and the client is the owner of and responsible for managing the asset (e.g., road or railway).

3.4 Decision Making under uncertainty

As briefly mentioned in section 1.1, preliminary design and public procurement decisions are made under uncertainty. To manage the uncertainties present, a description of uncertainty itself and ways to manage the different types of uncertainty need to be disclosed. This chapter will, therefore, present uncertainty in decision-making and SBD as a method for decreasing uncertainty.

3.4.1 Uncertainty

For decision-makers, decisions can be taken with certainty or uncertainty depending on the available information and knowledge of the decision-maker in any given decision context (Malczewski, 2006). Certainty in decision-making is whenever the decision-maker has perfect knowledge, i.e., a full understanding of the consequences of the decision. Uncertainty in engineering problems can, therefore, be defined as a lack of knowledge for any given circumstance (Kiureghian & Ditlevsen, 2009). Furthermore, uncertainties can generally be categorized into two types: those that can be reduced by gathering more data and those inherent to randomness, which can only be understood rather than minimized.

3.4.2 SBD in decision making as a method for decreasing uncertainty

Decisions made in early design, such as preliminary design, should consider broad ranges of alternatives, be easy to understand and implement, include decision-makers' preferences, and provide practical design guidance (Shahtaheri, Flint, & de la Garza, 2019). Along with these prerequisites for decisions, the decisions are made under uncertain conditions, both from the lack of data and inherent randomness, further complicating the decision-making process. Different decision-making tools and methodologies, such as SBD, are used to help decision-makers simplify the process.

Design space exploration is often used as an analytical method in research that applies SBD in early design and evaluates generated designs to model uncertainties. This process involves implementing evaluation criteria on solutions within a design space, as Specking et al. (2018) outlined. These criteria include various performance indicators of the designs, such as financial cost or system performance. The goals of the exploration are to identify the best design solutions and, perhaps more importantly, to uncover the trade-offs among different design choices. For example, in the early stages of design, the best solutions might evolve as more information becomes available throughout the project. Furthermore, the relationship between different key variables (e.g., cost, CO_2 emissions, and buildability) can be identified, providing valuable insights into the behavior of the design space for decision-makers. This method reduces uncertainties in early design by recognizing that initial designs are low-resolution and not finalized, leading to uncertainties about future optimal designs (N. Shallcross, Parnell, Pohl, & Specking, 2020). Although the behavior of the design space does not pinpoint the best future designs, it reveals how key variables interact and the ranges of design alternatives, enabling designers to identify trade-offs between different performance metrics through evaluation criteria.

4 Set-Based Design algorithm

This Section presents relevant loads and load combinations, bridge assessment controls, conceptualization of frame bridges, the SBD methodologies from previous scholars, evaluation of key variables, and how all this is implemented in the SBD algorithm.

4.1 Bridge design for railway bridges

The structural feasibility of bridge designs is evaluated towards its capability to withstand certain loading scenarios. These loads are specified in codes, establishing coherent guidelines for bridge designs throughout the European Union. However, these European standards are usually complemented by national standards accounting for the local environments. This Section presents loads, load combinations, and structural verifications used as basis for the design according to Eurocode, such as the Eurocode (e.g. SS-EN 1990:2023).

4.1.1 Loads and load models

According to *SS-EN 1990:2023* a bridge design must fulfill the requirements regarding Ultimate Limit State (ULS), Service Limit State (SLS), and Fatigue (FAT). In the ULS, the maximum sectional forces within the bridge dictate the need for reinforcement in concrete bridges. Similarly, in the SLS, factors such as deformations and crack widths are assessed. Although ULS and SLS controls do not fully provide a comprehensive bridge design on their own, they can be used to estimate material quantities.

In the Eurocodes, loads related to ULS and SLS are grouped into two categories: permanent loads and variable loads (*SS-EN 1990:2023*, 2023). Permanent loads are those associated with constant actions on the bridge, whilst variable loads stem from transient actions. Permanent loads related to frame bridge design are presented in Table 4.1 and variable loads associated with railway bridges are presented in Table 4.2 and Table 4.3.

Table 4.1: Description of permanent loads.

Load/Effect	**Description**	**In document**
Self weight	Weight from the structure.	
Weight of ballast	Weight of the ballast on the structure.	
Resting earth pressure	Horizontal pressure acting on the frame legs.	TK Geo 13 TDOK 2013:0667
Shrinkage	Time-dependent shrinkage due to drying and autogenous shrinkage.	SS-EN 1992-1-1 chapter 3.1.4
Creep	Time-dependent effect of solids undergoing deformations with sustained loading.	SS-EN 1992-1-1 chapter 3.1.4

Table 4.2: Description of variable loads.

Load/Effect	**Description**	**References**
Vertical load models	Vertical load models representing different loading scenarios.	SS-EN 1991-2 & TRVINFRA-00227
Traction	Horizontally acting force in the longitudinal direction of the bridge, represents a train accelerating or braking.	SS-EN 1991-2 chapter 6.5.3
Nosing	Transversely acting force, representing forces applied perpendicular to the direction of travel.	SS-EN 1991-2 chapter 6.5.2
Centrifugal forces	Radially acting forces if the train track is in a curve	SS-EN 1991-1 chapter 6.5.2
Temperature	Expansion and contraction of bridge elements due to temperature fluctuation.	TRVINFRA - 00227 chapter 7.2.1.1.2.1.1
Counteracting earth pressure	Counteracting earth pressure from traction and temperature loads	TRVINFRA - 00227 chapter 7.2.1.1.2.1 & TDOK 2016:0203 chapter B.3.2.2.2
Wind	Transversely acting load, representing wind load on the train and the structure.	SS-EN 1991-4
Surcharge	Additional horizontal earth pressure on frame legs from loading of adjacent soil.	SS-EN 1991-2 chapter 6.3.6.4

Vertical load models are defined in *SS-EN 1991-2* and *TRVINFRA-00227* and cover various loading scenarios. Load models relevant to railway bridges including those associated with vehicles traversing the foundation slab are presented in Table 4.3.

Load models LM1 and LM2 can be applied on the foundation of the closed-frame bridge if vehicles are permitted.

Table 4.3: Description of Load Models.

Load Model	**Description**	**In document**
LM71	Load model representing the effect of vertical loading from normal rail traffic.	SS-EN 1992-2 chapter 6.3.2
SW/0	Load model representing the vertical effect of vertical loading from normal rail traffic on continuous beams.	SS-EN 1991-2 chapter 6.3.3
SW/2	Load model representing the vertical effect of vertical loading from heavy rail traffic.	SS-EN 1991-2 chapter 6.3.3
Track changing machine	Load model representing vertical effect from a track changing machine.	TRVINFRA - 00227 chapter 7.1.6.2.1.3
LM1	Load model representing vertical effects from vehicles on the foundation slab.	SS-EN 1991-2 chapter 4.3
LM2	Load model representing vertical effects from heavy vehicles on the foundation slab.	EN 1991-2 chapter 4.3

4.1.2 Load combinations

Load combinations are simply combinations of variable and permanent loads. Load combinations associated with actions for persistent or transient design situations can be taken as the least favorable load action obtained from expressions 6.10a and 6.10b in *SS-EN 1990:2023*. Expressions 6.10a and 6.10b are used to determine the maximum load effects in ULS and are presented in Equation 4.1 and Equation 4.2 below.

$$\sum_{j\geq 1}\gamma_{G,j}G_{k,j}+\gamma_p P+\gamma_{Q,1}\psi_{0,1}Q_{k,1}+\sum_{i>1}\gamma_{Q,i}\psi_{0,i}Q_{k,i} \tag{4.1}$$

$$\sum_{j\geq 1}\xi_j\gamma_{G,j}G_{k,j}+\gamma_p P+\gamma_{Q,1}Q_{k,1}+\sum_{i>1}\gamma_{Q,i}\psi_{0,i}Q_{k,i} \tag{4.2}$$

Where: γ_G = Partial factor regarding permanent loading
G_k = Characteristic value of permanent load
ξ_j = Reduction factor for unfavourable actions of permanent loads
γ_p = Partial factor regarding prestressing
P = Characteristic value of prestressing load
γ_Q = Partial factor regarding variable loads
ψ_0 = Partial factor regarding variable loads
Q_k = Characteristic values of variable load
$\sum$ = Implies "the combined effect of"
$+$ = Implies "to be combined with"

The magnitude of the partial factors varies depending on the load type, i.e. wind load does not have the same partial factors as LM71. Hence several different sets of the same load combination should be regarded where the different load types are put as the main load, the characteristic variable load with a 1 as index i, to obtain the most unfavourable effects from the load combination.

Deflections should be assessed with frequent load combination according to *TRVINFRA-00227* chapter 7.2.9.2. The frequent load combination can be found as expression 6.16a in *SS-EN 1990:2023* and is presented in Equation 4.3.

$$\sum_{j\geq 1} G_{k,j} + P + \psi_{1,1}Q_{k,1} + \sum_{i>1}\psi_{2,i}Q_{k,i} \tag{4.3}$$

Where: G_k = Characteristic value of permanent load
P = Characteristic value of prestressing load
ψ = Partial factor regarding the variable load
Q_k = Characteristic values of variable load
$\sum$ = Implies "the combined effect of"
$+$ = Implies "to be combined with"

4.1.3 Ultimate Limit State

As previously mentioned in subsection 4.1.1, the ULS design determines the ultimate capacity of the structure which should be less than the sectional forces in any position of the structure.

When designing slabs, the torsional moment should be accounted for in the design moment (Björn Engström, 2014). This is done by simply including the absolute value of the torsional moment to the moment in the specified direction. If the negative moment is defined to give tension at the bottom of the slab, Equation 4.4

and 4.5 will determine the design moment for the bottom reinforcement. Similarly, equations 4.6 and 4.7 will provide the design moment for the top reinforcement.

$$m_{xr} = m_x - |m_{xy}| \quad \text{(Accept if negative, ignore if positive)} \tag{4.4}$$

$$m_{yr} = m_y - |m_{xy}| \quad \text{(Accept if negative, ignore if positive)} \tag{4.5}$$

$$m'_{xr} = m'_x + |m_{xy}| \quad \text{(Accept if positive, ignore if negative)} \tag{4.6}$$

$$m'_{yr} = m'_y + |m_{xy}| \quad \text{(Accept if positive, ignore if negative)} \tag{4.7}$$

When designing the shear reinforcement of slabs, the design value of the shear force should be taken as the resultant of the shear in x- and y-direction (Pacoste, Plos, & Johansson, 2012). The design value of the shear force is thus obtained with Equation 4.8.

$$V_{Ed} = \sqrt{v_x^2 + v_y^2} \tag{4.8}$$

4.1.4 Serviceability limit state

In SLS, deformations in the horizontal and vertical directions should be evaluated and stay within the limits of bridge norms. The Swedish transport administration has in *TRVINFRA-00227*, specified the Swedish requirements as well as applicable parts in the Eurocodes regarding deformation checks, deformation requirements are listed in Table 4.4. The vertical deformations should be limited to the length/800 with frequent load combination and the horizontal deformations should be limited to 5 millimeters.

Table 4.4: Deformation requirements in SLS.

Deformation	**Requirement**	**Load combination**	**In document**
Vertical deformation	<L/800	Frequent	TRAVINFRA-00227 chapter 8.2.4
Horizontal deformations from traction and breaking.	<5mm	Frequent	SS-EN 1991-2 chapter 6.5.4.6.1
Horizontal deformation from vertical loads	<5mm	Frequent	SS-EN 1991-2 chapter 6.5.4.6.1

4.2 Reinforced concrete frame bridges

Reinforced concrete frame bridges are defined by the interconnected substructure and the superstructure, creating rigid connections (Trafikverket, 2008). The stiff connections result in a continuous structure where sectional forces can be transferred between different parts of the bridge. The frame bridge types integrated into the algorithm consist of a closed and open frame and are based upon standardized frame bridges in the railway project Norrbottniabanan (Bruneby, Vedin, Ljundahl, & Uneklint, 2023). These conceptualizations are presented in Figure 4.1 and Figure 4.2.

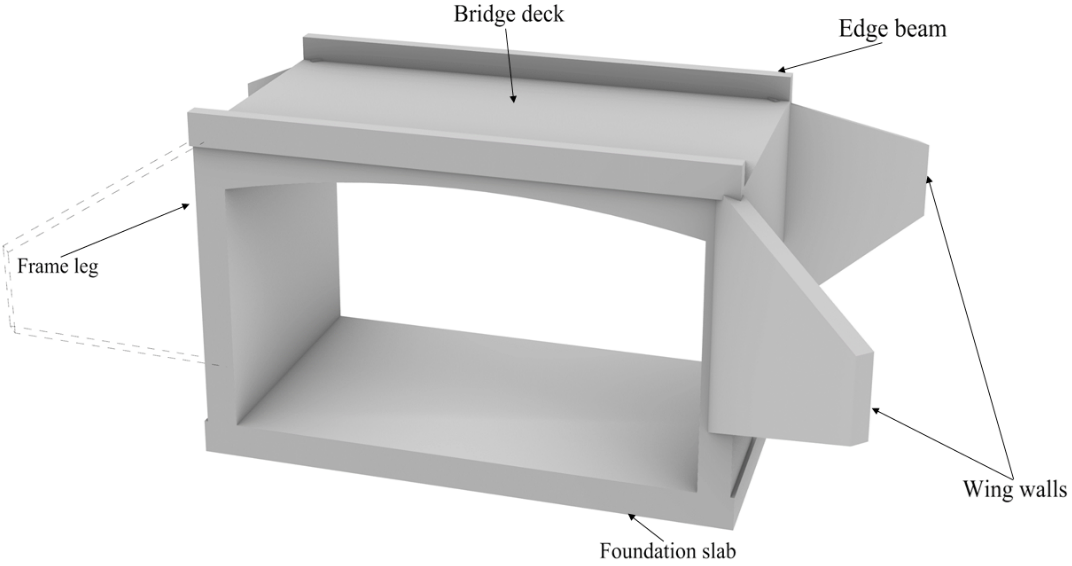


Figure 4.1: Conceptualization of the standardized closed frame bridge.

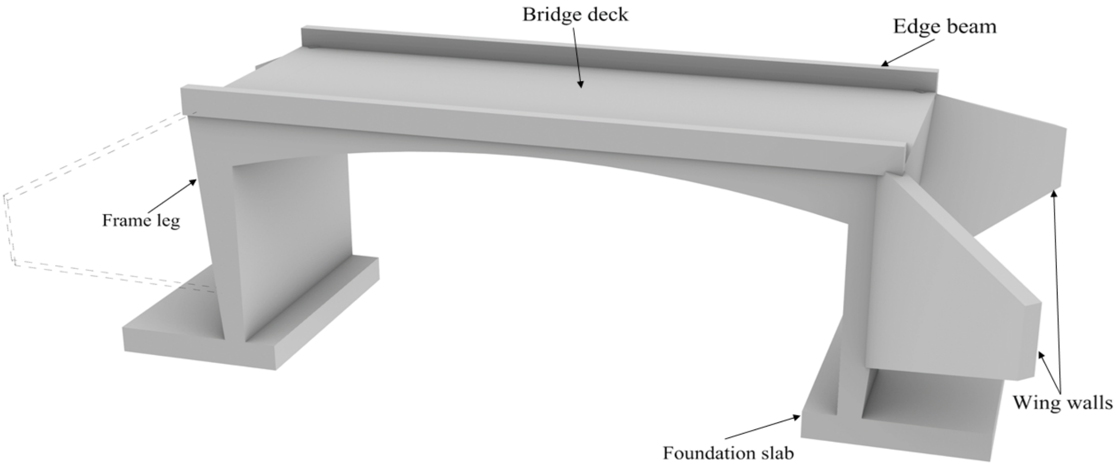


Figure 4.2: Conceptualization of the standardized open frame bridge.

The difference between the frame bridges makes them applicable in different settings. The closed foundation slab is advantageous in unfavourable ground conditions since the forces are spread over a larger area (Bruneby et al., 2023). However, more concrete is used in the foundation slab. Thus, it is usually used for smaller span widths, in this case, 12 meters. The open foundation slab uses less concrete than the closed frame slab as the total length of the foundation is shorter. The open frame is applicable in situations where a closed foundation slab is deemed unnecessary, redundant, or unsuitable (Trafikverket, 2008). Therefore, it is often built considering more favorable ground conditions or if the design conditions deem larger span widths, in this case, 16 meters. Also, the geometry of the frame legs differs; the closed frame bridge has straight legs, while the open frame bridge has a variable thickness. However, the superstructure (The bridge deck and edge beams) is designed similarly. The underside of the deck has a radius, yielding a thicker cross section towards the supports. The variable thickness contributes to a stiffness distribution, resulting in larger sectional forces towards the frame legs, which makes it possible to utilize a smaller cross-section in the span.

4.3 Finite element software BRIGADE/PLUS

BRIGADE/Plus is a structural analysis software using ABAQUS solver from SIMULIA (Technia, n.d.). The software is specialized for the modeling of civil structures and bridges. The software includes predefined live loads and load models from design codes, enabling an environment to easily assess the structural behavior of bridges. Furthermore, analyzes in BRIGADE can be parallelized. Meaning, several CPU:s can be used at once, enabling multiple tasks to run simultaneously.

In BRIGADE/PLUS the moments and shear forces for shell elements are denoted: SM1, SM2, SM3, SF4, and SF5 (SIMULIA, n.d.). The description of the denotations is presented in Table 4.5.

Table 4.5: Notation of sectional forces in BRIGADE/PLUS.

Denotation	**Description**
SM1	Bending moment force per unit width about local 2-axis.
SM2	Bending moment force per unit width about local 1-axis.
SM3	Twisting moment force per unit width in local 1–2 plane.
SF4	Transverse shear force per unit width in local 1-direction.
SF5	Transverse shear force per unit width in local 2-direction.

4.4 SBD in the preliminary design phase of bridges

This master thesis is a continuation of several other master theses (Fernández & Ramos, 2014; Löfgren, 2020; Johansson & Bohlin, 2021; Bergenram & Ulander, 2023) that have explored the potential of SBD in the preliminary design phase of bridge construction. In each thesis, an algorithm that implemented SBD was created to investigate if the design methodology could provide better design solutions for bridges than already built ones designed through PBD. Generally, the SBD algorithms have three main steps, which, in this report, are referred to as Generation, Verification, and Evaluation.

In the first step, "Generation," the initial design space is created by generating all possible bridge designs through modeling combinations of different parameter values. First, relevant parameters that constitute the bridge design of focus are introduced, along with allowable value ranges for the parameters (Fernández & Ramos, 2014; Löfgren, 2020; Johansson & Bohlin, 2021; Bergenram & Ulander, 2023). Following this, combinations — or designs — are created by combining the parameters. All possible designs for a certain type of bridge are therefore created by combining all allowable parameter value ranges. Each design is inherently unique due to a minimum of one parameter having to differ in value between each design. Lastly, the step is concluded by modeling each design's geometry. So, in this step, each possible bridge design — that is, a unique combination of parameter values — is generated, thus creating the initial design space for a certain type of bridge.

