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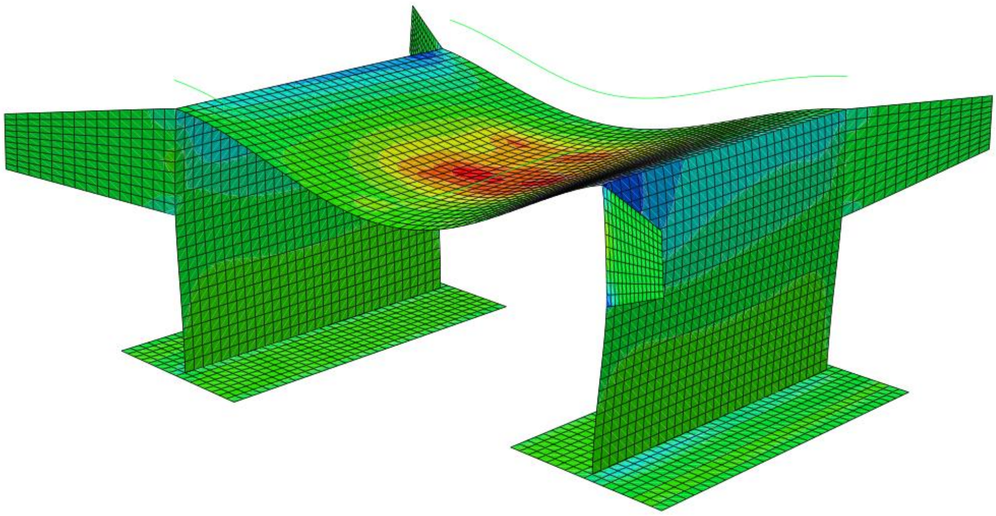

Set-Based Design of Frame Bridges

Development and Implementation

Master's thesis in master's program in Structural Engineering and Building technology

SIMON LÖFGREN

Department of Architecture and Civil Engineering
Division of Structural Engineering
Concrete Structures
CHALMERS UNIVERSITY OF TECHNOLOGY
Master's Thesis ACEX30-2020
Gothenburg, Sweden 2020

MASTER’S THESIS ACEX30-2020-NN

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Cover:
Finite element analyzed frame bridge in Brigade Plus.

Chalmers Reproservice/Department of Architecture and Civil Engineering
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ABSTRACT

The traditional design process of bridges in structural engineering is based on the design approach called Point-Based design. To minimize environmental impact and industrialize the design process, the theory of Set-Based design (SBD) has been recognized as a promising approach. Since frame bridges is one of the most common bridge types in Sweden, the main objective of this thesis is to develop and implement a SBD tool for frame bridges.

To be able to evaluate the different design alternatives generated by the design tool, evaluation criteria within buildability and sustainability are identified. Buildability is a concept within building industry that aims to improve productivity and safety within on-site production while also reducing the costs of the construction process. The building industry is one of the major contributors regarding impact on its surrounding. Therefore, there is a huge potential in improving the sustainability within the building industry. Sustainability is divided in Environment, Social and Economy aspects.

The design tool allows performing an automated and iterative structural preliminary design of several frame bridge alternatives specified within ranges of design parameters. The design alternatives are analyzed with Finite Element Analysis (FEA) and evaluated according to predefined evaluation criteria. By scripting the design tool in programing language Python, it is possible to control an FEA program, such as Brigade Plus, from the design tool as well as performing a preliminary design of frame bridges. The preliminary design is performed according to requirements in national building codes, Eurocode.

Finally, a case study is performed to investigate how a SBD tool can be implemented in an infrastructure project containing several frame bridges. In a large infrastructure project and with a SBD tool it is possible to find one optimum bridge solution that fulfills the need of several bridges in a set of bridges. The contractor can then industrialize parts of the construction of frame bridges, hopefully leading to a more sustainable and cost-effective building of frame bridges.

Key words: Set-Based design, Repeatability, Frame bridges, Preliminary design, Finite Element Analysis, Buildability, Sustainability, Cost-efficiency

Set-Based design av plattrambroar

Designutveckling och optimering

Examensarbete inom mastersprogrammet konstruktionsteknik och byggnadsteknologi

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SAMMANFATTNING

I traditionell brokonstruktion används en designmetod kallad Point-based design. För att minimera påverkan på miljön och kunna industrialisera brobyggandet, har teorin om Set-based design (SBD) lyfts fram som en lovande metod. Eftersom plattrambroar är en av de mest vanliga brotyperna i Sverige, så har huvudmålet med den här avhandlingen varit att utveckla och implementera ett SBD baserat designverktyg för plattrambroar.

För att kunna utvärdera designalternativen genererade av designverktyget identifierades utvärderingskriterier inom byggbarhet och hållbarhet. Byggbarhet är ett koncept inom byggindustrin med målet att öka produktiviteten och säkerheten på byggarbetsplatsen, samtidigt som byggkostnaden minskar. Byggindustrin är en av de sektorer som påverkar sin omgivning mest. Därmed finns det stor potential för att förbättra hållbarheten inom byggindustrin.