The second step, "Verification," entails narrowing down the design space by inducing hard constraints on the space, that is, conducting a structural analysis of each design to exclude unfeasible bridge designs. The design space created from the first step contains all types of designs, both feasible and unfeasible (Fernández & Ramos, 2014; Löfgren, 2020; Johansson & Bohlin, 2021; Bergenram & Ulander, 2023). In other words, designs that are and are not achievable according to current construction and design standards make up the design space, which means that the non-achievable (or unfeasible) designs need to be excluded. To narrow the design space and exclude unfeasible designs, hard constraints — structural design codes — are induced on the space, as per K. Parrish et al. (2007). This means that structural analysis, based on code requirements, is conducted on all the designs to verify that they fulfill current design standards (Fernández & Ramos, 2014; Löfgren, 2020; Johansson & Bohlin, 2021; Bergenram & Ulander, 2023). If not, they are excluded from the design space. In the previous theses, the structural analyzes comprised capacity and load response analyzes — SLS and ULS analyzes. Logically, the designs with higher loads than capacity were deemed unfeasible and excluded from the design space. Thus, in the "Verification" step, the design space is narrowed down by inducing hard constraints, leaving only feasible designs.

In the third and last step, "Evaluation," feasible designs are evaluated by some criteria to provide relevant information to relevant stakeholders. In the algorithms, evaluation criteria are introduced to analyze and inquire about relevant information about the design. In the theses, this step included criteria of economic Cost, CO_2-equivalent emissions, and buildability (Fernández & Ramos, 2014; Löfgren, 2020; Johansson & Bohlin, 2021; Bergenram & Ulander, 2023). This step also allows for narrowing down the design space based on stakeholder requirements and input. Based on stakeholders' requirements, "soft constraints", as per K. Parrish et al. (2007), can be introduced in the evaluation criteria. In doing so, designs that are not within the boundaries of a preferable design, according to stakeholders' requirements, can be excluded. To clarify, constraints can be set to the design space only to include designs with a maximum cost of x and/or CO_2 equivalents of y. This means that a final design space can be presented that only includes designs within certain boundaries of relevant criteria. In essence, designers can prove, with the help of SBD and in the preliminary design phase, that a certain amount of feasible designs within a specific set of criteria boundaries exists.

4.5 Evaluation Parameters for the Algorithm

The evaluation parameters for the SBD algorithm, namely financial costs, CO_2-eq emissions, and buildability, are all elusive. Thus, an exploration with the intent of defining them is apt. Since this work is a continuation of previous master theses, a similar approach to defining optimization criteria has been selected for the algorithm. This chapter will, therefore, present previous works' frameworks for calculating the optimization criteria used in the SBD algorithm, as well as updates and the equations of the criteria.

4.5.1 Production cost

In previous works (master theses), the cost aspect of the optimization has evolved from simply material costs to investment costs. In (Fernández & Ramos, 2014) the cost considered and implemented in the algorithm was solely the material cost. The total considered costs were then the sum of all material costs for each element in the design. Later, in (Löfgren, 2020), the cost was considered as a sub-category of a "sustainability" criterion, and similarly to (Fernández & Ramos, 2014), the material cost was only considered. The following thesis by Johansson and Bohlin (2021) used (Löfgren, 2020) as a reference, and the same consideration of cost was implemented, i.e., material cost.

Bergenram and Ulander (2023) developed the cost criterion to also include labor cost and defined it as investment cost. Inspired by Majid Solat Yavari, Costin Pacoste, and Raid Karoumi (2016), Bergenram and Ulander (2023) implemented the cost of related work to the different elements in the designs, such as formwork, concrete work, and reinforcement work, in the total cost. As will be presented more thoroughly in 4.5.2, the labor costs were increased by a factor dependent on the buildability of the design. Simply, the labor cost increased if the design was considered harder to build. Based on the previous theses, the investment cost criteria include total material costs and labor costs.

The algorithm's cost criteria used in previous theses are sufficient, but (Mathern et al., 2021) presents it more in detail. In their study, Mathern et al. (2021) created an evolutionary algorithm (not an SBD algorithm) for optimizing structural designs based on different objective functions. These functions act as the basis for evaluating design choices, similar to the evaluation criteria used in SBD. One of the objective functions (see Equation 4.9) focuses on production costs, which include, similarly to Bergenram and Ulander (2023) & Majid Solat Yavari et al. (2016), material cost and cost of construction works (i.e. total labor costs). However, conversely to Bergenram and Ulander (2023) & Majid Solat Yavari et al. (2016), Mathern et al. (2021) presents labor costs, and thus buildability, as a function of time multiplied by unit labor cost. Moreover, the sum of these costs was deemed as the total production cost instead of the investment cost. Although not deriving from an SBD paper, the objective function of production cost is deemed fitting, relevant, and sufficient. The equation for the production cost is presented in Equation 4.9, 4.10, and 4.11.

$$C(x) = C_m(x) + C_W(x) \tag{4.9}$$

$$C_m(x) = \sum_i \rho_{m,i} \cdot Q_{m,i}(x) \tag{4.10}$$

$$C_W(x) = \rho_W \cdot T_W(x) \tag{4.11}$$

Where $C(x)$ = Production cost, for bridge design x
$C_m(x)$ = Cost of Material, for bridge design x
$C_W(x)$ = Cost of Construction Works, for bridge design x
$\rho_{m,i}$ = Unit price for each material i
$Q_{m,i}(x)$ = Quantity of each material i, for bridge design x
ρ_W = Unit labor cost
$T_W(x)$ = Time of Construction Works, for bridge design x

4.5.2 Buildability

Bergenram and Ulander (2023) was the first and only master thesis thus far to successfully include buildability as an evaluation criterion in their algorithm. As briefly mentioned, buildability was considered as a function of labor costs dependent on the designs' degree of difficulty to build. By using buildability numbers from Majid Solat Yavari et al. (2016) and Khouri Chalouhi (2019), Bergenram and Ulander (2023) was able to include the buildability as a criterion adjacent to the cost criterion. Moreover, Bergenram and Ulander added further buildability numbers gathered by interviews with engineers at Skanska. The buildability was then evaluated and incorporated as an incurred cost on designs by using labor cost as a multiplicative and constant cost for formwork.

The work of Mathern et al. (2021) focused specifically on time and considered buildability as a function of 2 things; time of construction works (eq. 4.12) and the design parameter height of beam. However, the design parameter had a relatively small impact on the result of the algorithm in their study. Thus, a sole focus on the construction time is apt when considering buildability. So, buildability is regarded as the time of construction work for the designs.

$$T_W(x) = \sum_1 t_{m,i} \cdot Q_{m,i}(x) \tag{4.12}$$

Where $T_W(x)$ = Time of Construction works, for bridge design x
$t_{m,i}$ = unit construction time for the activites related for each material
$Q_{m,i}(x)$ = Quantity of each material i, for bridge design x

4.5.3 Environmental impact

Throughout the previous master theses, excluding Bergenram and Ulander (2023), the environmental impact has been considered as CO_2-eq emissions and included in the optimization criteria. Fernández and Ramos (2014) included the CO_2-eq emissions estimations of the material amounts as an evaluation criterion of the models generated. These estimations included extraction, production, and manufacturing of the materials. In the following master thesis, Löfgren (2020) included more general sustainability criteria, in which an environmental sub-criteria was included. In this sub-criteria, Löfgren used material CO_2-eq emissions of the material used in the models, similar to Fernández and Ramos (2014). Johansson and Bohlin (2021) followed Löfgren's (2020) research, and used the same evaluation criteria for environmental impact, that is, CO_2-eq emissions. However, Bergenram and Ulander (2023) introduced a more inclusive criterion than the previous theses, which considers more environmental impact factors other than CO_2-eq emissions.

In their thesis, Bergenram and Ulander (2023) used the work of Majid Solat Yavari, Guangli Du, Costin Pacoste, and Raid Karoumi (2017) to create their objective function for environmental impact. Majid Solat Yavari et al. used the *ReCiPe Method* (Which is considered one of the most comprehensive LCIA methodologies and analyzes more than 1000 substances (Du, Safi, Pettersson, & Karoumi, 2014)) to create an objective function for environmental impact for optimizing structural designs. However, in public road and railway projects, as presented in Section 3.2, CO_2-eq emissions are used when calculating the environmental impact (Miliutenko, 2022). Thus, only the evaluation procedure correlating to CO_2-eq emissions presented by Majid Solat Yavari et al. (2017) is used in this thesis. The functions, formulated by Majid Solat Yavari et al., to calculate the total CO_2-eq emissions for a bridge design, are presented in Equation 4.13 and is simply the sum of CO_2-eq emissions for concrete and reinforcement. The functions for CO_2-eq emissions regarding concrete and reinforcement are presented in Equation 4.14 and Equation 4.15 respectively.

$$E(x) = E_r(x) + E_c(x) \tag{4.13}$$

$$E_c(x) = \sum eq_{\mathrm{c}} \cdot Q_c(x) \tag{4.14}$$

$$E_r(x) = anchoragefactor \cdot \sum eq_{\mathrm{r}} \cdot Q_r(x) \tag{4.15}$$

$$\begin{aligned}
\text{Where} \qquad E &= \text{Total CO}_2\text{-eq emissions for bridge design x} \\
E_c(x) &= \text{Total CO}_2\text{-eq emissions of concrete for bridge design x} \\
E_r(x) &= \text{Total CO}_2\text{-eq emissions of reinforcement for bridge design x} \\
eq &= \text{kg CO2e/kg} \\
Q_{m,i}(x) &= \text{Quantity of material for bridge design x} \\
c &= \text{Concrete} \\
r &= \text{Reinforcement} \\
anchoragefactor &= 1.4
\end{aligned}$$

4.6 Method for creating the SBD algorithm

The SBD script followed the same structure as in previous papers presented in Section 4.4. The script was divided into three parts; generation, verification and evaluation. The script was created in accordance with the legally binding documents listed in Table 4.6.

Table 4.6: Binding documents on which the SBD-algorithm is based.

Binding documents	*Document title*
TSFS 2018:57	The Swedish Transport Agency's regulations and general advice on the application of Eurocodes.
TRVINFRA-00227	Bridge and bridge-like structures, Constructing.
TDOK 2013:0667	The Swedish Transport Administration's technical requirements for geoconstructions, TK Geo 13.
SS-EN 1990:2023	Basis of structural and geotechnical design.
SS-EN 1991-1-5	Actions on structures - Part 1-5: General actions - Thermal actions.
SS-EN 1991-2	Actions on structures – Part 2: Traffic loads on bridges.
SS-EN 1992-1-1:2023	Design of concrete structures – Part 1-1: General rules and rules for buildings, bridges and civil engineering structures.

4.6.1 Generation

Firstly, the initial design space was defined by parametrizing certain geometry parameters of the conceptualization of the standardized frame brides in Figure 4.1 and Figure 4.2. However, the wing walls and edge beams were disregarded from the parametrization since they do not contribute to the structural capacity but rather act as dead weights on the structure. The used parameter ranges and additional model inputs are presented in Table 4.7 and refer to the parameters illustrated in Figure 4.3. The span lengths were dictating if the bridge was modeled as a closed or open frame. The 12-meter span implied a closed frame, while the 16-meter span implied an open frame. Combining the input parameters resulted in an initial set of 7,020 bridge designs with unique geometries.

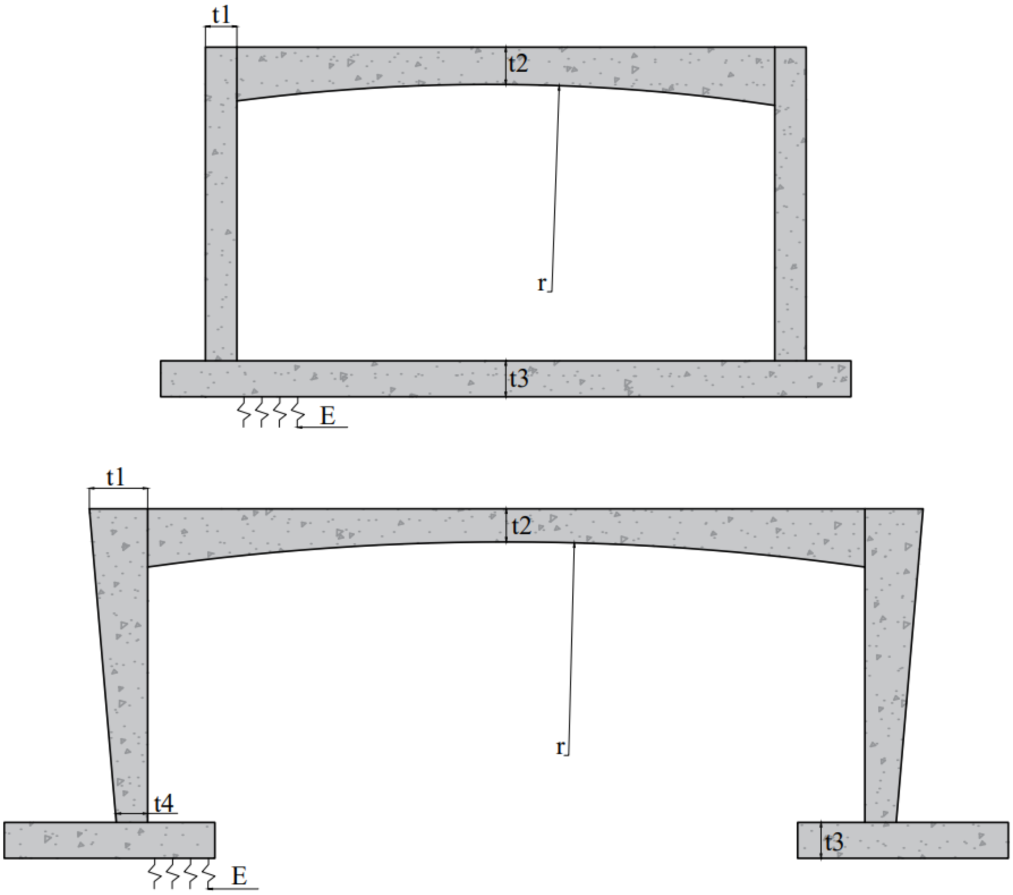


Figure 4.3: Geometrical inputs of closed and open frame bridges.

Table 4.7: Parameter ranges and model inputs in the SBD-algorithm

Geometric bridge inputs	*Value*
Span length	12,16 meters
Width	7.2 meters
Leg Height	7.2 meters
Variable geometric inputs	*Range*
[t1] Leg thickness at top	[0.5,1.4] in steps of 0.1 meters
[t2] Deck thickness in the center	[0.6,1.4] in steps of 0.1 meters
[t3] Thickness of foundation	[0.6,1.2] in steps of 0.1 meters
[t4] Leg thickness at bottom	[0.5,1.4] in steps of 0.1 meters but ≤ t1
[r] Radius of underside bridge deck	[3,6,16] times the span length
Other model inputs	
[E] Elastic stiffness of the foundation	50 MPa (Elastic modulus of coarsely crushed stone)
Concrete class	C35/45

Secondly, a Python script was created to model the bridges parametrically. The models consisted of shell elements with thicknesses that complied with input geometries. The finite element models for the closed and open frame bridge are depicted in Figure 4.4 The interaction of the foundation to the soil was modeled as springs in accordance to (Bergdahl, Ottosson, & Stigson Malmborg, 1993), A verification analysis of each bridge type with arbitrary geometry inputs was conducted to ensure the adequacy of modeling. The verification details can be found in Appendix D.

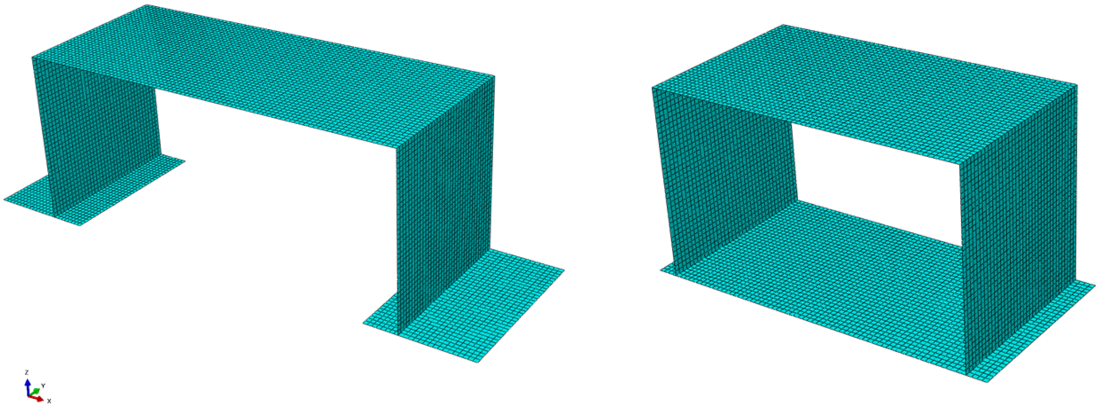


Figure 4.4: Finite element models of the open and closed frame bridge.

Thirdly, the loads, load models, and load combinations acting on the bridge were added to the Python script. The variable loads were limited to mainly include the vertical loads, excluding wind and centrifugal forces from Table 4.2. Load model

71 was used to determine the vertical load effect from train loads, while LM1 and LM2 were applied on the closed foundation slab. Additionally, the permanent loads in Table 4.1 were incorporated into the Python script. The edge beams, assumed to have a cross-section of 300x800 mm, were included in the self-weight category. The ballast on the bridge deck was modeled with greater thickness beneath the train track. The load inputs for the variable and permanent loads are detailed in Table 4.8.

Table 4.8: Additional load inputs for geotechnical, material, temperature, and train loads.

Geotechnical inputs	*Value*	*Reference*
[γ_{gs}] Coarsely crushed stone	20 kN/m^3	TK Geo 13, table 5.2-1
[ϕ] Friction angle coarsely crushed stone	45°	TK Geo 13, table 5.2-1
[γ_M] ULS partial factor	1.3	TK Geo 13, chap 2.3.1
Material inputs	*Value*	*Reference*
[γ_c] Concrete weight	25 kN/m^3	SS.EN 1991-1-1 table A.1
[γ_b] Weight of ballast	20 kN/m^3	SS-EN 1991-1-1 table A.6
[t_{b1}] Ballast thickness underneath track	850 mm	
[t_{b2}] Ballast thickness rest of bridge deck	470 mm	
[t_f] Fill thickness underneath foundation	500 mm	
[t_{bf}] Ballast thickness on foundation slab	500 mm	
[α_c] Expansion coefficient concrete	$10 \cdot 10^{-6}$ $1/°C$	
Temperature inputs	*Value*	*Reference*
[$T_{e,min}$] Minimum temperature in Umeå, Sweden	-35 °C	TSFS2018:57 fig 8.1
[$T_{e,max}$] Maximum temperature in Umeå, Sweden	28 °C	TSFS2018:57 fig 8.2
[T_0] Casting temperature	10 °C	
Train load inputs	*Value*	*Reference*
[α] Adaptation factor	1.33	SS-EN 1991-2 chap 6.3.2
[ϕ_2] Dynamic factor	Calculated in the script	SS-EN 1991-2 chap 6.4.5.2

To reduce computational time, each load and load model were modeled as static loads. A pre-parametric study with load model 71 was performed on a smaller set of bridges to map its most unfavorable positions regarding bending moment and shear force. Three positions of load model 71 were used to approximate the maximum and minimum sectional forces in the bridge deck. The first position correlated to the maximum moment in the span, the second to the maximum moment in the support, and the third correlated to the maximum shear force close to the frame legs. Additionally, the traction load was modelled to act in either direction of the track and the nosing force was addressed in two positions, one in the center and one close to the frame legs.

After the loads were modeled, specific loads were unified to create certain load groups. Load model 71, traction, and the nosing force were grouped into load groups lgr11, and lgr12 in accordance with SS-EN 1990. Furthermore, the loads were combined in the load combination module in BRIGADE/PLUS with the corresponding partial factors for ULS and SLS presented in Appendix A. Moreover, a convergence study of the mesh size was performed with the ULS load combination expressed in Equation 4.1, From the convergence study, a mesh size of 200 millimeters was chosen to be adequate. The convergence study is presented in Appendix B.

4.6.2 Verification

The script was designed to perform finite element analyzes of the load combinations, on one bridge geometry at a time. Following the analyzes, the verification was divided into two major steps, deflection check in SLS and ultimate capacity check in ULS.

The deflection check was performed by assessing the maximum deformation from paths on the bridge deck and frame legs. Paths were positioned in the center and 500 millimeters from the edge, as can be observed in Figure 4.5. The maximum vertical deformation was evaluated from the paths on the bridge deck, while the maximum horizontal displacement was evaluated from the paths on the frame legs. If the deformation exceeded the requirements listed in Table 4.4, the script was designed to start over with the next bridge combination. Otherwise, the script proceeded with the checks in ULS.

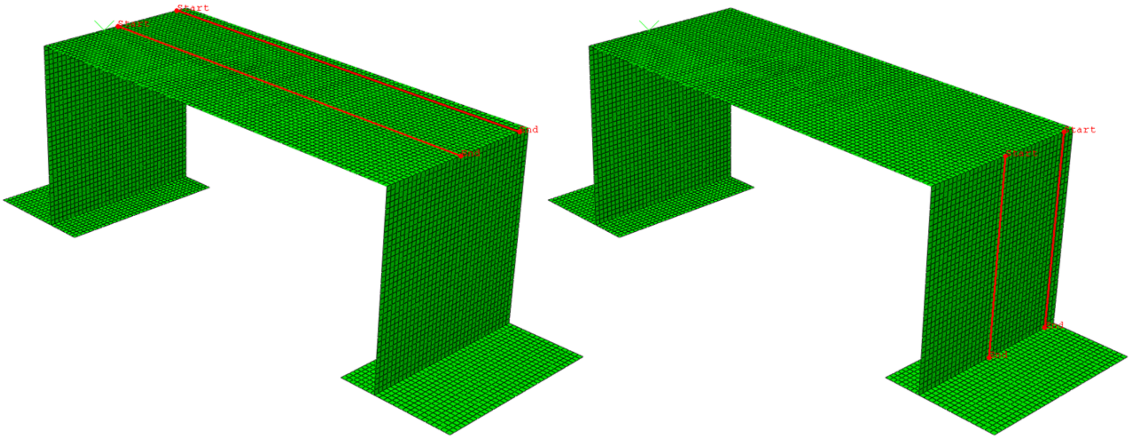


Figure 4.5: Vertical and longitudinal paths on the FE-models where the vertical and horizontal deformations were assessed in SLS. The figure represents the 16-meter-long bridge.

In the ULS analysis, the bridges were partitioned into segments, as can be observed in Figure 4.6, based on the magnitude of the sectional forces. In each segment, the maximum and minimum sectional forces were used to verify the adequacy of the cross-sectional capacities.

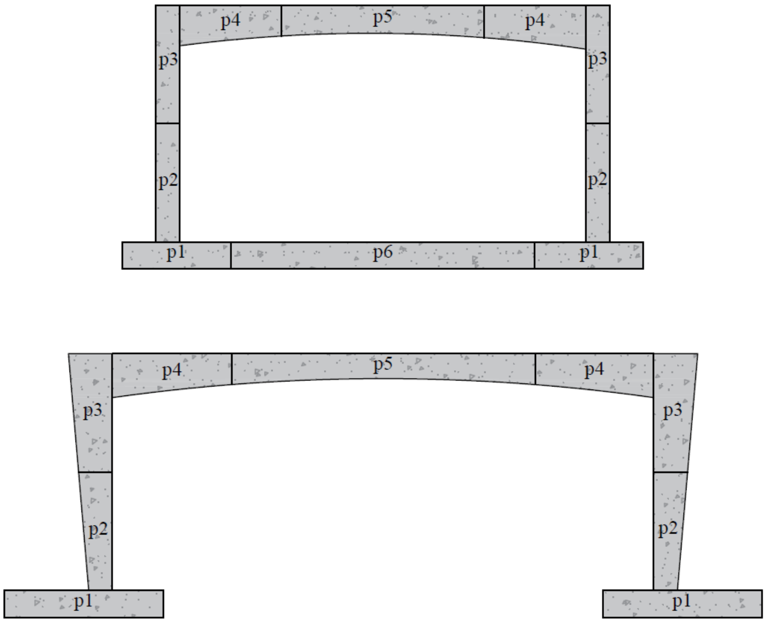


Figure 4.6: Partitions of the bridge variants where the structural analyzes in ULS were performed.

The maximum and minimum sectional forces were obtained from longitudinal and transversal paths on each part. Longitudinal paths, one in the center and one 1,000 mm from one edge were defined to extract the sectional forces SM1, SM3, SF4, and SF5 from each part. Transversal paths, one close to either edge and one in the center were defined to extract SM2 in each part. The longitudinal and transversal paths on part p4 are illustrated in Figure 4.7. Furthermore, the maximum and minimum sectional forces were then applied in the equations in Section 4.1.3 to obtain the design moments and shear forces in each partition.

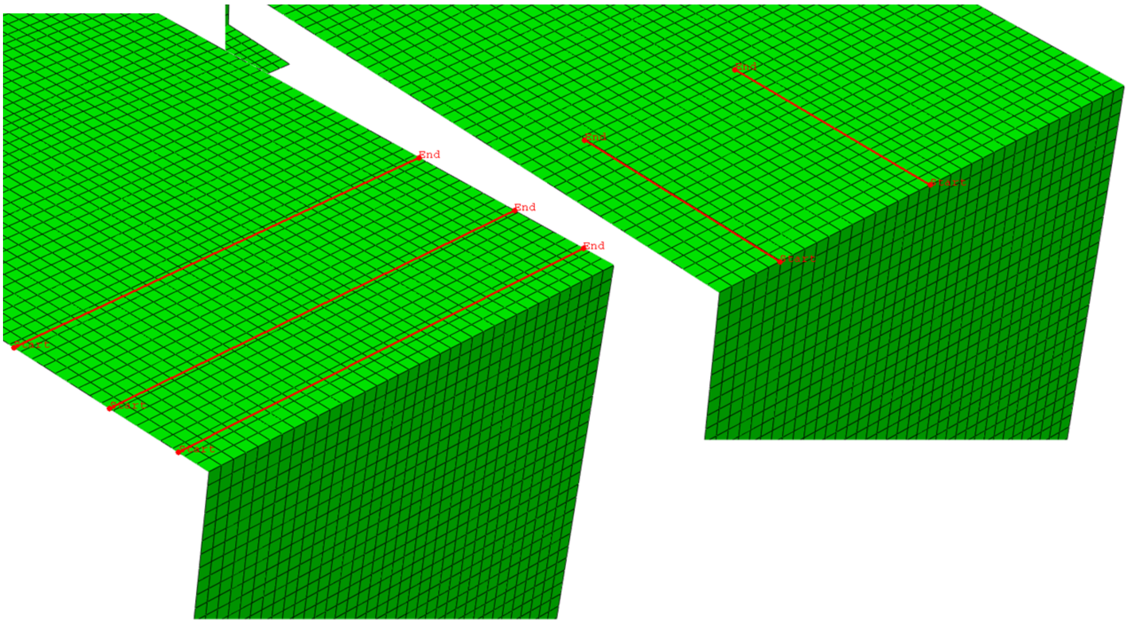


Figure 4.7: Transversal and vertical paths on the FE-models where the maximum and minimum moments and shear forces were obtained from part p4 in Figure 4.6.

In each partition, the longitudinal reinforcement configuration was parametrized. In the parametrization, the tension reinforcement was designed with two layers, with the reinforcement bars in the second layer being positioned above the bars in the first layer. The tension side of the cross-section was determined by the largest magnitude of the positive and negative bending moment. If the magnitude of the positive moment was larger than the negative moment, the tension reinforcement was placed at the top of the cross-section, and vice versa. The reinforcement size could be either 16, 20, or 25 mm, and was consistent throughout the cross-section. The spacing of the compressive reinforcement was not part of the parameterization, it was determined by the design moment as a factor of the spacing of the tension reinforcement. Moreover, the amount of transversal reinforcement in each part was determined from the transversal design moment. The shear reinforcement was added in those parts with inadequate shear capacity. The parameter ranges are detailed in Table 4.9 and correspond to the variables in Figure 4.8. As a result of the parameterization, the moment capacity of 32 different configurations was evaluated to suffice the design moment in each part of the bridge.

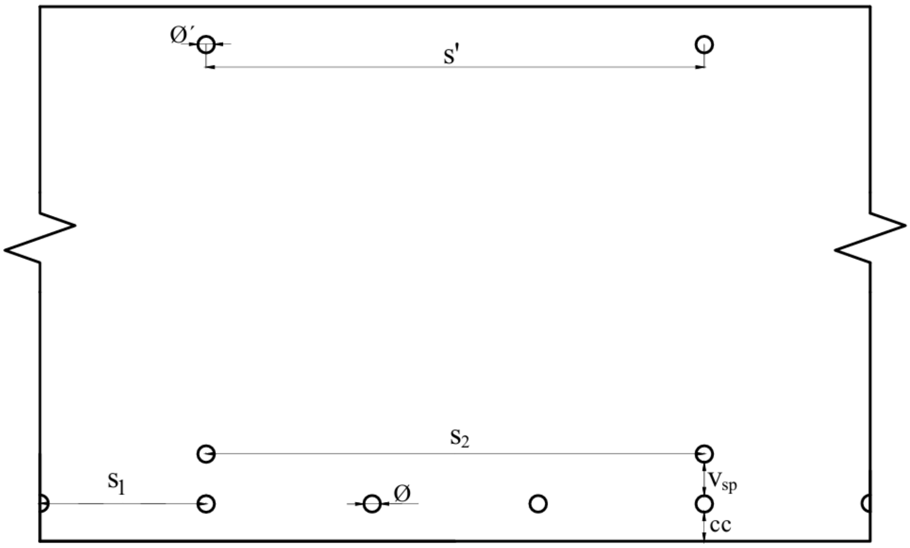


Figure 4.8: Parametrization of longitudinal reinforcement.

Table 4.9: Parametrization ranges of the longitudinal reinforcement configuration and inputs regarding the transversal reinforcement and shear reinforcement.

Longitudinal reinforcement inputs	*Value*
[s_1] Spacing tension layer 1	[100,300] mm with steps of 50 mm
[s_2] Spacing tension layer 2	[1,2,3] times s_1
[s'] Spacing compressive layer	sp1 times a factor
[Ø] Size tension layers	[16,20,25] mm
[Ø'] Size compression layer	same as [Ø]
[cc] concrete cover	35 mm
[v_{sp}] vertical spacing	40 mm
Other reinforcement inputs	*Value*
[$Ø_{trans}$] Size transversal reinforcement	same as [Ø]
[$Ø_{shear}$] Size of shear reinforcement	12 mm

The reinforcement configurations fulfilling the structural checks in ULS were stored in a dictionary to be further processed in the evaluation stage.

4.6.3 Evaluation

The reinforcement configurations proceeding from the verification stage were further processed by calculating the key variables: material cost, build cost, and CO_2-eq emissions. The key variables were calculated according to Section 4.5 with the coefficients presented in Appendix C. In the evaluation of material costs, the cost of concrete, reinforcement, and formwork were calculated. In the evaluation of build costs, the labor costs of reinforcement works, concrete works, and formwork works were calculated. The CO_2-eq emission involved the emissions from concrete and reinforcements. In the script, all parts and their reinforcement configurations were assessed and the data were written into CSV files. When the files had been written, the script continued with the next bridge geometry. The script ran on a virtual machine with 4 CPUs, which enabled parallelization of tasks in BRIGADE.

The data from the CSV files were post-processed, combining the data from the parts in Figure 4.6. The assembling of bridge parts was performed with the following constraints on the reinforcement configurations:

1 - All parts should have the same reinforcement size.
2 - The spacing between the reinforcement should be divisible with the reinforcement spacing in adjacent parts.

All combinations of parts that fulfilled the aforementioned constraints were stored in a new CSV file. The process of combining the parts was scripted in Python utilizing the parallelization possibilities of the virtual machine. The material cost, production cost, and CO_2-eq emissions were then illustrated in plots.

5 Mapping and Exploration of Design Space

In this chapter, the feasible design spaces of the 12-meter and 16-meter bridge designs are presented regarding the key variables: material costs, build costs, and CO_2-eq emissions.

5.1 The feasible design spaces

With the setup of geometries presented in Section 4.6, the generation of the feasible design space took approximately seven days. Six of those days were dedicated to performing automated structural analyzes in Brigade. The last day of the runtime included post-processing the data, which involved combining the reinforcement configurations among the segments illustrated in Figure 4.6 for each bridge geometry.

The initial set of bridge combinations, variances in geometry, and reinforcement positions resulted in more than 100,000,000 combinations. Among these, over 48,000,000 belonged to the 12-meter variant, and over 52,000,000 belonged to the 16-meter variant. The feasible design spaces, those fulfilling the requirements in SLS and ULS, contained approximately 8,000,000 bridge designs for the 12-meter variant and 2,300,000 bridge designs for the 16-meter variant.

5.2 Material cost

The evaluation of the material cost included the material cost of concrete, reinforcement, and formwork. In Figure 5.1 the mapping of the feasible design spaces within the initial design spaces is presented. The x-axis represents the normalized material cost and is normalized from the minimum material cost in the initial set, hence the x-axis starts from 1.

The normalized distribution in Figure 5.1 is a way to scrutinize the adequacy of the initial design space and check that the results from the SBD lie within the predefined bounds of the parameterization. Firstly, it can be established that the feasible design spaces lie within the initial sets. This indicates the algorithm has run as intended. Secondly, the initial design spaces have wider ranges compared to the feasible design spaces. The initial design spaces stretch from 1 to approximately 2.6 whilst the feasible design spaces are located in the upper bounds of the initial sets. Hence it can be concluded, that the initial conditions are adequate as they cover bridge designs that have much lower material costs compared to the feasible designs.

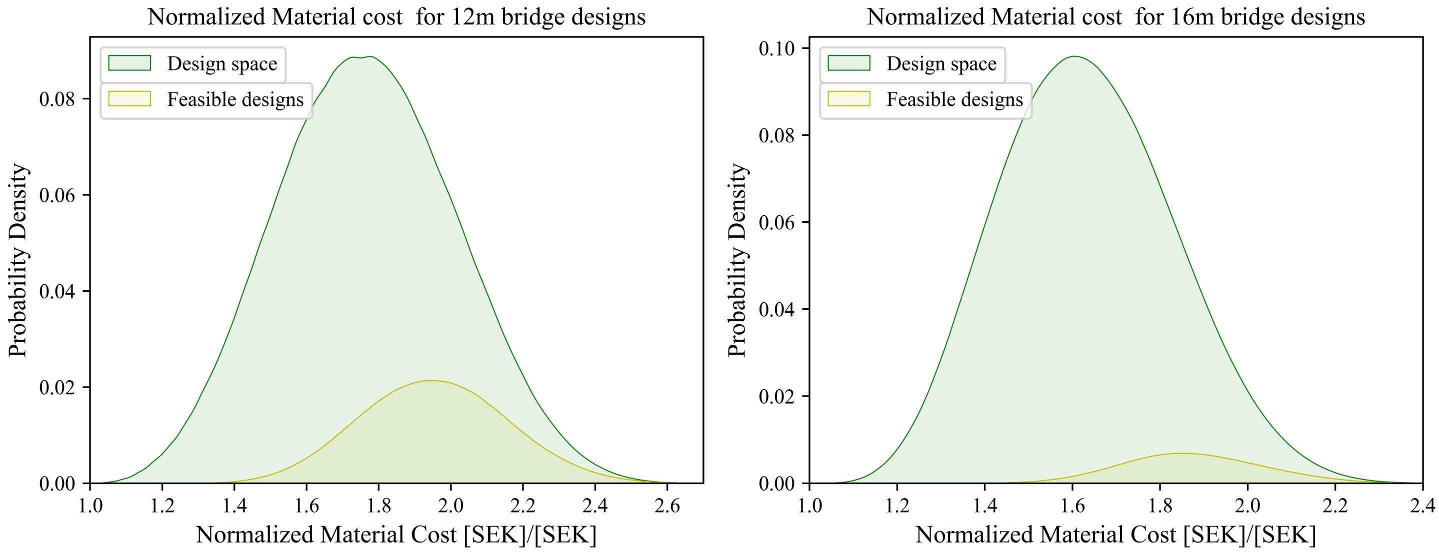


Figure 5.1: Normalized material costs of the initial design space and feasible designs for the 12-meter and 16-meter bridge designs.

The feasible design spaces are presented as the cumulative probability in Figure 5.2 and as the normal distribution in Figure 5.3. Both alternatives illustrate the feasible design spaces but each highlights different aspects of the distribution of designs.

The cumulative probabilities in Figure 5.2 illustrate how likely bridge designs within the feasible design spaces are to cost less than a certain amount. More concretely, the curves represent how the percentiles of bridge designs within the feasible design spaces, on the y-axis, correspond to material costs, on the x-axis. Furthermore, the material costs are roughly 160,000 SEK more for at the 50th percentile for the 16-meter bridge compared to the 12-meter. This means the 16-meter version uses more material, although the 12-meter variant has a closed foundation slab.