Designverktyget gör att en automatiserad och iterativ preliminär design av flertalet broalternativ kan utföras inom en specificerad mängd parametrar. Designalternativen analyseras med Finita Element analys (FEA) och utvärderar alternativen med avseende på de fördefinierade utvärderingskriterierna. Genom att programmera designverktyget i programspråket Python är det möjligt att kontroller ett FEA-program, så som Brigade Plus, inom designverktyget och också utföra preliminär design av plattrambroar. Preliminär designen utförs enligt krav i nationella normer, så som Eurocode.

En fallstudie genomfördes för att undersöka hur ett SBD baserat designverktyg kan implementeras i ett infrastrukturprojekt innehållandes flertalet plattrambroar. I ett stort infrastrukturprojekt och med ett SBD baserat designverktyg, är det möjligt att hitta ett optimalt broalternativ som kan uppfylla kraven för flera broar i en grupp av broar. Entreprenören kan då industrialisera byggandet av delar av byggprocessen av plattrambroar, vilket förhoppningsvis leder till ett mer hållbart och kostnadseffektivt brobyggande av plattrambroar.

Nyckelord: Set-based design, Repeterbarhet, Plattrambroar, Preliminärdesign, Finita Element Analys, Byggbarhet, Hållbarhet, Kostnadseffektivitet

Contents

Preface

This Master's thesis was performed between January and September 2020, at the Division of Structural Engineering, Department of Architecture and Civil Engineering, Chalmers University of Technology and at the structural design group at NCC Sverige AB.

The thesis started as a collaboration between Simon Löfgren and Armel Alibašić but for different reasons Armel decided not to proceed with the project. Nevertheless, Armel's contribution to the thesis have been vital. Thank you, Armel, for the collaboration and the job you have done.

To be able to run the FEA software needed in the project, Scanscot kindly granted licenses to the Brigade Plus software.

The thesis has been carried out with supervisor Jesús Armesto Barros, Structural Engineer at NCC and supervisor Lic. Alexandre Mathern, Doctoral student at Chalmers University of Technology and Structural Engineer at NCC. Ass. Prof. Rasmus Rempling, at Chalmers University of Technology, Division of Structural Engineering has been examiner of the thesis. My profound thanks and appreciation to all of you. Your support has been excellent and the provided knowledge indispensable.

Extra thanks to Jesús, who have put up with my concerns and questions almost daily. You have been an excellent supervisor.

Simon Löfgren

September 16, 2020

Notations

Roman upper case letters

A_s	Area of steel
E_g	Young's modulus of soil
E_{pl}	Young's modulus of foundation slab
V_{Ed}	Design value of applied shear force
$V_{Rd,c}$	Design value of shear resistance of concrete

Roman lower case letters

b	Width
b_{ef}	Effective width
f_{yd}	Design yield strength
k_0	Earth pressure coefficient at rest
k_v	Modulus of subgrade reactions
l	length
m_{rx}	Longitudinal top reinforcement
m'_{rx}	Longitudinal bottom reinforcement
m_{ry}	Transverse top reinforcement
m'_{ry}	Transverse bottom reinforcement
s	Spacing
t	Thickness
v	Support angle
q	Pressure
z	Depth

Greek letters

γ	Weight of soil
φ	Diameter

Abbreviations

FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Method
LC1	Load Case 1
LM1	Load Model 1
PBD	Point-Based Design
SBD	Set-Based Design
SCC	Self Compacting Concrete
SLS	Service Limit State
SM1	Sectional Moment in Local Longitudinal Direction
SM2	Sectional Moment in Local Transverse Direction
SM3	Twisting Moment
SF1	Sectional Force in Local Longitudinal Direction
SF4	Transverse Shear Force in Local Longitudinal Direction
SF5	Transverse Shear Force in Local Transverse Direction
ULS	Ultimate Limit State

1 INTRODUCTION

To deal with the challenges of sustainability and to get a more cost-efficient process in bridge design, optimization and industrialization of the design process is important in the construction industry. Sustainable product development aims at fast and reliable creation of design alternatives able to address the needs of different stakeholders and one of the promising approaches is Set-Based Design (SBD).

The traditional approach in structural design is known as Point-Based Design which is based on single solutions for each step of the creation chain (Tarazona & Luis, 2014). This approach often leads to modifications and setbacks later in the process due to new constraints, which leads to waste of time due to reworking. Thus, alternative design approaches have been developed, such as SBD.

In contrast to Point-Based Design, in SBD the decisions in the design process are not made with a single alternative, instead various alternatives are created by the stake holders and successively filtered based on the limitations and decisions of those who are running the project. Compared to traditional design approach SBD is based on a much wider range of alternatives and reduces the risk of reworking (Tarazona&Luis,2014).

SBD was developed in the mid-1990 when researchers studied the design process at Toyota. It is widely used in the car industry but the implementation in Structural Engineering has been low (Rempling, Mathern, Tarazona Ramos, & Luis Fernández, 2019).

SBD approach has been recognized as an effective method, developed in order to improve the design process by avoiding drawbacks, costly reworking and increase the efficiency in the design process. There have been done several assessments of applicability of the mentioned method in the field of structural engineering. The assessments have shown more optimal design alternatives for already existing structures with a significant cost reduction of the final product and a great potential of application of the design approach in the field of structural engineering.

The project was focused on application of SBD of frame bridges. Frame bridges are the most common bridge type in Sweden. Of all the bridges owned by the Swedish road administration (Trafikverket) 75% have a construction length of 20 m or less, and 46% of these bridges are frame bridges (Uppenberg, Ekström, Liljenroth, & Al-Ayish, 2017). Thus, if a more efficient design process and an industrialized production of frame bridges can be achieved, the building industry will be able to move to a more sustainable and efficient future.

1.1 Purpose and objectives

The purpose of this project is to develop, document and implement a design routine based on SBD of frame bridges that optimizes and leads to a more sustainable structural design process. In order to be able to achieve the purpose of the project and measure the outcoming result the following objectives are defined as guidelines for the work:

- Identify and compile sustainability and buildability evaluation criteria for preliminary design stage according to the specific needs from different stakeholders for evaluation of different design alternatives.

- Develop a script based on SBD approach that enables an automated and iterative structural design of frame bridges. The script should be able to perform Finite Element Analysis and design according to requirements in national building codes.

- Implement the most suitable evaluation criteria in the design script and assess the different design alternatives by these criteria.

1.2 Limitations

Within construction industry, the product, in this case a bridge, is usually developed during the preliminary and detailed design stages. Due to the limited time available this project is focused on the preliminary design stage only. For that, the most common checks from design standards are accounted for based on linear elastic analysis.

For simplicity only one span concrete frame bridges are considered.

2 METHODOLOGY

In order to understand the differences between the traditional design approach and the principles of SBD a literature study of the subject was done. There have been several research reports on the topic. Also, previous master theses that refer to both SBD and structural engineering were studied.

In this project the evaluation of design alternatives was done according to buildability and sustainability criteria. To identify the buildability criteria, a literature review of scientific papers on buildability was performed. To support the findings from literature, interviews were held with two construction site managers, Per Arvidsson and Peter Johansson and one expert in reinforcement, Nicklas Käck from Swedish Construction Company, NCC. Also, an interview with Peter Simonsson from Trafikverket was held on this topic. Identified buildability criteria are compiled in Table 1. In order to identify sustainability criteria an interview was held with Kristine Ek, an expert on life cycle analysis at Chalmers University and NCC. A literature study on the topic Sustainability was also carried out. Sustainability is described in Chapter 3.3.2 and criteria of interest is compiled in Table 2.

The literature review was mainly based on enhancing buildability and sustainability within a civil engineering project in general and not specifically regarding building of bridges. It was done in this way because there is a decently large amount of literature within both buildability's and sustainability's effect on the building industry, but almost none that is specific for bridges. The more general criteria, compiled in Chapter 3.3, are later narrowed to suitable options for frame bridge design in Chapter 5.

Checks regarding standardizations were performed according to Eurocode and local regulations. A study of which checks and demands that are most suitable for a preliminary design of frame bridges was carried out.

In order to analyze a large set of frame bridges in Brigade Plus, a script was written in Python. Owing to this script an automated and iterative structural design could be performed in the finite element program Brigade plus 6.2. How the checks for the preliminary design previously mentioned were best implemented in the script was studied as well.

A short case study off the planed railway project, North Bothnia Line, was carried out. The study was done to investigate how a design tool, based on SBD, can be implemented in a large infrastructure project like North Bothnia Line. In the North Bothnia Line project over 100 bridges are planned to be built. Many of these bridges are frame bridges. This makes the North Bothnia Line project an ideal reference to apply the ideas and results from a SBD tool. The Swedish transport administration (STA) have a vision for the North Bothnia Line project to separate the tendering procedure of contractors for groups of bridges. If contractors then implement SBD and a repeatability in the building of the frame bridges, there is a huge potential in lowering the environmental impact and increasing the profit.

The case study was also the basis when considering the input parameters in the design tool. Span length, widths, foundation types, type of loading are all parameters in the design tool, that was considered and refined with the North Bothnia Line case in mind.

Trying to find one set of parameters that in the most optimal way can fulfill evaluation criteria, as best as possible, for several bridges in the case. Therefore, and on the basis of SBD, a large dataset of different design alternatives were generated from the design tool. A final study was done to try to find parameters in the dataset that influence a certain result the most. This was done with help from an algorithm implemented in the programming language R.

3 THEORY

In this chapter the theory behind Point-Based and SBD will be described. Also, some theory about frame bridges and the evaluation criteria buildability and sustainability will be presented.

3.1 Design approaches

In the following chapter, the traditional design approach and SBD are described and illustrated.

3.1.1 Point-Based Design

In order to better understand the SBD approach we need to take a closer look at the traditional design process.

The conventional and widely used product development methodology followed among structural designers is the so called "Point-Based Design" approach. This is a linear design process consisting of several steps or points. At each step of the creation chain designers consider many alternative solutions to the identified problem. The alternatives are then analyzed and evaluated according to the specific criteria and available information until the best solution is found for that single step. If the solution is not feasible in order to move to the next step, the iteration process begins by re-working and refining that single design until a satisfactory and feasible solution is found, see Figure 1 (Liker, Durward, Sobek, Ward, & Cristiano, 1996).

However, this is a very simplified explanation of the process. Unfortunately, the world isn't linear and is often more complex. During the design process there will always be feedback loops. They usually tend to come later in the process often after solutions for previous steps in the design process already have been decided (Sobek, Ward, & Liker, 1999). If a new constraint, a customer requirement or critique from downstream design steps is added, the design may progress thru man iterations in order to reach the final goal. Those iterations in turn can force reconsideration of earlier decisions, sometimes moving you all the way back to the starting point causing a lot of rework, delay and increased cost.