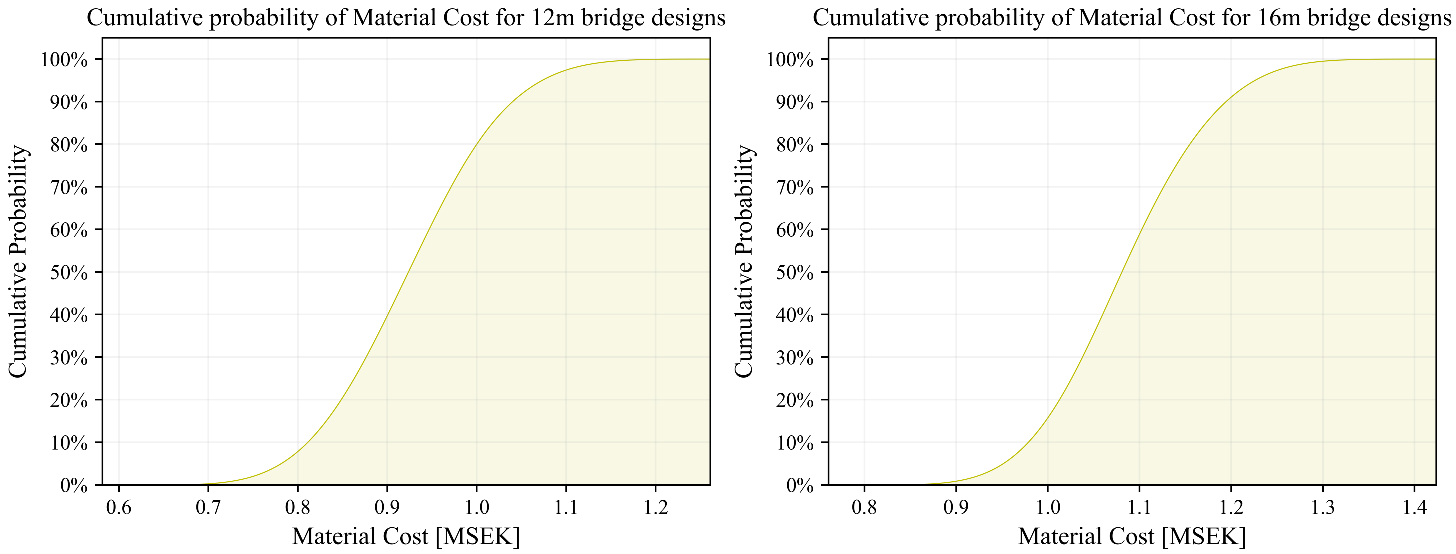


Figure 5.2: Cumulative probability of the feasible design spaces regarding material costs for the 12-meter and 16-meter bridge designs.

The normal distribution curves of the feasible design spaces are presented in Figure 5.3. These graphs give an illustrative understanding of the density distribution of feasible designs within the set. The larger the density, the more designs are located around that specific material cost. Moreover, the 5th, 25th, and 50th percentiles are drawn in the graphs and correlate to the percentiles in Figure 5.2. Thus, Figure 5.3 can be used to understand the distribution of the feasible design space as well as pinpointing specific material costs within the 5th, 25th, and 50th percentiles. If other percentiles are of interest, Figure 5.2 can be utilized as supportive information.

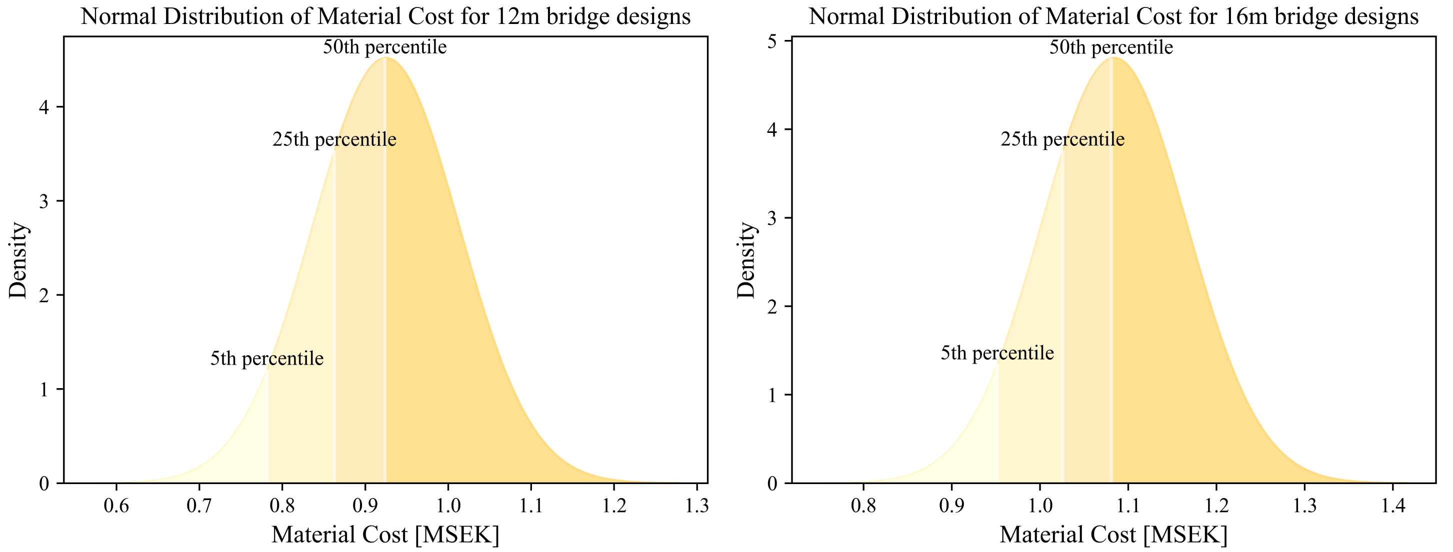


Figure 5.3: Normal distributions of material costs in the feasible design space for the 12-meter and 16-meter bridge designs.

5.3 Build cost

The control of the adequacy of the initial design spaces follows the same argumentation as in Section 5.2. The feasible design spaces lie within the upper bounds of the initial design space in Figure 5.4. Thus, the initial design spaces regarding build costs are adequate since they cover bridge designs with less build costs than in the feasible design spaces.

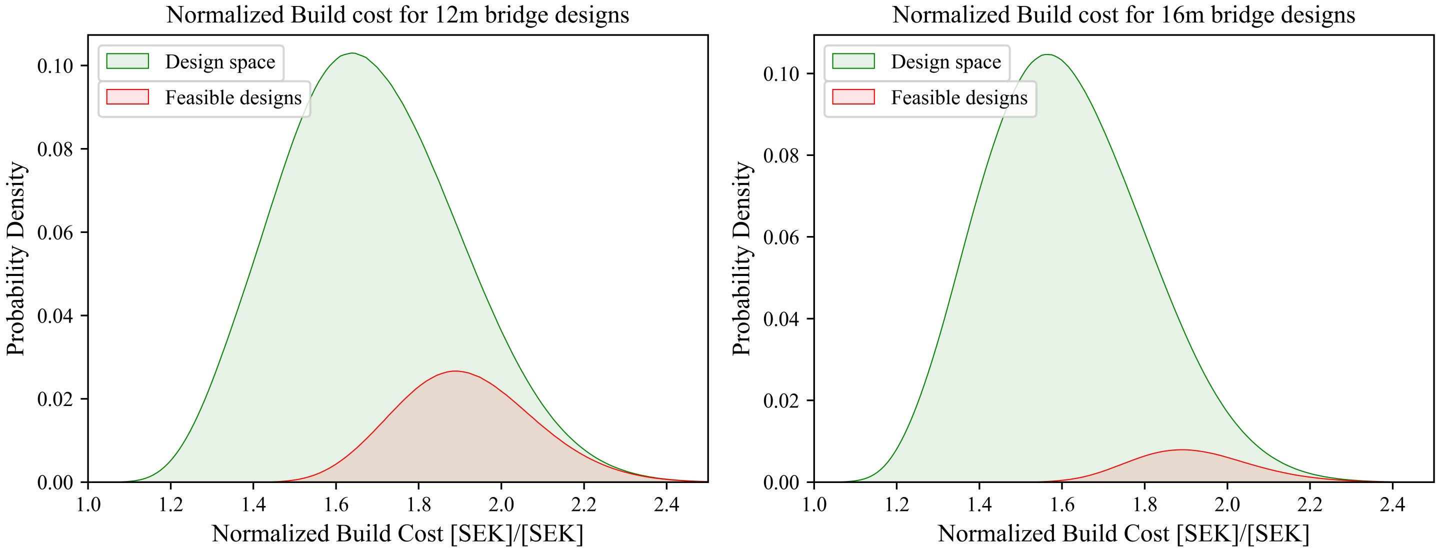


Figure 5.4: Normalized build costs of the initial design space and feasible designs for the 12-meter and 16-meter bridge designs.

The cumulative probabilities of the build costs are presented in Figure 5.5. From the graphs, it can be concluded that the build costs are approximately 230,000 SEK more for the 16-meter variant compared to the 12-meter designs at the 50th percentile mark of the feasible design spaces. The difference in build costs is greater between the two bridge variants compared to the material costs presented in Section 5.2. The greater difference in build costs can be explained by assessing the procedures for obtaining the data. The material costs, as presented in Section 4.5.1, are determined by three parameters, the amount of reinforcement, formwork, and concrete. The build costs, on the other hand, are dependent on the unit construction time for the activities related to each material and the quantity of each material, as presented in Section 4.5.2. This means more factors play a role in determining the build costs, thus larger differences between the 12-meter and 16-meter variants can occur. Furthermore, the material cost of reinforcement, formwork, and concrete compared to the labor cost per hour are factors affecting the difference in terms of SEK. But with the cost-related inputs presented in Appendix Appendix C, these are the resulting design spaces.

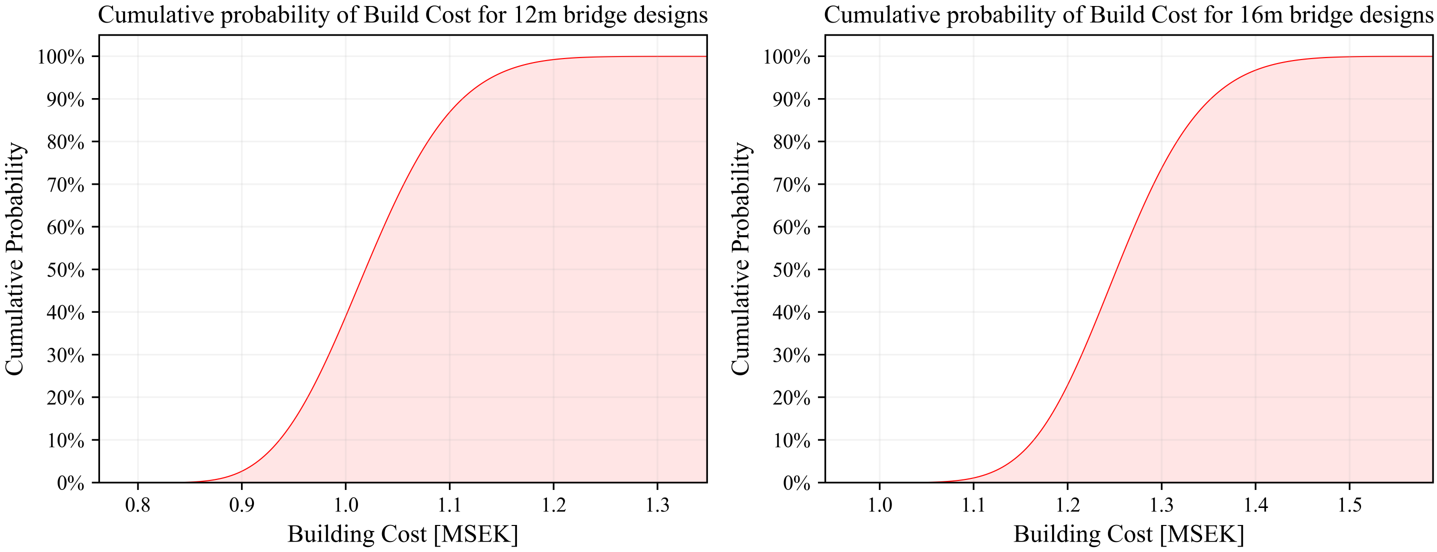


Figure 5.5: Cumulative probability of the feasible design spaces regarding build costs for the 12-meter and 16-meter bridge designs.

The normal distributions of the build costs in Figure 5.6 are presented similarly to the material costs in Figure 5.3. Notably, just comparing normal distributions of build costs and material costs of the feasible design spaces the build costs are larger than the material costs. The reason for this follows the same discussion as in the previous paragraph. The build costs are determined with more parameters and the unit cost per material in comparison to the hourly cost of labor dictates the differences between the build cost and material cost.

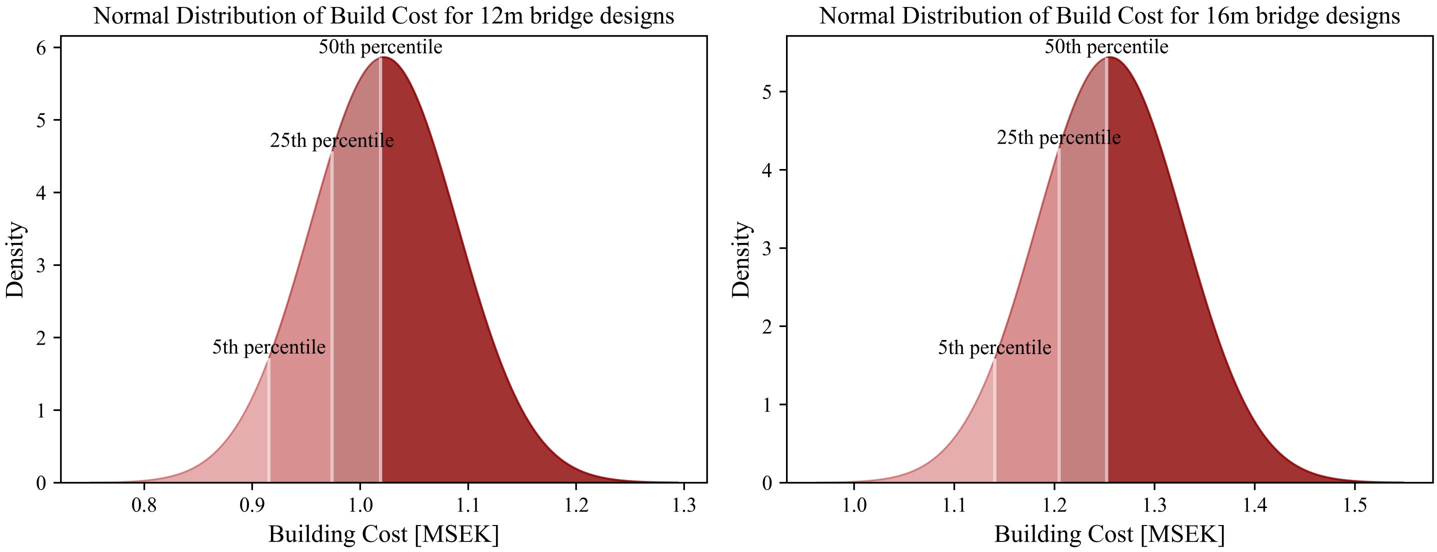


Figure 5.6: Normal distribution of build costs in the feasible design space for 12-meter and 16-meter bridge designs.

5.4 Production Cost

The production costs are simply the combined costs of materials and labor presented in Section 5.2 and Section 5.3. The cumulative probability of the production costs can be observed in Figure 5.7. The difference in total costs between the 12-meter and 16-meter variants is approximately 370,000 SEK at the 50th percentile in Figure 5.7. However, by summing these differences for material costs and build costs, independent of which costs belong to which bridge design, the difference becomes approximately 390,000 SEK at the 50th percentile. This indicates there may be a linear correlation between the material costs and build costs. This will be discussed further in Section 5.6.

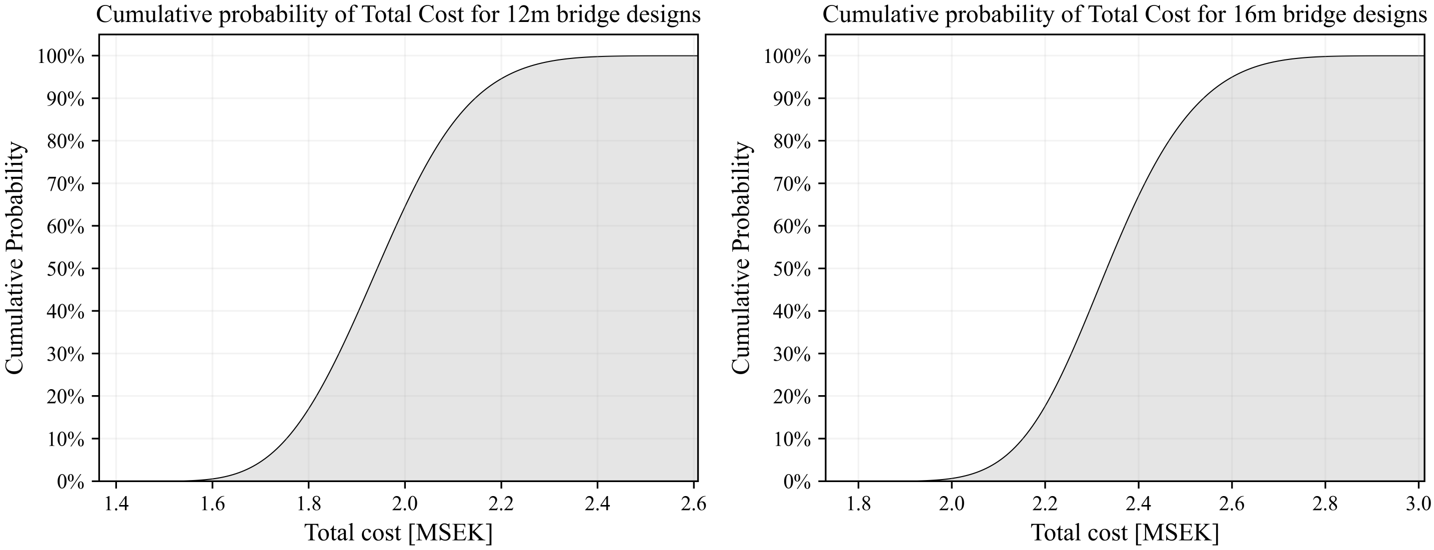


Figure 5.7: Cumulative probability of the feasible design spaces regarding production costs for the 12-meter and 16-meter bridge designs.

The normal distributions of the production costs in the feasible design spaces are presented in Figure 5.8. The normal distributions are presented similarly to the Figure 5.3 and Figure 5.6.