Traditional design practice tends to quickly converge to a solution in each step of the design process without considering the needs or taking into account the experience and expertise of different stakeholders involved in the project. For instance, the designer in the first step may have found the best solution for that single step but is not necessary the optimal design in other aspects such as production, cost or maintenance (Parrish, Wong, Tommelein, & Stojadinovic, 2007).

3.1.2 Set-Based Design

Set-based concurrent engineering or "second Toyota paradox" (Sobek et al., 1999) was introduced when researchers studied product design and development process at Toyota. At first, the process looks very clumsy and inefficient but resulted in a more effective overall product development. Unlike other manufacturers, Toyota considered a much broader range of design solutions and delayed the decisions as long as possible, yet they had the most efficient and fastest product development cycles (Sobek et al., 1999).

Compared to traditional Point-Based Design approach, Set-Based Design (SBD) is representing another way of product design and development process. SBD is a design approach where designers think and reason about sets of design alternatives (Raudberget, 2011).

In SBD the process, like in traditional approach, starts with creating and considering a wide set of different design alternatives. In contrast to Point-Based Design, the designer's reason about, communicate and improve the sets of possible design solutions in parallel. The set of possible solutions are then gradually narrowed by eliminating infeasible and weaker alternatives based on information from analysis, research, development, testing, customer or another participant. While design progress they get new information for remaining alternatives. The process continues until the set of possible design alternatives converges to a final solution (Liker et al., 1996), see Figure 1.

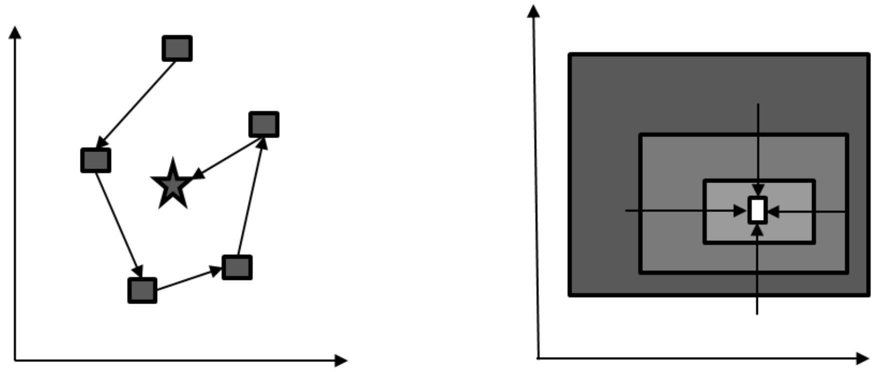

Figure 1 Point-Based vs Set-Based Design process (Tarazona & Luis, 2014)

SBD assumes that by communicating and reasoning about sets of different design alternatives it will lead to more robust, optimized design solutions and a more efficient design process (Sobek et al., 1999). Some authors claim that SBD to be four times more productive than traditional methods (Raudberget, 2011). By applying the principals of SBD all negative iterations and back-tracking can dramatically be reduced in the design process (Sobek et al., 1999).

The three main principles of SBD as described in (Sobek et al., 1999):

1. Map the design space
   - Define feasible regions
   - Explore trade-offs by designing multiple alternatives
   - Communicate sets of possibilities

2. Integrate by intersection
   - Look for intersections of feasible sets
   - Impose minimum constraint
   - Seek conceptual robustness

3. Establish feasibility before commitment
    - Narrow sets gradually while increasing detail
    - Stay within sets once committed
    - Control by managing uncertainty at process gates

SBD is said to have many benefits compared to traditional design approach (Ballard, 2000). Some of the most important ones are:

- SBD enables trustworthy and efficient communication among designers avoiding reconsideration of earlier taken decisions and iteration in design process.
- Allows for a much greater parallelism in the process, with more effective use of sub teams early in the process.
- Allows the most critical decisions to be based on data.
- Promotes institutional learning.
- Considerably reduces the time wasted on design alternatives that are not feasible to be built.
- Allows decisions to be delayed and design options to remain open until sufficient knowledge of perspectives exists (Raudberget, 2011).
- Eliminates unnecessary meetings and reduces the length of the needed ones.

3.2 Frame bridge

Different bridge types can be classified in many different ways. For example, by the type of traffic on the bridge or by the type of material of construction. When considering the structural behavior of the bridge, two of the most common bridge types are slab and beam bridges. The slab and beam bridge are called frame bridges if the slab or the beams are restrainedly connected to the end supports(frame leg) and if the reinforcement is continuous over the exterior upper frame corners (Vägverket, 1996).

The frame bridge can be constructed either in one or several spans, however one span frame bridges are more common. It is generally economical in spans up to 25 m without prestressing and up to 35 m with prestressed concrete (Vägverket, 1996).

A bridge superstructure is the part of the bridge that is constructed to take the direct load from traffic. For frame bridges the superstructure consists of the bridge deck, see Figure 2. The bridge deck is usually done as a homogeneous slab. To reduce the slabs self-weight and the material consumption the slab can be designed with ducts. (Trafikverket, 2020)

The bridge deck transfers the loads down to the substructure that consists of the frame legs and base slab. The substructure then transfers the loads down to load carrying soil (Bergström & Bodin, 2011).