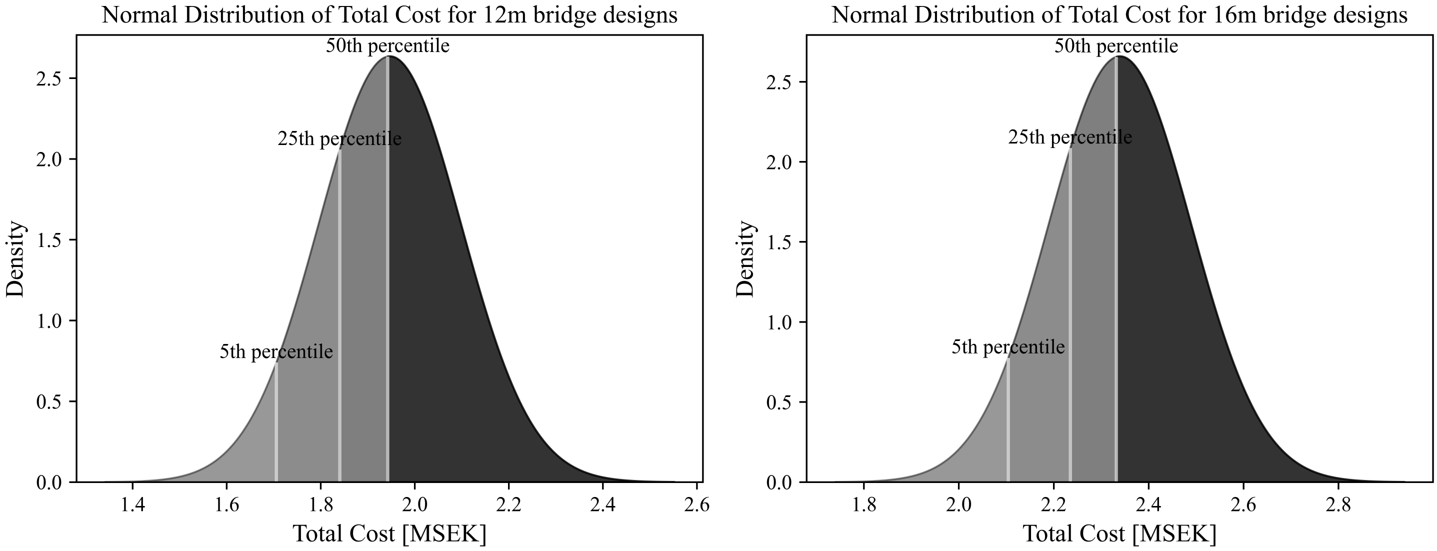


Figure 5.8: Normal distribution of production cost in the feasible design spaces for the 12-meter and 16-meter bridge designs.

5.5 CO_2-eq Emissions

The initial and feasible design spaces regarding CO_2-eq are presented in Figure 5.9. The feasible design spaces lie within the design space. The feasible design spaces are located toward the upper bounds of the initial design space. Hence, the initial design spaces are adequate since they cover bridge designs that have less CO_2-eq emissions compared to the feasible design spaces.

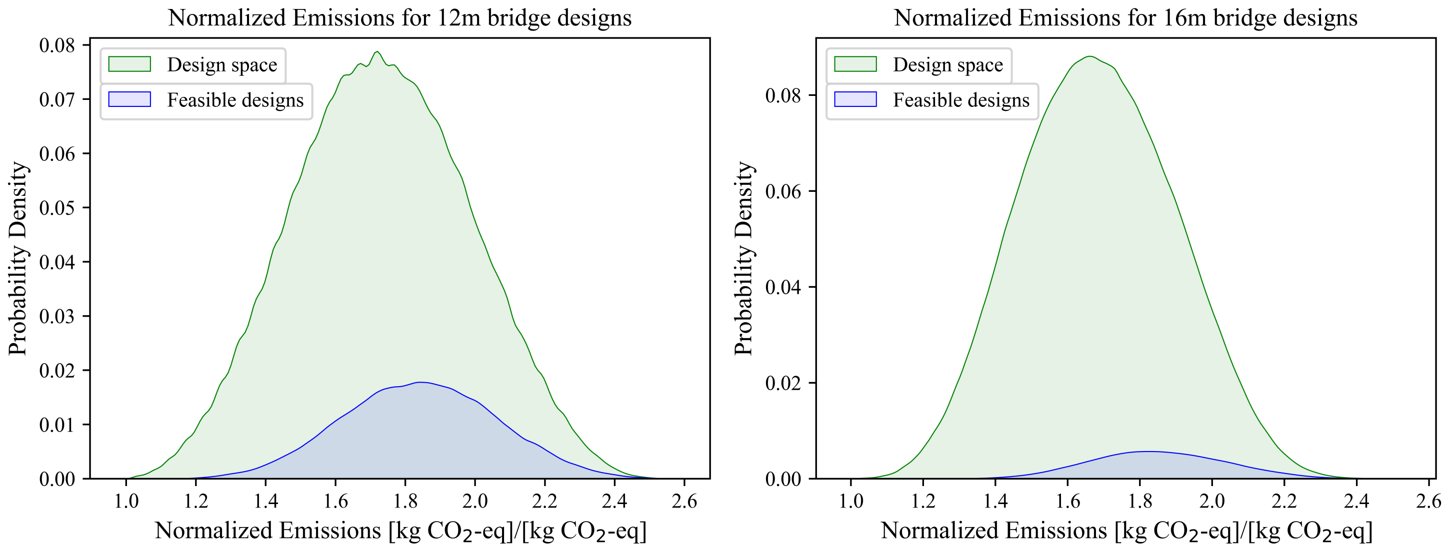


Figure 5.9: Normalized CO_2-eq emissions of the initial design space and feasible designs for the 12-meter and 16-meter bridge designs.

The cumulative probabilities of the CO_2-eq emissions in the feasible design spaces are presented in Figure 5.10. The CO_2-eq emissions differ by approximately 15,000 kg CO_2-eq between the 12-meter and 16-meter variants at the 50th percentile.

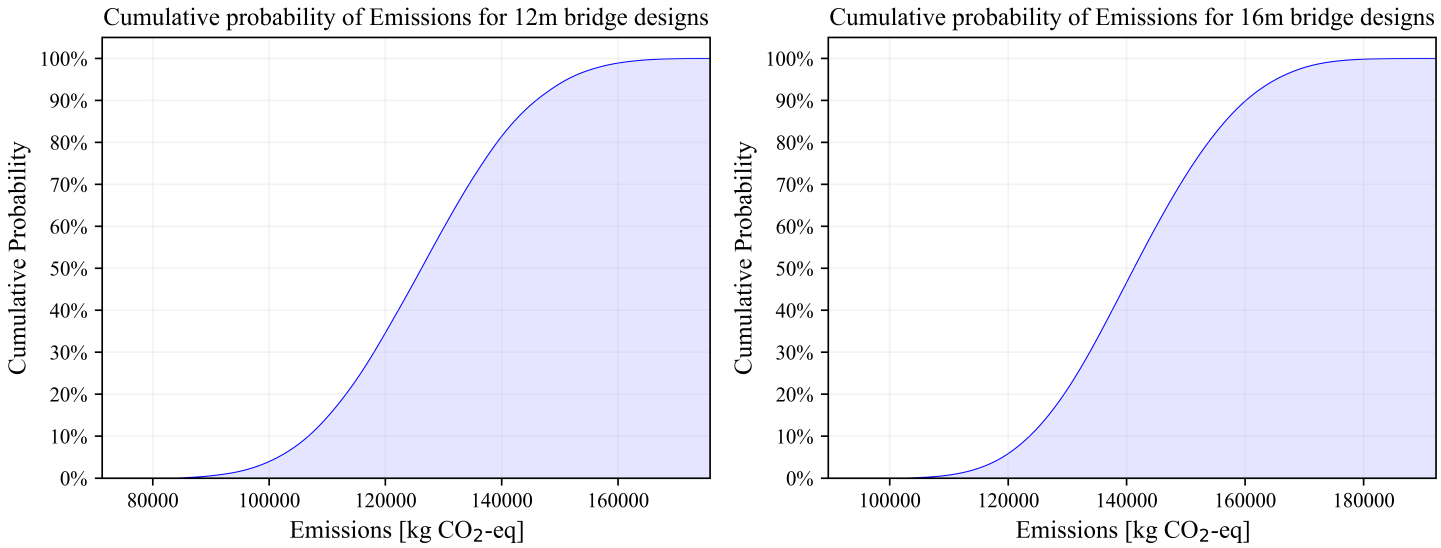


Figure 5.10: Cumulative probability of the feasible design spaces regarding CO_2-eq emissions for the 12-meter and 16-meter bridge designs.

The normal distribution curves of CO_2-eq emissions in Figure 5.11 are presented similarly to Figure 5.3, Figure 5.6 and Figure 5.8. The usability of the normal distributions in Figure 5.11 follows the same discussion as for the material costs in Section 5.2

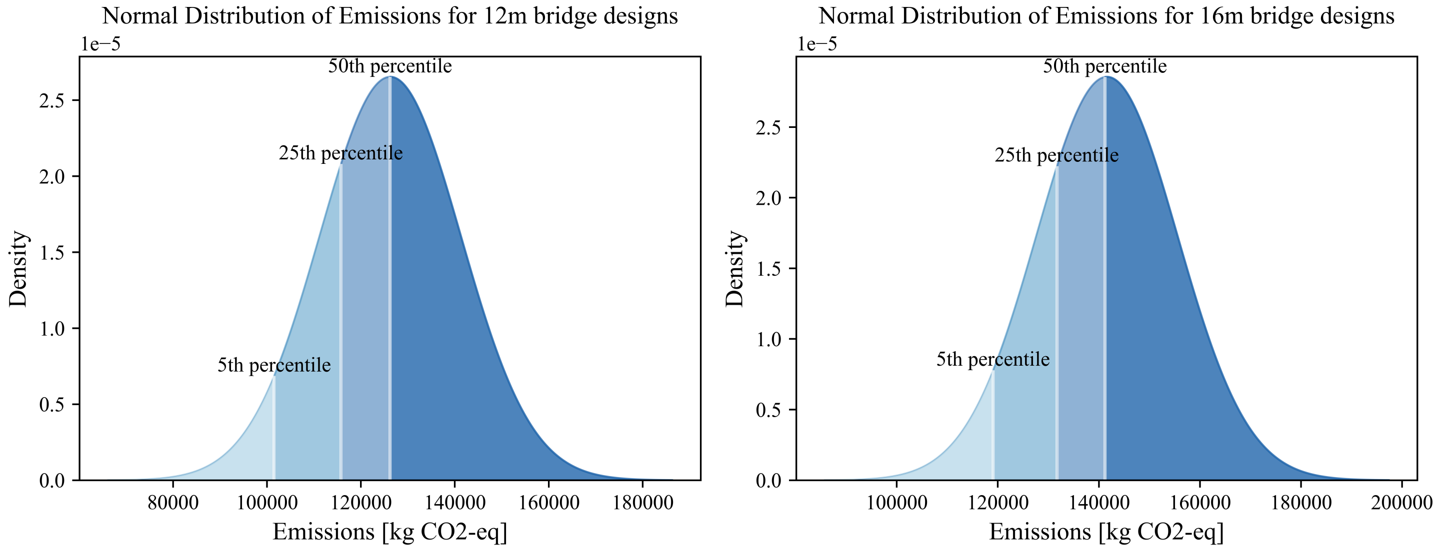


Figure 5.11: Normal distribution of CO_2-eq emissions in the feasible design spaces for the 12-meter and 16-meter bridge designs.

5.6 Relation between evaluation criteria

The representations of the feasible design space in Section 5.2, Section 5.3, and Section 5.5 describe how each evaluation parameter is distributed within the space. However, by displaying the evaluation parameters separately, the interrelations of the evaluation parameters are overlooked. Thus, to fully explore the feasible design space, the interrelations of the evaluation parameters are presented in this chapter.

As previously stated in section 5.4, there is an indication of a linear correlation between material costs and build costs. The relation can be observed in Figure 5.12. From the figure, it can be concluded that there is a linear correlation but within bounds. The build costs of the 12-meter bridge designs have a spread of approximately ±95,000 SEK from the trendline, For the 16-meter designs the spread is increased to approximately ±120,000 SEK. Therefore, it can be argued that with increased span lengths, the correlation between material costs and build costs decreases. However, in this study, just two different bridge variations with varying span lengths have been assessed. Thus, it can not be concluded.

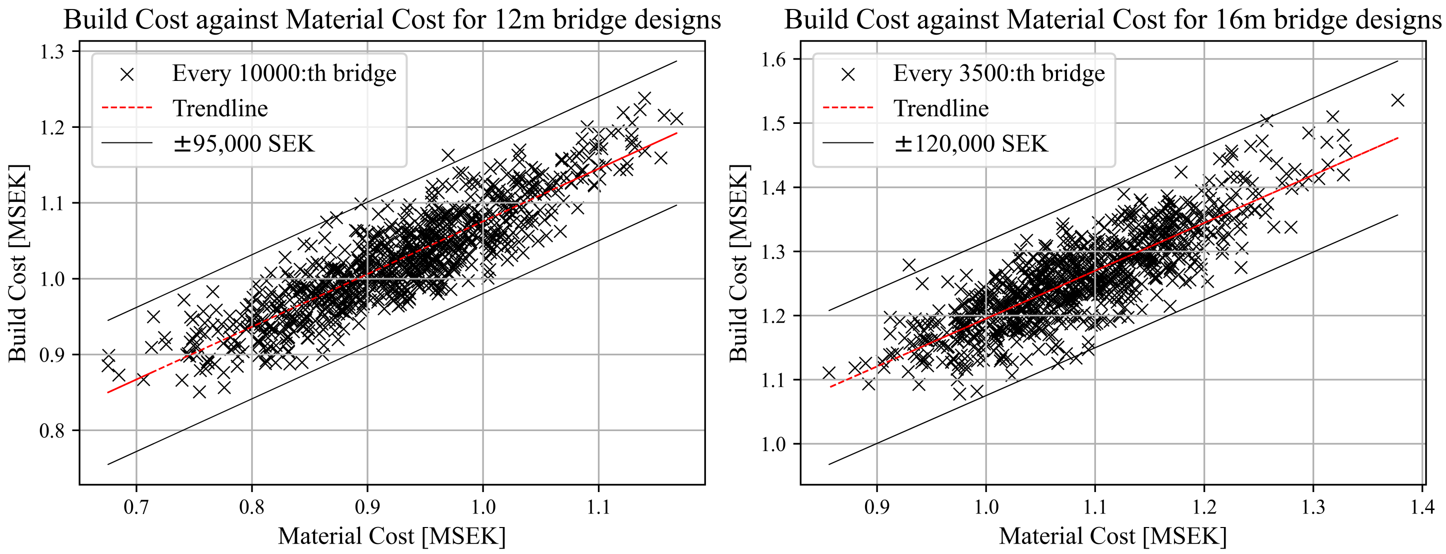


Figure 5.12: Correlation between Build Costs and Material Costs in the feasible design spaces for the 12-meter and 16-meter bridge designs.

There is a strong linear correlation between material costs and CO_2-eq emissions, as can be observed in Figure 5.13. However, there are some deviations in material costs from the trendlines, and the spreads around the trendline seem to be larger for the 16-meter variant.

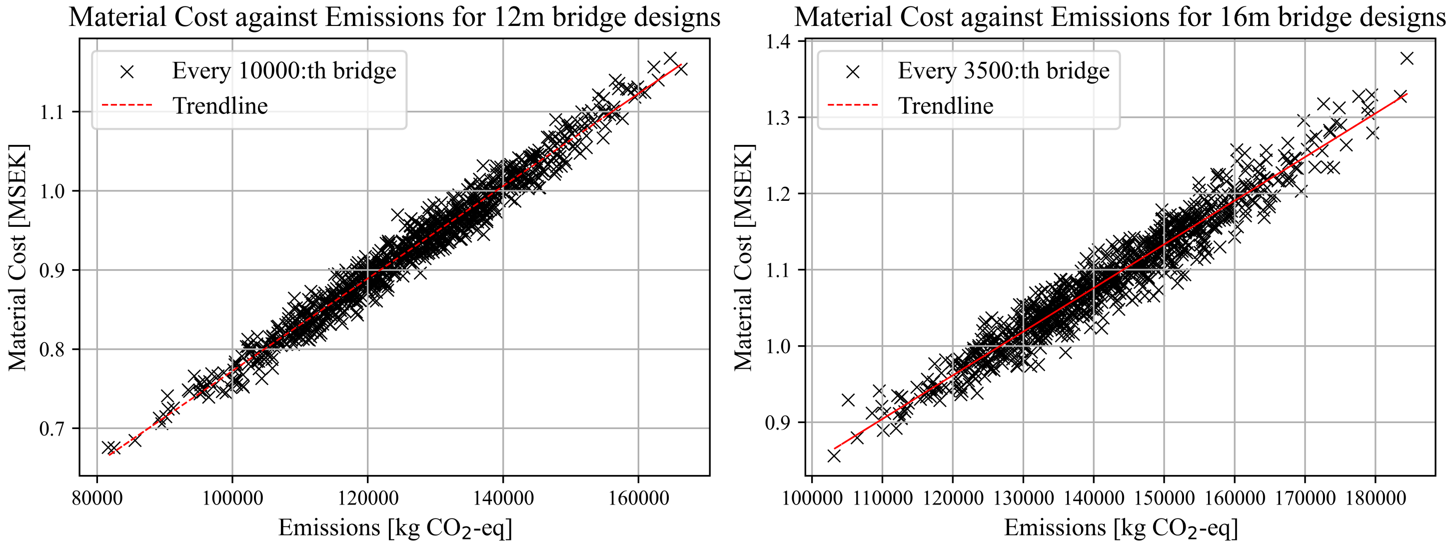


Figure 5.13: Correlation between Material Costs and CO_2-eq emissions in the feasible design spaces for the 12-meter and 16-meter bridge designs.

The relation between the build costs and CO_2-eq emissions is presented in Figure 5.14. A weak linear correlation between the evaluation parameters can be observed, with larger deviations from the trendlines compared to material costs in Figure 5.13.

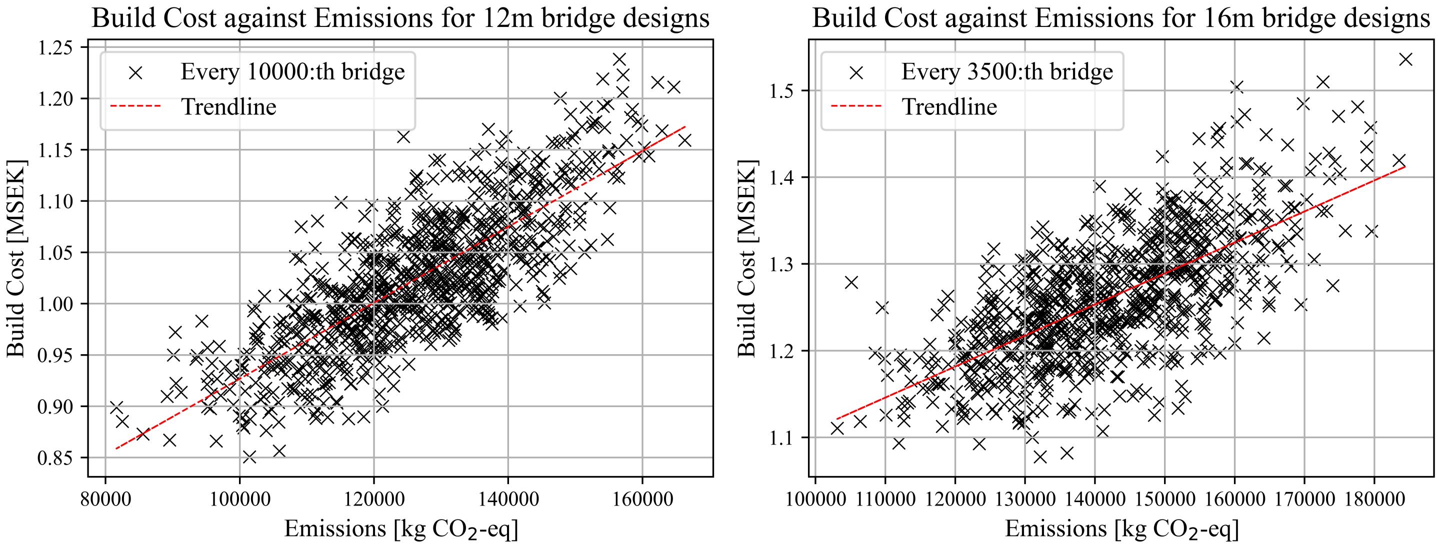


Figure 5.14: Correlation between build costs and CO_2-eq emissions in the feasible design spaces for the 12-meter and 16-meter bridge designs.

The production costs, build costs, and material costs combined, against the CO_2-eq emissions are presented in Figure 5.15. The linear relation is from the combined effect from Figure 5.13 and Figure 5.14. Furthermore, the percentiles from the feasible design space regarding the CO_2-eq emissions in Figure 5.10 are illustrated as a secondary x-axis. If a certain percentile in feasible design space regarding CO_2-eq emissions is of interest, the expected variation in production cost at that specific percentile can be obtained from Figure 5.15.

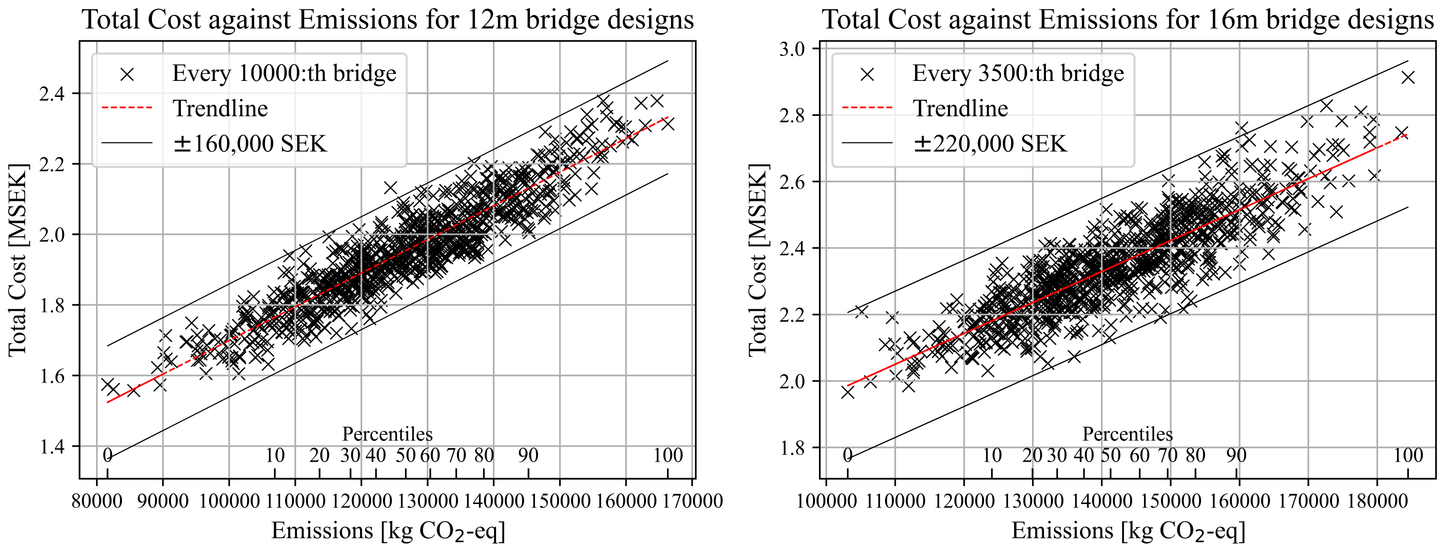


Figure 5.15: Correlation between production costs and CO_2-eq emissions, with associated percentiles representing the feasible design spaces for CO_2-eq emissions for the 12-meter and 16-meter bridge designs.

6 Interview Study

This chapter presents the results of all of the interviews conducted and the themes recognized.

6.1 Backgrounds of interviewees

The backgrounds of the interviewees can be found in Table 6.1 varied, from design consultants to contractors and clients.

Table 6.1: Backgrounds of interviewees

Interviewee	Background	Experience with SBD
A	Client, Technical and Environmental Manager, responsible for contractual issues	Substantial knowledge
B	PhD, Designer & Contractor	Previous knowledge
C	Designer & consultant	No previous knowledge
D	Design engineer, adjunct professor of structural engineering, Contractor,	Substantial knowledge
E	Bridge designer, civil engineering specialist, technical tender documents, Client	No previous knowledge
F	Strategic Buyer in small and large public and private organizations, Client	No previous knowledge
G	Production manager for contractor, Contractor	No previous knowledge

6.2 Implementation of SBD

The interviews discussed implementing SBD in the road-railway plan, covering the limitations, opportunities, and prerequisites for this implementation.

6.2.1 Limitations of Set-Based Design

Interviewees *B*, *C*, and *D* discussed the observed limitations of SBD in bride designs. *B* mentioned that the amount of code needed to create an SBD script is vast, and the code needs to be split into multiple sub-codes to enable collaboration among designers. *B* further stated that it is difficult to determine what key variables to optimize for and that the optimization is unique to the situation it is optimized for. This means that if the situation changes —other soft parameters— then the optimization needs to be redone, incurring additional costs.

C also discussed potential limitations with SBD. *C* mentioned that the geotechnical aspects are challenging to incorporate into SBD due to the inherent uncertainty of the data. Furthermore, according to *C*, the limited time — about two weeks — for the formulation of the technical documents for procurement and tender documents limits SBD due to the time needed to create a script.

In the interview with *D*, the practicalities of implementing a new technology were discussed. Friction to change and lack of experience were mentioned as key limitations for implementing SBD in the construction industry. Moreover, in response to potentially creating a database with SBD, *D* argued that it requires a big investment for a future and non-certain pay-off.

6.2.2 Opportunities of Set-Based Design and prerequisites for implementation

A, *B*, *D*, & *E* all specifically mentioned opportunities with implementing SBD in bridge design. Interviewees with prior knowledge of SBD (*A*, *B*, & *D*) all saw SBD's capacity for multi-criteria optimization of designs as a great opportunity. They all argued that the possibility of finding the optimal solution based on multiple criteria helps find the best solution for any given context. Moreover, *A*, *D*, and *E* mentioned that SBD might help get more information earlier in the design process. It was argued that climate and economic cost information can be retrieved earlier in the process by creating an overview of the cost distribution of different bridge designs. Lastly, it was mentioned that SBD helps find the cost-saving measures in designs and prohibits missing optimized designs.

The prerequisites for successfully implementing SBD in an early bridge design context were also discussed. First, a product (e.g., bridge elements or the bridge itself) that can be standardized needs to be of focus, and an optimization effort can be conducted by exploring combinations of varying parameters. However, interviewee *A* mentioned that optimization of designs should occur later in the project process — during the *Detailed Design* phase. *A* argued that the specifics of the designs created in the preliminary design should not be, and are not, finalized due to the following procurement and detail design. Therefore, *A* deemed it unwise to optimize and restrict designs too early in the process. Lastly, the soil conditions are often unknown or have a low degree of certainty, inhibiting the designs from being accurate in later stages.

In summary, the interviews examined the implementation of SBD in road-railway bridge projects, highlighting both challenges and benefits. Some of the identified key limitations included the extensive coding requirements, difficulties in parameter optimization, and integration of uncertain geotechnical data. Furthermore, time constraints and resistance to implementing new technologies were also identified as barriers to implementation. However, interviewees noted that SBD offers valuable opportunities for multi-criteria optimization and obtaining information on key variables, such as climate impact and economic costs, early in the design process. Thus, the interviews provided insights into the potential benefits and practical challenges of implementing SBD in the road-railway plan.

6.3 Accuracy of calculations

The interviews raised questions about the accuracy of calculations throughout the project process. First, they discussed the variance of the figures and estimations made in the preliminary design compared to the final product. They also covered the limits of the STA's project calculations.

Contractors have a more detailed calculation process for project costs and emissions than other actors. When contractors are designing tenders, they make calculations based on previous projects. Based on previous projects, the volumes and work stages related to the tender and material and labor costs from previous projects dictate the calculations. The calculations are then rough estimates and depend on the complexity of the tender. Then, to validate and verify the cost and emission calculations of their tender, contractors hire consultants to develop alternatives to compare calculations. Furthermore, contractors have a risk and opportunity list alongside the calculations. Experience guides the setting of monetary figures on the risks and opportunities, where the monetary figure is estimated through the probability of risk occurring times the estimated cost of risk. If the risk does not materialize, it becomes a savings opportunity.

The client and design consultants have simpler calculation processes for the cost and emissions of designs. According to the consultant, design calculations in terms of cost and emissions are based on material volume options. The designs are then often evaluated based on the sum of these calculations. However, the STA does not have a standardized process for calculations of designs' costs and emissions. Regarding risk management, the STA sees uncertain outcomes, like the contractors, as risks or opportunities dependent on whether they occur. Risk identification is done from scratch for each project. The STA then manages risks, which they can identify as added value or requirements in contracts, depending on the degree of impact of the risk. Lastly, hard-to-identify risks are taken as AAD works if they are realized.

All interviewees said there is a variance between the preliminary design and the final product. One factor for the variance was the previously mentioned estimation that is apparent in the preliminary design. The designs are estimates and best-guesses in the preliminary design phase, which then are refined in later stages, leading to a variance between the final product and the preliminary design. The contractors also mentioned that insufficient geotechnical data in the tender documents is a culprit for the variance between the won tender and the final product. The client, *E*, also mentioned that insufficient geotechnical data in early design phases is the main cause for the variance between the preliminary design and the final product. *E*further stated that the cost estimates made throughout the project process often underestimate what the project will cost. The majority of the interviewees pointed out that the variance can be attributed to an increasing level of detail as the project progresses, leading to finding errors or problems that increase the costs. Lastly, in the construction phase, unforeseen events and complicated foundations often lead to more expensive projects.

The STA has limits in their calculations. It was mentioned in the interview with the client, *A*, that the STA has inaccurate calculations in terms of costs and emissions, which risks unrealistic tenders winning contracts in lowest price procurement since the STA can not accurately determine a realistic price. Furthermore, according to the client, *E*, STA needs to know what things cost and that there is significant variance in cost for similar projects. The client,*F*, stated that it will always be more expensive than the STA thinks and that the focus is more on key figures for the project rather than key figures for individual elements. The consultant, *C*, was in accordance with the clients and estimated that the accuracy of STA's calculations is about plus-minus 30%, whilst the contractors have a plus-minus 5 % accuracy. So, STA's calculations have a low accuracy.

The reasons for the limit of STA's calculations were also discussed in the interviews. *A* & *F* mentioned that the inaccuracy of calculations is due to an inaccurate calculation database. *C* argued that the STA has low accuracy in calculations because their calculations need to be more detailed. In the context of STA's inaccurate calculations, *C* said *"You have to go into the details and make those judgments to get a good estimate. That's what the contractor does when they calculate their cost at the tender stage. Then they make a better cost estimate, more detailed cost estimates against what the Swedish Transport Administration has done because they must be able to stand for it and do not want to lose a lot of money"*. The accuracy of calculations is, therefore, dependent on the accuracy of the calculation database and the level of detail of the calculation.

6.4 Contracts and procurements

One area of focus for the interviews was contracts and procurements. These discussions covered price and quality in contracts, quality parameters in contracts, and implementation of a normal distribution in procurement.

6.4.1 Price and quality

In the interviews, lowest price procurement and quality were discussed. Generally, the interviewees were critical of the procurement type in assuring quality. The client, *E*, even went as far as to say that the lowest price was useless, comparing it to buying the cheapest clothes and expecting sufficient quality. Simply, the argument by *E* was that contractors are not incentivized to over-perform in lowest-price procurement. However, the consultant, *C*, provided some arguments for lowest-price procurement. In regards to quality, *C* argued that if the tender sums are relatively close, there will not be any quality issues. If not, as *C* put it *"But if you have a bunch of tenders where you have one who has submitted 100 million, one who has submitted 180, 190 and 200 and 220 and you have to choose the one who has submitted 100 million. Then you will have quality problems."*. Both *C* and *B* also mentioned that lowest-price procurements favours the tenders with the most risk-taking behavior. Contractors add risk costs to their tenders by simply multiplying the probability with the incurred cost of the risk. Thus, contractors can lower their tender sum by reducing the probability of the risk. Therefore, according to the interviewees, the lowest price procurement needs soft parameters such as added value in risk management in tenders. However, in the words of *C*, *"For simpler projects, I think fixed prices are great. For more complicated projects with greater uncertainties...., you can't really buy at a fixed price. It doesn't make sense. For that, you have to find other ways to do it. "*. Quality issues correlated to lowest price procurement seem to stem from faulty risk management either by the client or the contractor.

6.4.2 Regulatory Requirements for Quality Evaluation in Procurement

Regulatory requirements were discussed extensively in the interviews with the clients. Regulatory requirements, such as mandatory and non-mandatory, can be incorporated in the tender documents to ensure quality in lowest-price procurement. First, hard constraints such as mandatory requirements can be included. The mandatory requirements are the baseline for the project and should easily be met by contractors. Second, softer constraints and evaluation criteria—–non-mandatory requirements—–can be included in the documents. The non-mandatory requirements result in added value for tenders. Lastly, bonuses and fines can be incorporated to incentivize quality in the contract.

As mentioned, Mandatory requirements are hard constraints in the tender documents and act as the baseline for the project. This means that tenders that do not fulfill these requirements are dismissed. Therefore, contractors must easily meet mandatory requirements to maintain neutrality as per LOU. Furthermore, according to the interviews, the shall-requirement would preferably not include the choice of materials to facilitate innovation and competition. If, however, materials were to be included in the documents, everyone must have access to the materials. Moreover, if calculations of emissions were to be included the STA's climate calculation tool would be used.

According to the clients, risks are identified before the procurement and are often included in the tender documents. The identified risks are evaluated based on probability and costs. Based on this, the risks are either included as requirements in the documents or taken as AAD costs later for the STA. If the risk is probable and the cost is substantial, then risk management is included in the documents. If, however, the risk is low, then the STA takes it as costs later, independent of the cost of the risk.

In the interview with the client, *F*, non-mandatory requirements, and added value were discussed in detail. Non-mandatory requirements in the contract are requirements that the client would prefer the contractor to fulfill but are not required to. All non-mandatory requirements are based on the baseline set by the mandatory requirements. Simply, the mandatory requirements are the baseline level of quality, and the non-mandatory requirements are the quality levels above the baseline. If a tender fulfills a non-mandatory requirement, then the tender gets added value, thus reducing the tender sum. The non-mandatory requirements are then included to consider performance in the procurement. In short, non-mandatory requirements allow clients to incorporate quality evaluation in the lowest-price procurement.

As mentioned, non-mandatory requirements can result in added value for the tenders. The tender documents describe risks and opportunities identified by the STA and will assume added value if the contractors can describe how they intend to treat the risks and opportunities. The evaluation models of the added value rewarded by the non-mandatory requirement must be absolute, i.e., not relative. This means that one must base added value on available information before procurement. For instance, if a tender fulfills non-mandatory requirement y, the STA deducts x of SEK from the tender. Therefore, the added value is not connected to the tender sum and is based on the calculated project cost before the procurement.

According to the client, *F*, there are several things to consider when including added value in tender documents. First, added value needs to be balanced based on which suppliers can fulfill it and what it costs for the suppliers. This means that the added value needs to be profitable for the suppliers, i.e., the non-mandatory requirements must induce a lower cost for the contractors than that of the sum of the added value. For instance, the added value is not balanced if the added value is 5 million kr and it costs 5,5 million for suppliers to achieve it. Basically, added value is balanced based on the perceived value of a function for the client and the supplier's cost to supply it. Secondly, added values in procurement are easily appealed. Many are afraid to include non-mandatory requirements and added values in procurement because, in the words of *F*, *"....the more added value you have, the more you exposed your throat to an appeal"*. Thus, the risk of appeal and procurement failure heightens by having non-mandatory requirements and added value in contracts. So, the evaluation of added values for tenders needs to be transparent, whilst the added value themselves needs to be set at a profitable level for contractors.

Because of the risk of appeal when incorporating added value, there is a need for a more objective added value model. Interviewee E mentioned that a model with yes/no questions needs to exist to clarify the evaluation process and avoid appeal. F said, in the context of risk for appeal in added values, *"for the Swedish Transport Administration, we are consistent in our judgement and show that we are transparent....Then the frequency of appeals will decrease because people will simply trust us more."*. So, the clients believe that the risk for appeal is reduced by having a more transparent and consistent evaluation model for setting and evaluating added values in tenders.

Lastly, bonuses can be included in the tender documents to incentivize performance after the documents are signed. The difference between added value and bonuses is as follows: added value is something you get on the deal (tender), and a bonus is something that is paid if you deliver more than the conditions you have received the deal on. The bonuses are described and included in the tender documents, but unlike added values, they can be relative to the tender sum. So, bonuses follow the same principle as added value — reward performance— but are rewarded during and at the end of contract execution rather than the beginning and can be relatively set.

6.4.3 Implementation of normal distribution

In the interviews, the possibility of using spans of costs and emissions of designs gathered from SBD in procurement was discussed among the actors.

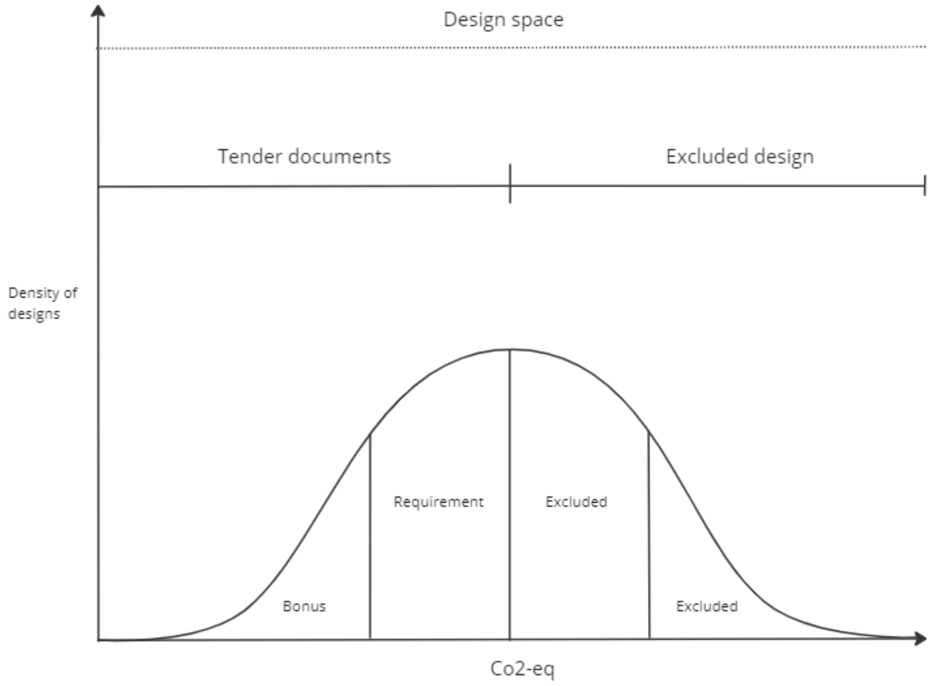


Figure 6.1: Proposed normal distribution

The clients see great potential in incorporating a normal distribution of designs' costs and emissions in procurement. First, databases created with SBD can be used as sources of evaluations and requirement-setting for the client, according to interviewee *E*. *A* thinks bonus setting according to the normal distribution is the short-term way forward. Furthermore, setting an allowable range of solutions is fine according to LOU, as the ranges are known to everyone if they are included in the documents. If the distributions are based on the STA's climate calculation tool, bonuses can be awarded according to the distributions. However, *A* thinks that the industry is not quite there yet to evaluate tenders based on emissions. *A* also mentioned that the industry would negatively perceive setting requirements on costs because the STA does not know how to set that range. The STA's estimations will be more approximate calculations than those the contractor does. There is much that affects price later on, so one should beware of locking ranges (using normal distributions for mandatory requirements) for solutions. The client, *E*, thinks that the curves can be used as proof that it is not impossible to create cheaper designs with lower emissions. It can also be used in the evaluation documents to evaluate how good tenders are. For instance, clients can argue to a contractor *"your solution is in the bottom 15 percentile" - E.* Lastly, *E* believes that normal distributions for amounts of concrete and reinforcement are most important. Furthermore, to evaluate tenders based on this, there must exist requirements for the contractors to show amounts of concrete and reinforcement in the tender documents.