According to recommendations from the STA the height of the frame legs should be more than 25 % of the span length if the frame bridge is constructed without prestressed concrete. To avoid uneven stresses in the different frame legs and its base slab, the two frame legs should be approximately of the same height (Vägverket, 1996).

Regarding the thickness of the frame legs, they are usually constructed with a uniform thickness if the need of thickness is maximum 0,6 m. Sometimes a thickness larger than 0,6 m is required close to the bridge deck, then the frame legs can be designed thinner at the base slab.

Usually frame bridges also consists of wing wall and haunches, see Figure 2. The haunches are the slabs thickening that are placed at the slabs supports. The haunch helps to transfer the shear force and moment to the frame leg. For shorter spans, less than 12 m, there is enough to put a smaller haunch where the bridge deck meets the frame leg. For spans between 12-20 meters STA recommends a haunch that is approximately 20% of the span length. If the span is longer than 20 m the haunch often extends over the whole span length in a parabolic shape.

The wing walls are fixed to the frame leg and can be constructed either parallel to the bridge deck or inclined. If the wing wall is parallel to the road it is required that the wing wall overlaps the embankment at a length of at least 0,5 m. Wing walls are mainly designed to resist the earth pressure and self-weight (Ekman & Sandin, 2018).

For fastening of railings, edge beams are constructed. The edge beam is usually constructed only for this purpose and are therefore a non-load carrying element (Trafikverket, 2020).

The base slab of a frame bridge is usually constructed as two separate slabs connected to each frame leg. If the frame bridge is constructed on soil with low load bearing capacity, as clay, some frame bridges are constructed with a single base slab. In this case the span length should not exceed 12 m due to the extra stresses in the slab (Vägverket, 1996).

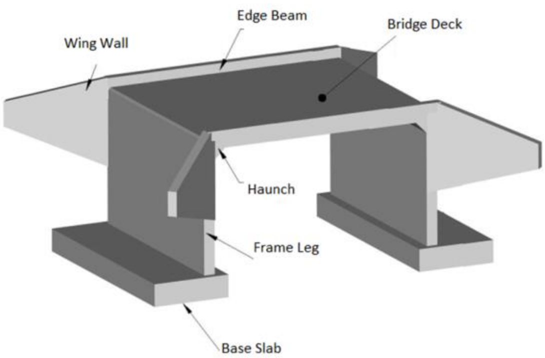

Figure 2 Different parts of a frame bridge (Vägverket, 1996)

3.2.1 Skewed angled frame bridge

When a bridge is built to cross another road and these two roads do not cross perpendicular to each outer, the bridge might be constructed with a skewed angle. This is often the case in Sweden, where the requirements for road alignments is stricter compared to many other countries.

It is complicated to construct a frame bridge with skewed angle, both regarding to design and building of the frame bridge. Constructing a skewed angled frame bridge often leads to much larger frame legs and higher amount of reinforcement.

The economical cost and complexity are higher when constructing a frame bridge with skewed angle. However, the alternative of straightening out the alignment of the connecting road, has often an even higher cost than constructing the bridge with skewed angle (Vägverket, 1996). Another alternative, if the bridge deck width is rather small, is to make the span longer. This will also increase the cost of the bridge though.

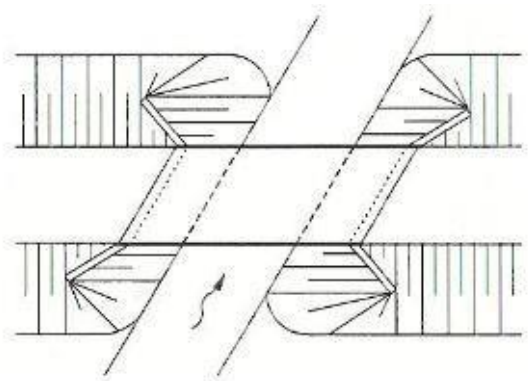

Figure 3 Frame bridge with skewed angle (Vägverket, 1996)

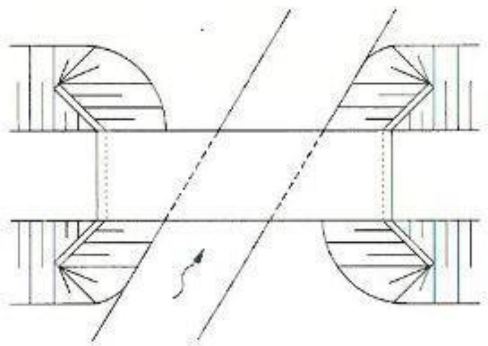

Figure 4 Perpendicular frame bridge with longer span (Vägverket, 1996)

If the bridge is constructed without a separate abutment, some of the soil pressure from the embankment needs to be transferred through the superstructure. This causes a moment that needs to be transferred down to the foundation, causing an uneven pressure on the foundation if the bridge at the same time is constructed with a skewed angle. The problem gets particularly severe if the foundation is done with piles or slab on soil with low bearing capacity. (Vägverket, 1996)

STA gives some recommendations for the size of the support angle if the frame bridge should be constructed with a skewed angle. In case of good soil conditions, the support angle should not be below 50 degrees, and with poor soil conditions not be below 75 degrees.
Also, the frame bridge should be designed so that the dimensions of “a”, in Figure 5, is bigger than 0.3·b (Vägverket, 1996).

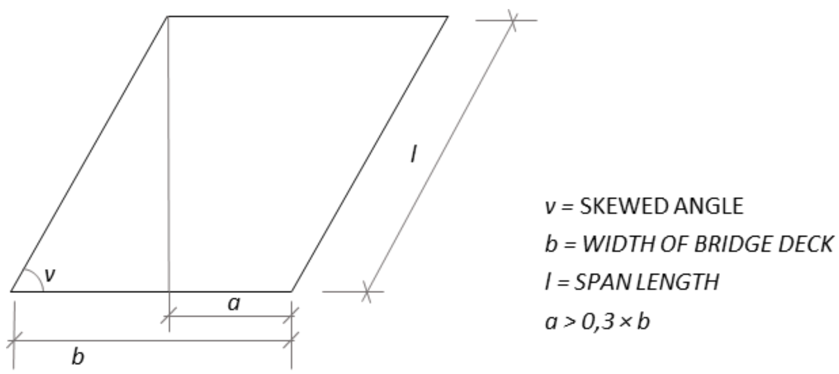

Figure 5 Support angel (Vägverket, 1996)

3.3 Evaluation criteria

In the following chapter, the two criteria buildability and sustainability are described. Based on literature review and interviews with researchers and individuals working in building production, buildability and sustainability criteria were identified and compiled in Table 1 and Table 2.

3.3.1 Buildability

In literature there are many definitions of buildability and its closely related term constructability. Both concepts have a similar goal, they both aim to improve productivity and safety of on-site production while at the same time reducing the costs of the construction process (Simonsson, 2011). The term buildability was first defined by CIRIA (Construction Industry Research Information Association) in UK and is defined as:

> *The extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building (CIRIA, 1983).*

The term constructability was first presented by CII (Construction Industry Institute), based in USA and is defined as:

> *The optimum use of construction knowledge and experience in planning, design, procurement and field operations to achieve overall project objectives (CII, 1986)*

From the definitions of the two terms it is clear that the responsibility of incorporating the buildability into the design relies on the design teams (Lam, Wong, & Chan, 2006). This statement coincide with the result from a questionnaire survey done by Simonsson (2011a) where the result indicates that the contractor only partly can improve the buildability while client and designers have the highest possibility to improve buildability. Constructability on other hand emphasize on management across all stages of the construction process (Lam et al., 2006). This thesis concerns implementation of buildability early on in the design process and how SBD and an industrialized production of frame bridges influence and facilitate on the ease of construction. Further on the term buildability will be used.

Buildability is by simple words all actions taken in early design phase in order to enhance and facilitate an easy, more efficient and safe on-site production. Possibility to improve the buildability is larger in early stages of the project and decreases with time as the project develops and decisions become more important (Gavrell, 2018). Ignoring to consider buildability early on in the project may imply more complicated production methods and design details that will lead to a less efficient on site production (Simonsson, 2011).

Likewise, the definition of buildability in literature there are a broad range of factors that affect buildability. The main issue is how to identify and quantify the most important ones. By performing a questionnaire survey, Wong et al. (2006) identified 63 attributes of designs from which they derived nine key buildability factors. The questionnaire was performed for building designs and are not directly applicable on civil engineering projects but can be used in order to give designers a better understanding of factors that affect the buildability of their outputs.

Simonsson (2011a) performed a questionnaire survey targeting different stakeholders within the Swedish civil engineering construction industry in order to collect their opinions on factors affecting buildability and to identify hindrances and opportunities of buildability for a civil engineering project. Among the participants where contractors, consultants and the major public client in Sweden, STA. The survey showed that out of 18 factors the top five factors affecting buildability of civil engineering projects in Sweden are:

- Early involvement of contractor
- Workplace organization
- Available space on construction site
- Production planning
- Prefabrication of reinforcement

Furthermore, based on the timeline of a typical STA civil engineering project (Simonsson, 2011) identified the most influential buildability factors that relate to "Design for ease of construction".

- Production method
- Work descriptions
- Communication
- Standardization
- Working environment

Related to above mentioned buildability factors, Peter Simonsson described and demonstrated several examples that improve the buildability in a civil engineering project and that can directly be considered in the design phase, (Simonsson, 2011).

Reinforcement plays a significant part in concrete structures. Reocurrence of reinforcement bars, dimension of reinforcement bars, general placement of main reinforcement bars, distance between bars and geometrical shape of bars are factors identified to affect buildability of concrete structures (Gavrell, 2018).

By introducing and considering buildability early on in the design phase many, benefits can be achieved. By implementing new production methods, the productivity on site will be increased which implies more cost-effective production. Safety and working environment can significantly be improved and the overall quality of the project increased (Simonsson, 2011).

Buildability entails many factors. Table 1 represent some of the most important ones identified and compiled based on literature review and interviews.