According to the consultant, emission requirements should be included in the tender documents. However, the consultant stated that it is difficult to accurately determine the emissions of designs in the preliminary design phase. Therefore, the interviewee argued that setting emission requirements on materials versus design in the early stages is easier. *C* said that emissions go hand in hand with economics in projects and climate optimization is therefore connected with economic optimization. However, if requirements were to be set on design emissions, the client must set rules and clarify how to calculate emissions for designs in the tenders. Basically, the client needs to formulate how emissions should be calculated for the design in the tenders. Lastly, when asked about including a normal distribution curve, *C* stated that it is difficult to hit the right normal distribution curve and set reasonable challenges for the contractors in the early stages. So, the consultant thinks that emissions requirements should be included, but proposed material requirements rather than design requirements.

All the interviewed contractors saw the proposal to implement normal distributions of designs' emissions and/or costs in the tender documents positively. *B* thinks it is good to challenge the contractors by having defined spans of acceptable emissions. The contractor also liked the idea of knowing the emission budget for projects and the possible bonuses connected to that. It was also seen positively to include added value based on the environmental benefit of the tender.

D thought that it would work to control contractors on costs and CO_2 emissions. There exist conditions for implementing the curve, and it enables the contractors to optimize both cost and emissions. However, *D* was unsure of how the contractors would interpret that you can consider many different design solutions. It was clarified that no one opposes implementing it, but it is strange to work with something unfamiliar. *D* thought it would be good to show the distribution curve in the documents. When asked whether to put emission requirements on material or designs, *D* answered that it is more ambitious to consider the emissions of designs, since it is a more conclusive approach. Rather than focusing on using less concrete, focusing on the most optimal design is more ambitious and might lead to finding the design with the lowest emissions rather than the lowest usage of concrete. Because reduced concrete and reinforcement in design can lead to increased emissions in other parts, such as formworks. Lastly, *D* said that separate curves for money and CO_2 should be used, so you give the contractor the possibility to optimize based on either cost, CO_2, or both.

The contractor, *G*, saw the proposal of incorporating a normal distribution curve for formulating bonuses positively. In the context of setting levels for bonuses and non-mandatory requirements, *G* said *"We like that"* and that contractors may be more bonus-hungry than designers and consultants. *G* primarily sees it as a good way to challenge the contractors and have it as an incentive.

7 Discussion

This section contextualizes the results from the literature review, the case study, and the interview study to provide answers to the research questions.

7.1 Set-Based Design as a design method

In this thesis, the SBD approach to design bridges was implemented to define the design space, providing an overview of the ranges regarding the key variables. However, to broaden the perspective of SBD in the context of preliminary design, the limitations of design optimization were included as a topic in the interviews (see Section 6.2). One interviewee mentioned difficulties in determining what parameters to optimize with an SBD algorithm. Especially because the optimization of the bridge design is unique to the situation in which it is optimized. This could be translated in the context of mapping and exploring the design space. The external constraints change from project to project, implying revised input data in the SBD algorithm to match the design conditions. Another interviewee highlighted the inherent uncertainty of such an aspect in the preliminary design, the geotechnical aspect. Therefore, in using SBD to incorporate key variables beyond the lowest price in public procurement, it is essential to simulate various scenarios to account for a wide range of external constraints.

The results presented in Section 5 demonstrate how the algorithm can visualize the feasible design space as normal distributions of the key variables for a range of parameters. However, only two span lengths with one geotechnical scenario are covered in this report, yielding an inadequate holistic perspective of frame bridge designs.

Another limitation of using the SBD algorithm, highlighted during the interviews, is the time-consuming process of creating the algorithm. For context, developing the algorithm used in this thesis took four months and primarily included quantity estimations of materials resulting from ULS and SLS conditions. Creating a more sophisticated algorithm encompassing a comprehensive design approach would require more time and resources. As mentioned by interviewee C, the timeline for formulating the technical documents does not align with the time investment needed to develop such a tool. However, once a complete SBD script is developed, one could input a wide range of constraints and wait for the algorithm to map the design space, with minimal additional effort. Thus, SBD requires an initial time investment that might pay off in the long term.

7.2 Uncertainty Reduction through Set-Based Design

In the context of the procurement phase in the project process and from the client's point of view, the tenders received seem to be random in some sense. The client, F, mentioned that the STA does not have any idea what things cost and has to take the tenders at face value. Therefore, the tenders are somewhat inherently random, in the client's point of view.

SBD can then be implemented to manage random uncertainties. First, by defining a design space for a project, in our case, frame bridges, designers can map out all the potential tenders' designs. Following this, key variables for evaluation (cost and CO_2-eq emissions) can be introduced into the design space. After this, exploration and validation of the design space can be initiated, resulting in finding optimal designs according to the key variables. Furthermore, the distribution of designs in the design space based on key variables can be determined. Public procurement decision-makers (e.g., clients) can then produce tender documents based on this exploration. For instance, the exploration can help the client set quality standards and requirements in the procurement documents. We propose that the clients should include a method of design space exploration — e.g. normal distribution curves — to set non-mandatory requirements and include added values in the tender documents based on that. To then manage the uncertainty and restrict it in a predictable way and prioritize quality in procurement.

With the normal distribution and design space, the STA can work towards its climate-neutrality goal more deterministically. The design space and the subsequent exploration provide limits for projects in terms of the key variables. This enables the STA to better determine what the projects' climate and financial budget should be. With the gathered normal distributions of the key variables (as presented in Section 5), the STA can estimate what the project´s emissions most likely will be. Furthermore, the design space exploration provides the span of the key variables, which can provide best- and worst-case scenarios regarding the key variables to the STA. This, in turn, can help the STA determine if they can afford the worst-case scenario. Thus, the STA can get a more deterministic understanding of the projects' key variables by exploring the design space.

To summarize, the tenders received in public procurement are then, in nature, random, and creating a design space that covers the possible range for the tenders is then a method of understanding the randomness. Thus, set-based design can act as a tool for decision-makers to reduce and understand the uncertainty in public procurement. With this gathered understanding, decision-makers can then implement quality measurements, regarding emissions of tenders in public procurement by including non-mandatory requirements and added values in procurements.

7.3 Enhancing Quality Criteria in Public Tendering

As mentioned in Section 3.2.2, the evaluation criterion in simple projects for tenders is often solely the lowest price. The quality of tenders for these projects is therefore disregarded. However, to be clear, as noted in the interviews, the procurement documents include mandatory requirements for baseline quality for projects. This means that the STA sets a baseline for the required function, which explains what the tenders need to fulfill not to be dismissed. However, from the interviews, it can be observed that the mandatory requirements are the only quality evaluations that are made in the public tendering process for simple projects. The approach for procurements is then: "The tender with sufficient quality and lowest cost wins". This creates a competition of who can fulfill the client's required function for the least amount of money. This logic and approach are sound in the context of only prioritizing functionality and money. However, given the STA's goal of climate-neutral infrastructure by 2040, the logic must change to reach the goal. Because the competency that the STA rewards by the current approach is efficient design and building in terms of cost — *"Who can design and build for the least amount of money"*. The approach must then change into — *"Who can design and build for the least amount of money AND emissions"*, to reach the 2040 goal. According to the client *A*, the clients are not quite there yet to evaluate tenders solely based on emissions, meaning that we can not disregard money as an evaluation criterion in procurement. However, given the legal framework of LOU, the lowest cost must be included in the procurement process. Then, either the laws need to be changed to include emissions in the lowest cost evaluation or the lowest cost evaluation needs to be managed in a way.

One thing worth noting is that, as discussed in the interviews, the STA must be careful when setting mandatory requirements in the tender documents, as it sets the baseline level of quality for the project. Also, considering that the public procurement process and the client must not be discriminatory when awarding contracts, the mandatory requirements cannot be too restrictive. To then set mandatory requirements in the preliminary design when the level of available information is low is troublesome. It is therefore not recommended to use the design space exploration presented in Section 4 to determine levels of mandatory requirements in the contract, as it risks excluding potential suppliers.

7.3.1 Non-mandatory requirements and added values

One way of "avoiding" procuring only on cost and to include the environmental impact of tenders is to include non-mandatory requirements for environmental impact in tender documents. This means that the performance of the environmental impact of tenders can be regarded as a measurement of quality. Identified environmental impact levels from the previous climate calculations prior to procurements by the client can then be used as relative measurements for defining non-mandatory requirements, resulting in added values and bonuses. However, as discussed in the interviews, the STA is quite inaccurate in cost and emission calculations — in terms of predicting tenders' costs and emissions — due to lower levels of detail present earlier in the project process and "inaccurate" calculation databases. There is, therefore, a need to achieve higher levels of detail earlier in the process and/or create more accurate calculation databases in order to implement non-mandatory requirements and added values in tender documents accurately. Because the non-mandatory requirements and added values must be absolute and need to be included in the tender documents. Thus, the added values and non-mandatory requirements must be identified and formulated before the actual procurement. This is problematic because, as of now, they are based on a single feasible solution, not a CO_2-based design space.

As mentioned, the design calculations for costs and emissions lack precision due to the low levels of detail in the preliminary design phase, which might be managed by implementing SBD rather than PBD. When using PBD, cost and climate calculations of designs are "best guesses" based on the current level of available information. This means that, while the calculations are accurate within their current context (level of available information), they are likely to be revised as the project progresses. This provisional nature makes it challenging to draw definitive conclusions from them, which inhibits the possibility of including accurate non-mandatory requirements. This, in turn, yields over or under-dimensioned figures for added values. However, SBD might be able to provide better conditions for this.

By implementing SBD, we can map out the design space, which includes all feasible designs for determined parameters and their combinations, as demonstrated in Section 4. Through the subsequent design space exploration, we can understand the behavior of the solution space. As shown in Section 5, this exploration, particularly in the context of costs and emissions, can present the distribution of costs and emissions of the feasible designs. While we can't pinpoint where the distribution tenders will land, we can conclude that designs within the tenders will fall somewhere in the distribution. Moreover, based on the design space exploration, we can differentiate between good and bad designs in terms of costs and emissions. This means that SBD can provide a solid basis for evaluating the quality of tenders based on emissions. In essence, by having all feasible designs available, we can gain a better understanding of what constitutes high quality in terms of emissions.

Importantly, the design space and feasible designs can be created in the preliminary design phase, that is, before procurement. One key finding from the interview with E was that the amount of added value needs to be absolute and defined in the tender document. This means that the client must define absolute figures of how much will be redacted from the tenders' sum if they fulfill the non-mandatory requirements. These figures must also be defined in the preliminary design phase to successfully be included in the tender document. In Section 5, we have showcased that we can gather information on key variables already in the preliminary design of frame bridges by creating and exploring their design space. Based on the information, as previously discussed, we can create absolute figures to include in tender documents to determine non-mandatory requirements and added values. In Figure 7.1, one proposal for this is presented, which presents a conceptualization of how the absolute figures of the added values and the non-mandatory requirements can be presented in the tender documents. Moreover, Figure 7.1 shows how the result from the SBD-script can be used to determine the levels of the non-mandatory requirements. So, by implementing SBD in the preliminary design phase, we can set transparent levels for non-mandatory requirements and added values in tender documents.

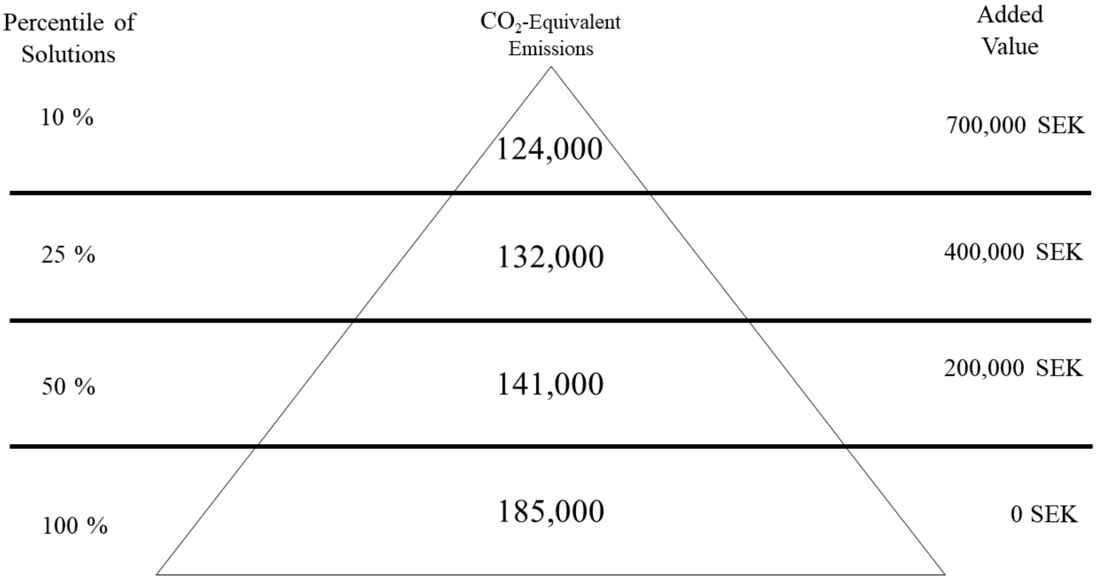


Figure 7.1: Representation of how to integrate added value in tender documents for the 16-meter frame bridge. Emphasizing the percentiles of possible solution and their corresponding CO_2-eq emissions.

The gathered information on the key variables can also be used to define bonus ranges. The normal distribution of the design space enables us to determine what emissions level we deem high quality, which can later determine different levels of bonuses. However, as the client *E* pointed out, bonuses are something you get for delivering more than what you promised in the tender. Bonuses are, therefore, not evaluation criteria to be used for consideration of quality in tender evaluation. Rather, the bonuses are incentives during contract execution for higher quality than agreed upon in the tender. This entails that bonuses can be relatively set, meaning that they can be based on the won tender sum. The STA can, therefore, define bonuses to be relative to the tenders received, thus avoiding the limitations of the low levels of detail present in the preliminary design phase. It is, therefore, unclear whether an implementation of SBD in the preliminary design phase is needed to successfully include bonuses in public procurement.

The STA must also determine how much CO_2-eq emissions are worth in monetary terms for them and how much it costs for the contractors to achieve them to set reasonable added values in the tender documents. According to the interviews, the added values need to be balanced between the perceived value of a function for the client and the supplier's cost to supply it. So, the STA must determine how much they value lower emissions in tenders and what the contractor must invest to reach the non-mandatory emission requirements connected to the added values. One proposal is to include Ecotax for this (See Finnveden et al. (2013); Ahlroth and Finnveden (2011)).

Lastly, the identified best- and worst-case scenarios for the key variables in the project can also be regarded as risks and opportunities in the procurement documents. According to the interviews, non-mandatory requirements are often based on the risks and opportunities the STA has found in the preliminary design. Added values are then assumed if the contractors can describe how they intend to treat the risks and opportunities. For example, a risk/opportunity in the tender documents can be regarded as the project's top/bottom 10% of emissions. Added value can then be assumed if the contractor describes, through the climate calculation tool that the STA provides, how their design falls into the bottom 10% of emissions. In short, by also including the tails of the distribution of the key variables as risks and opportunities, the STA can include the emission of designs as non-mandatory requirements.

7.3.2 Future research

The main key finding of this thesis was that the normal distributions of key-variables gathered by using SBD can be used to consider tenders' environmental performance, by regarding CO_2-eq emissions as quality and leveraging the current laws of price and quality in public procurement. However, this is only in theory. There are therefore three main areas of suggested research regarding this: literature, interviews, and case studies. One area is to conduct a literature study on emissions as quality (and quality itself) in public procurement to find out how we can design and create the best non-mandatory requirements and added values. To combine this with the literature study, a more in-depth interview study should be conducted to contextualize the findings from both this study and the literature study. The interview study(-ies) should focus on investigating how to practically implement findings from this, and the literature study should be based on interviews with the industry. Lastly, a case study in which SBD is used to implement our suggestions (using SBD to gather the normal distribution of key variables and including them in tender documents) and the findings from the other studies to find out if they are applicable in practice.

Future research regarding the development of the SBD algorithm

In this thesis, the structural analyses in the SBD algorithm were somewhat simplified. Thus, further research includes, integrating fatigue analyses and wind loads into the algorithm to further narrow the design space. Furthermore, it would be of interest to incorporate a holistic construction approach by including the impact of preparatory site work and different foundations (e.g impact of soil stabilizing measures or piling) on the key variables.

Further development of the SBD algorithm includes making it create structural drawings of the frame bridges. This will not only create a more sophisticated database of frame bridges but also strengthen the credibility of the data represented in the normal distributions.

8 Conclusion

This study explored the implementation of Set-Based Design (SBD) in the early stages of infrastructure projects, specifically bridge design, to manage uncertainty and enhance decision-making. The analysis demonstrated that SBD offers a structured approach to consider multiple feasible designs simultaneously, enabling better management of material cost, build cost, and environmental impact uncertainties by showcasing the solution space of said key variables.

Key findings include the recognition that SBD allows for a comprehensive exploration of the design space, offering a clearer understanding of the trade-offs between cost, buildability, and environmental impact compared to the traditional design methodology (PBD). The SBD approach not only supports more informed decision-making but also aligns with sustainability goals by incorporating environmental criteria into the evaluation process of tenders in public procurement.