Table 1 Identified factors in enhancing buildability of a civil engineering project. Adopted from (Simonsson, 2011), (Gavrell, 2018) and interviews

No.	Buildability criteria
BF1	**EARLY INVOLVEMENT OF CONTRACTOR**
BF2	**WORKPLACE ORGANISATION (5S)**
BF3	**AVAILABLE SPACE ON CONSTRUCTION SITE**
BF4	**PRODUCTION PLANNING**
BF5	**PRODUCTION METHODS**
	Prefabrication of reinforcement
	Rebar carpets
	Rebar cages
	Use G shaped shear reinforcement
	Recurrence of reinforcement bars (use stock lengths and dimensions)
	Dimensions of reinforcement bars (max 20-25 mm)
	General placement of main reinforcement bars
	Distance between bars (max 200-250 mm)
	Geometric shape of bars (Use straight bars)
	SCC (Self Compacting Concrete)
	Left or re-use concrete form systems
BF6	**WORK DESCRIPTIONS**
	Develop conceptual 3D BIM models and virtual work descriptions
BF7	**COMMUNICATION**
BF8	**STANDARDIZATION**
	Group bridge types during tender and not due to geographical areas.
	Standardize base slab, bridge deck, frame legs and wing walls.
	Standardize the cross-sectional dimensions.
BF9	**WORKING ENVIRONMENT**
	All production methods enhance working environment.
	BIM (Building Information Models)
BF10	**DESIGN OF STRUCTURES**
	Design bridges according to Figure 3 or 90 degrees against railway.
	Design straight bridges without curvatures.
	Design base slab, frame legs and bridge deck without angels and inclinations.
	Lift up the bottom of the edge beams for easier formwork.
	Avoid haunches if possible for easier formwork.
	If possible, design wing walls in line with frame legs.

3.3.2 Sustainability

Building industry is one of the major contributors regarding impact on its surrounding and environment. The industry stands for approximately 10% of Sweden's BNP and civil engineering projects stands for approximately 60 % of the building industry total emissions. While the building industry in total stands for around 19 % of Sweden's total emission of greenhouse gasses (Boverket, 2020). With regard to those facts there is a huge potential identified in order to improve the three pillars of sustainability, environment, social and economy (Brinkhoff, 2015).

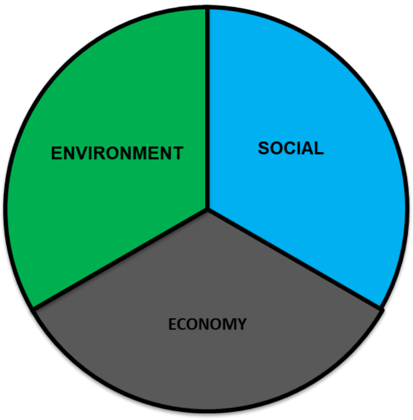

Figure 1 The three pillars of sustainability

Assessment of sustainability performance of civil engineering projects is of vital role in order to decrease the negative impacts of the industry. With focus on sustainability and use of proper assessment methods the negative impacts can remarkably be improved. Likewise buildability the possibility to improve the sustainability is larger early on in the design process and decreases with time as the project develops (Brinkhoff, 2015).

CEEQUAL- a British certification system for civil engineering projects is one system for sustainability assessment of civil engineering projects. Another tool used and developed by the Swedish Traffic Administrator Trafikverket together with other national road administrators in Europe is SUNRA (Sustainability-National Roads Administration). Based on CEEQUAL:s manual version 5.1 (Brinkhoff, 2015) identified and compiled key criteria together with sustainability criteria from SUNRA. Those criteria can be used in a multi criteria analysis in order to assess different design alternatives or as a check list for what needs to be considered or optimized in a project.

EPDs (Environmental Product Declarations) are open source declarations provided from material manufacturers. From EPDs several quantitative sustainability criteria can be identified. EPDs classify life cycle stages in so-called modules. Only one criteria from each of the two dimensions Environment and Social is specified in Table 2, Global warming potential total (GWP-total) and Human toxicity, cancer effects (HTP c).

Since the construction industry is one of the major impactors not only on environment but also on economy and social aspects, there is great potential in improving the sustainability in civil engineering projects.

Table 2 Concluded sustainability criteria. Adopted from (Brinkhoff, 2015), SUNRA and EPDs.

Criteria
Economy
Design and planning cost
Material cost
Production cost
Operation and maintenance cost
Deconstruction and restoration cost
Recycling cost
Environmental cost
Social
Health and safety of workers
Sound and vibrations
Human toxicity, cancer effects (HTP c)
Environment
Global warming potential total (GWP-total)
Waste
Resource strategy and usage
Excavation of new material
Reuse of materials and products
Materials and components with long life time
Limited climate impact
Trafic emissions
Construction Machinery emissions
Material usage
Transportation of materials
Energy efficiency

4 DESIGN TOOL

To be able to develop a design routine that enables an automated and iterative structural design and perform Finite Element Analysis (FEA), a script that can control a FEA software was developed. The FEA software used in the project was Brigade Plus 6.2, a FEA program based on Abaqus that includes the capability of applying moving traffic loads into the structures modelled. Since this software is based on the programming language Python, the script was written in this language.

In this chapter the structure and content of the script will be presented and how the preliminary design and evaluation criteria are implemented.

4.1 Building of the script

By the means of SBD a large number of bridge geometries were generated by the script. One by one, these alternatives were checked against demands in Eurocode and weighted against the predefined evaluation criteria.