Additionally, SBD can be a way to manage the limitations of inaccurate calculations of key variables in the early stages of bridge design. The use of SBD can lead to absolute and reliable figures of non-mandatory requirements and added values in tender documents, enabling tender evaluation based both on price and climate performance. Overall, the adoption of SBD in the preliminary design phase of infrastructure projects presents significant potential for improving decision-making under uncertainty, emphasizing quality in public procurements, and advancing the infrastructure sector towards the 2040 climate goals.

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A Applied Partial Factors in Load Combinations

This appendix includes the applied partial factors in SLS and ULS. The partial factors are obtained from:
TSFS 2018:57 page 10
TSFS 2018:57 table 4.3 and table 4.4
SS-EN 1990 Table A2.3
SS-EN 1991-2 Table 6.11

Table A.1: partial factors permanent loads in ULS

Permanent Loads	γ_d	$\gamma_{G,unfav}$	$\gamma_{G,fav}$	γ_{sup}	γ_{inf}	ξ_{red}
Self weight	1	1.35	1	1	1	0.89
Ballast ± 30%	1	1.35	1	1.3	0.7	0.89
Shrinkage	1	1.35	1	1	0	0.89
Earth pressure	1	1.35	1	1	1	0.89

Table A.2: partial factors permanent loads in SLS

Permanent Loads	γ_{sup}	γ_{inf}
Self weight	1	1
Ballast	1	1
Shrinkage	1	0
Earth pressure	1	1

Table A.3: Partial factor variable loads

Load Case	γ_d	$\psi_{Q,unfav}$	$\psi_{Q,fav}$	ψ_0	ψ_1	ψ_2	$\psi_{Q,loadcomb}$
lgr11							
LM71	1	1.5	0	0.8	0.8	0	1
Traction	1	1.5	0	0.8	0.8	0	1
Nosing	1	1.5	0	0.8	0.8	0	0.5
lgr12							
LM71	1	1.5	0	0.8	0.8	0	1
Traction	1	1.5	0	0.8	0.8	0	0.5
Nosing	1	1.5	0	0.8	0.8	0	1
gr1a							
LM1 boggi	1	1.5	0	0.75	0.75	0	
LM1 distributed	1	1.5	0	0.4	0.4	0	
gr1b							
LM2	1	1.5	0	0	0	0	
Temperature loads	1	1.5	0	0.6	0.6	0.5	
Surcharge load	1	1.5	0	0.8	0.5	0	

Table A.4: Load factor for 6.10a and 6.10b in ULS

Permanent loads	6.10a **Unfavourable**	6.10a **Favourable**	6.10b **Unfavourable**	6.10b **Favourable**
Self weight	1.35	1	1.20	1
Ballast ± 30%	1.75	0.7	1.56	0.7
Shrinkage	1.35	0	1.20	0
Earth pressure	1.35	1	1.20	1
Variable loads	6.10a **Main load**	6.10a **Other load**	6.10b **Main load**	6.10b **Other load**
lgr11				
LM71	1.2	1.2	1.5	1.2
Traction	1.2	1.2	1.5	1.2
Nosing	0.6	0.6	0.75	0.6
lgr12				
LM71	1.2	1.2	1.5	1.2
Traction	0.6	0.6	0.75	0.6
Nosing force	1.2	1.2	1.5	1.2
gr1a				
LM1	1.125	1.125	1.5	1.125
LM1 distributed load	0.6	0.6	1.5	0.6
gr1b				
LM2	0	0	1.5	0
Temperature loads	0.9	0.9	1.5	0.9
Surcharge load	1.2	1.2	1.5	1.2

Table A.5: Load Factors for frequent load combination, 6.16a, in SLS

Permanent loads	**6.16a Unfavourable**	**6.16a Favourable**
Self weight	1	1
Ballast	1	1
Shrinkage	1	0
Earth pressure	1	1
Variable loads	**6.16a Main load**	**6.16a Other load**
lgr11		
LM71	0.8	0
Acceleration and breaking	0.8	0
Nosing force	0.4	0
lgr12		
LM71	0.8	0
Acceleration and breaking	0.4	0
Nosing force	0.8	0
gr1a		
LM1	0.75	0
LM1 distributed load	0.4	0
Temperature loads	0.6	0.5
Surcharge load	0.5	0

B Convergence Study

In this appendix, the convergence study of the bridge deck and frame legs is presented. The convergence study was performed with the maximum moment from variable SM1 in Load combination 10.6a. The convergence study was performed on the open frame bridge with a free span of 16 meters.

In figure B.1 and figure B.2 the convergence study of the bridge deck is presented. The lines in the graphs represent the moment distribution of different elements. As can be observed in figure B.2, the variance in SM1 lies in the connection between the legs and the deck.

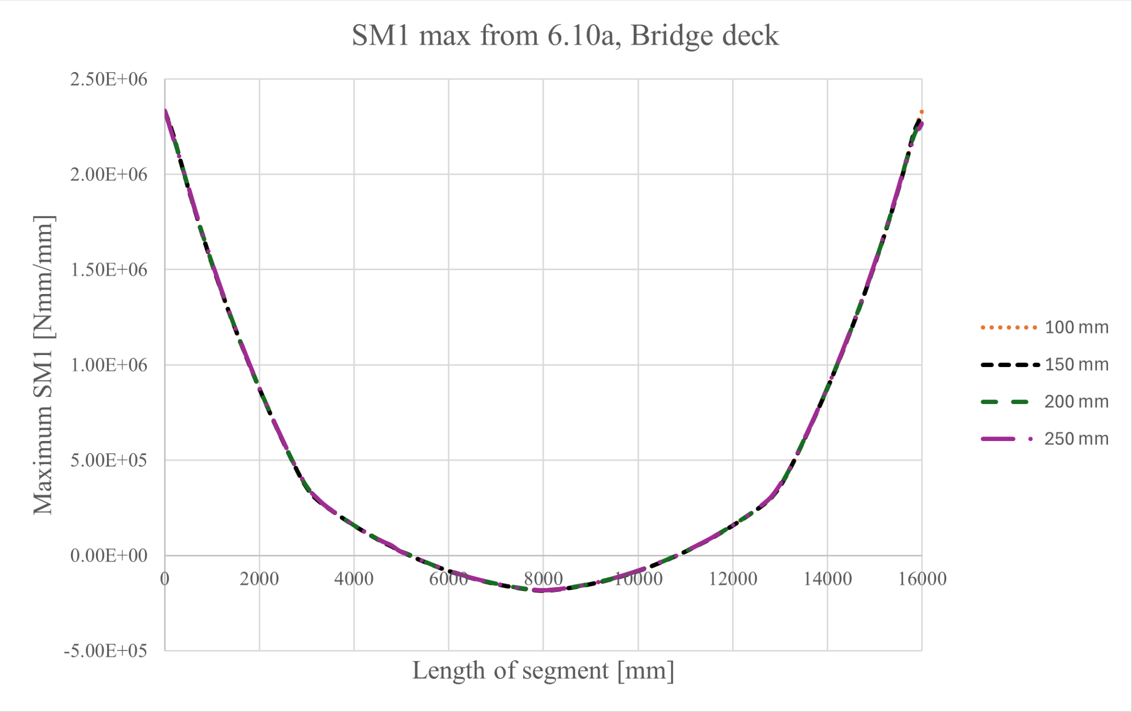

Figure B.1: Convergence study of bridge deck

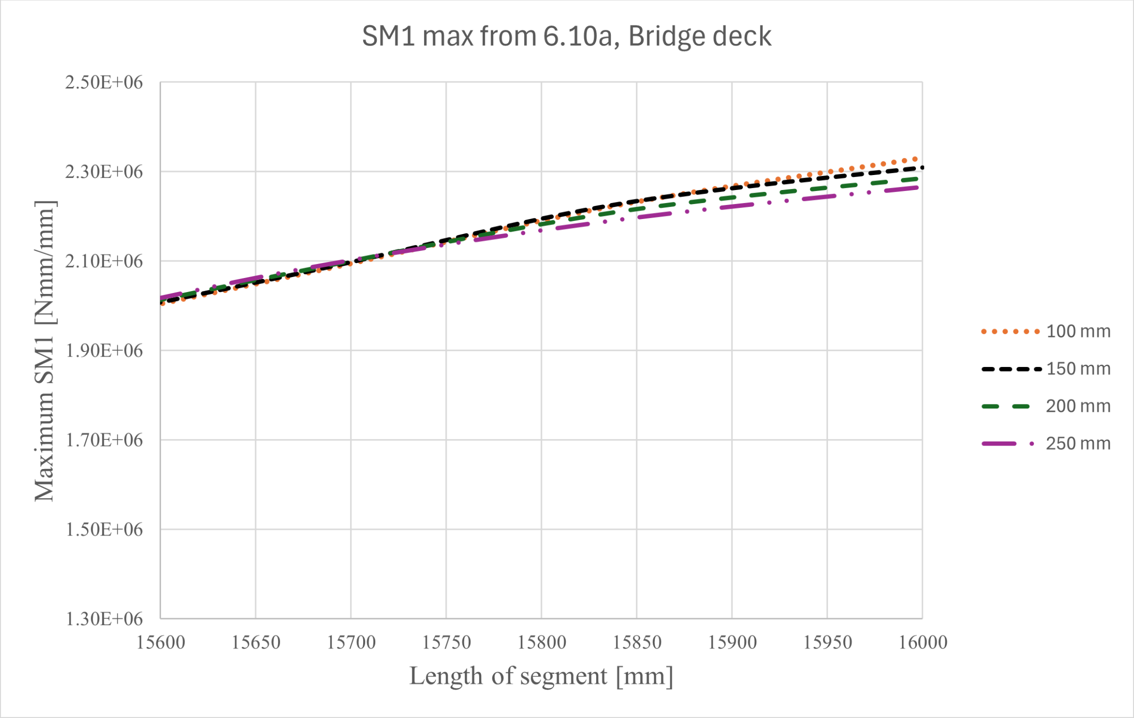

Figure B.2: Convergence study of bridge deck, zoomed in

In Figure B.3 and Figure B.4, the convergence study of the frame legs is presented. The lines in the graphs represent the moment distribution of different elements. As can be observed in Figure B.4, the variance in SM1 lies in the connection between the legs and the deck.

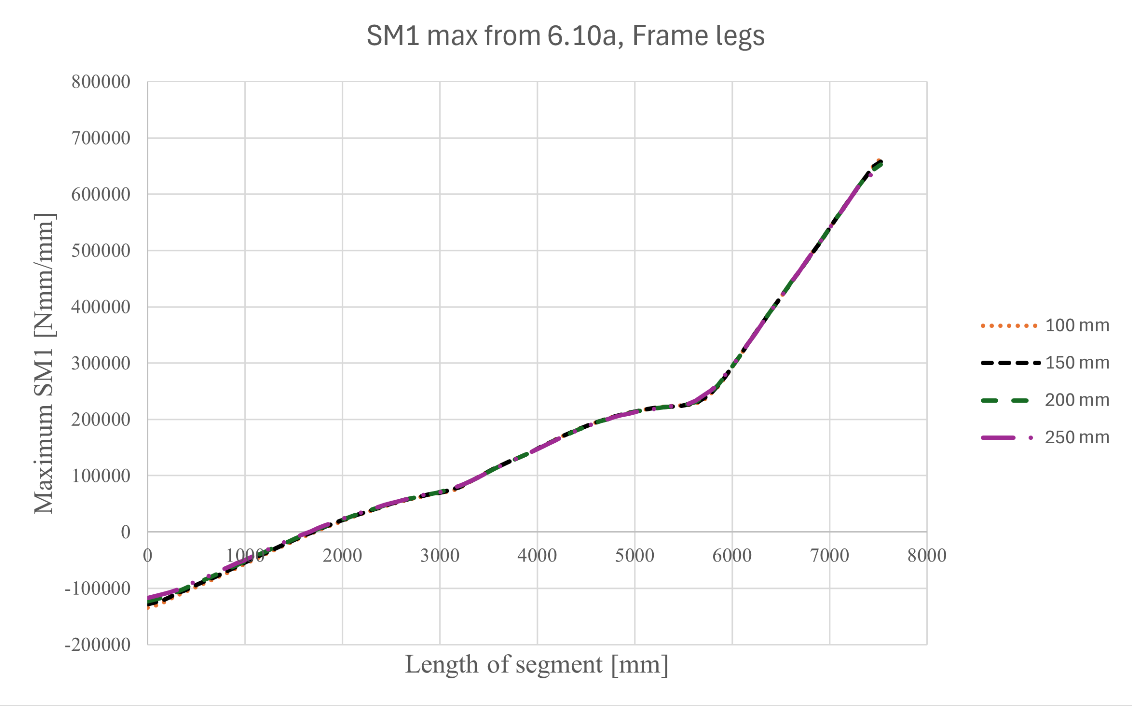

Figure B.3: Convergence study of frame leg

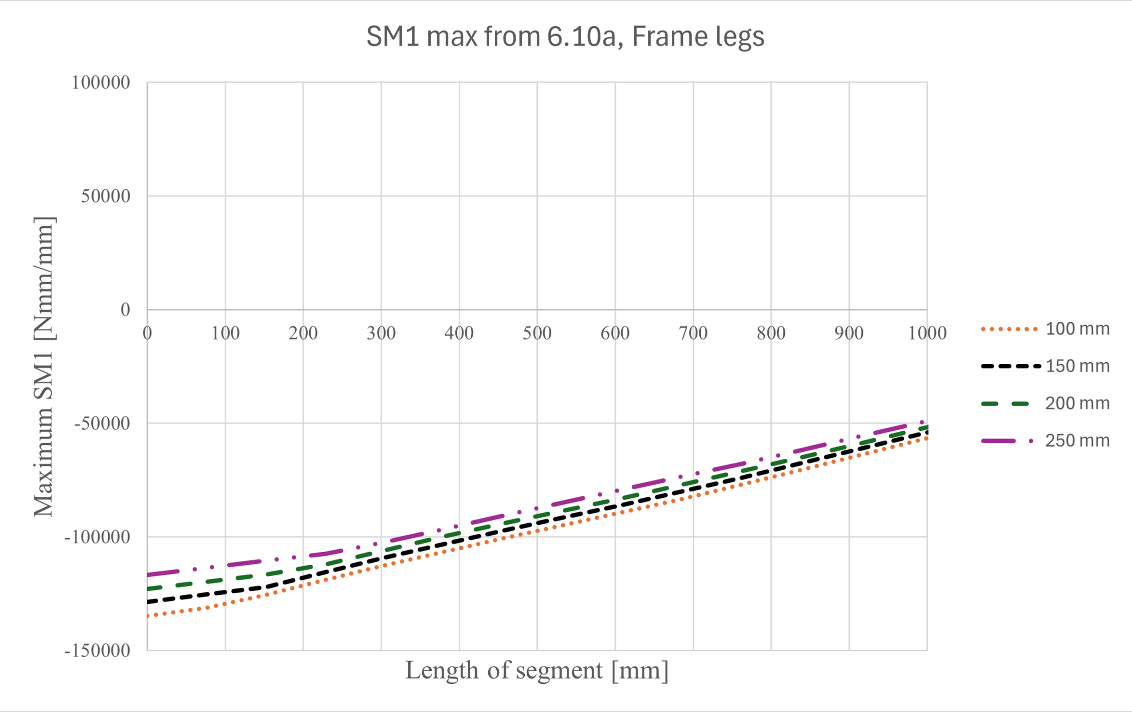

Figure B.4: Convergence study of frame leg, zoomed in

From the convergence study, the element size of 200 mm was chosen to be implemented in the algorithm. Although, 100 mm gave larger moments, the running time could be cut by 50% by increasing the element size to 200 mm for the whole bridge. However, using the element size of 200 mm does not have a significant change in SM1 compared to the element size of 100mm.

C Evaluation parameters for key variables

In this appendix, the material-specific variables used in the evaluation of material costs, build costs, and climate impact are presented. The unit construction time per activities related to each material is presented in table C.1 and where obtained from Majid Solat Yavari et al. (2016). The material and labor costs are presented in table C.2 and were obtained from Majid Solat Yavari et al.. The CO_2-eq emission per unit mass related to concrete and reinforcement is presented in table C.3. The value for concrete was gathered from Majid Solat Yavari et al. (2017) and for reinforcement was gathered from (Trafikverket, 2023).

Table C.1: Unit construction time for the activities related to each material

Activities	**Bridge deck**	**Frame leg**	**Foundation**	**Unit**
Formwork	1.50	1.50	1.50	h/m^2
Formwork if variable thickness	2.00	2.00	2.00	h/m^2
Concrete work	2.00	1.50	1.50	h/m^3
Reinforcement work	274.75	235.50	235.50	h/m^3
Factors for reinforcement labor to be multiplied with **Reinforcement work**				
If (thickness of concrete member < 40 cm)	1.20	1.20	1.20	-
If (40 cm ≤ thickness of concrete member < 60 cm)	1.10	1.10	1.10	-
If reinforcement size is $\phi 16$	1.25	1.25	1.25	-
If reinforcement size is $\phi 20$	1.14	1.14	1.14	-
If reinforcement size is $\phi 25$	1.00	1.00	1.00	-
If Shear reinforcement	1.56	1.56	1.56	-

Table C.2: Costs

Cost of materials	$\rho_{m,Bridgedeck}$	$\rho_{m,Framelegs}$	$\rho_{m,Foundation}$	**Unit**
Formwork with Consistent thickness	500	200	200	SEK/m^2
Formwork with Variable thickness	500	300		SEK/m^2
Concrete class C35/45	1800	1800	1800	SEK/m^3
Reinforcement	9	9	9	SEK/kg

Labor costs	ρ_W	**Unit**
Unit labor cost	500	SEK/h

Table C.3: Environmental Impact of Materials

Material	**eq**$_i$	**Unit**
Concrete class C35/45	0.15	$kgCO_2 - eq/kg$
Reinforcement	0.70	$kgCO_2 - eq/kg$

D Verification of finite element models

The models were verified by checking the total moment from the gravity load of the bridge deck in the models in BRIGADE/PLUS and comparing it with the moment of a cantilever beam.

The 12-meter closed frame bridge.

L = 12.7m (Total length of bridge deck)
g = 25 kN/m^3 (Weight of concrete)
t = 0.95 m (average height of bridge deck)
q = 23.75 kN/m^2 (load from concrete)

Moment from hand calculations
$M_{hand,calc}$ = q · L^2/8 = 478.83kNm

Moment from BRIGADE/PLUS
$M_{support}$ = 178.636 kNm
M_{span} = -291.809 kNm
$M_{support}$-M_{span} = 470.445 kNm

The moments correspond well with each other regarding the 12-meter bridge variant.

The 16-meter open frame bridge.

L = 17.308m (Total length of bridge deck)
g = 25 kN/m^3 (Weight of concrete)
t = 0.95 m (average height of bridge deck)
q = 23.75 kN/m^2 (load from concrete)

Moment from hand calculations
$M_{hand,calc}$ = q · L^2/8 = 889.34 kNm

Moment from BRIGADE/PLUS
$M_{support}$ = 535.776 kNm
M_{span} = -356.83 kNm
$M_{support}$-M_{span} = 892.606 kNm

The moments correspond well with each other regarding the 16-meter bridge variant.

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