The script is built up by several defined functions. Within every function the script performs a specific task and then returns the needed information to the next function. As example, a function can be responsible for meshing of the bridge module, calculating need of reinforcement or collecting the needed input data from the user. To get the mesh-section running for example, the function needs to input certain results or variables from previous functions, as the geometry of the bridge. When the task within the mesh function is done, it returns the result to the next upcoming function.

By dividing the script in these functions, the script gets easier to survey. It is also easier to find and fix errors and to improve it and add more checks or capabilities in the future.

In Figure 6, a flow chart of how the script is structured is presented. At first the user needs to input the prerequisites. This is mainly the range of geometry dimensions, as which span lengths, frame leg heights or skewed angles that should be included. But also, different foundation conditions and material options as concrete and steel classes needs to be specified.

The script then combines all these alternatives into a list of variables. Every unique combination of these variables becomes one unique frame bridge model. After building of the model, an FEA analysis in Brigade is performed. When the analysis is done, the script collects required output data from Brigade, such as sectional forces, and uses these to calculate the need of bending and shear reinforcement. The requirements on maximal deflection is checked, and at last the predefined evaluation criteria are then quantified for the model.

All these actions are performed in a loop for each unique bridge until the last bridge is complete. Then all needed data from all bridges are extracted and written to a separate results document.

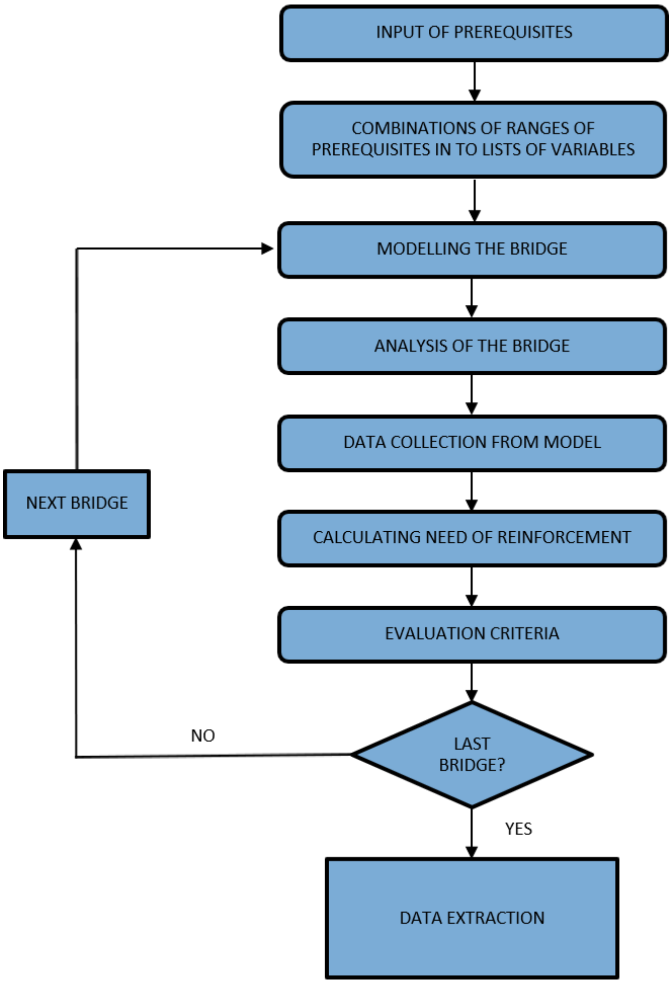

Figure 6 Flow chart of how the script is structured

4.2 Elements and geometry of the model

To model the frame bridge, shell elements are used for the bridge deck, frame legs, foundation slab and wing walls. The edge beam is modelled with beam elements.

The bridge deck is first established in the model. The frame legs and wing walls are then sketched, placed in the right position by creating datum planes, and added to the model as "planar shells" on to the datum planes. By doing this, the frame legs and wing walls are geometrically connected to the bridge deck, and thus also automatically mechanically connected in the FE-model.

The foundation slabs are created as separately parts and connected to the frame legs with tie constraints. The beam elements for the edge beams are also connected with tie constraints to the bridge deck.

4.3 Connection between the bridge and the soil

Due to the non-linear properties of soil, modeling of the connection between the structure and the soil can be difficult. Structure elements are often modeled with linearly elastic, homogenous and isotropic material behavior in an acceptable way.

However, modeling of soil behavior often requires consideration of the heterogeneous and anisotropic material behavior.

David, Krishnamoorthy and Mohamed Jais (David, Krishnamoorthy, & Mohamed Jais, 2015) highlight the biggest concerns for geotechnical analyses when modeling of soil structure interaction. First, is to state an appropriate constitutive model that can describe the material behavior and material parameters, as Mohr-Coulomb model. Then choosing how to couple the structural elements with the soil. Also, to consider the modelling of special boundary conditions and time dependent processes as consolidation and creep is mentioned.

For simplicity, no consideration of investigating an appropriate constitutive model or time dependent effects on soil material was taken in this project. Only tabulated material properties were used in order to create a model to couple the structural elements with the soil.

As seen in Figure 7, the connection between the bridge and the soil was modelled as springs connected to the foundation slab. At first the two base slabs are partitioned in steps of 0.5 m in both longitudinal and transverse direction. In the corners of every quadratic partition the spring connections were applied, see Figure 8.

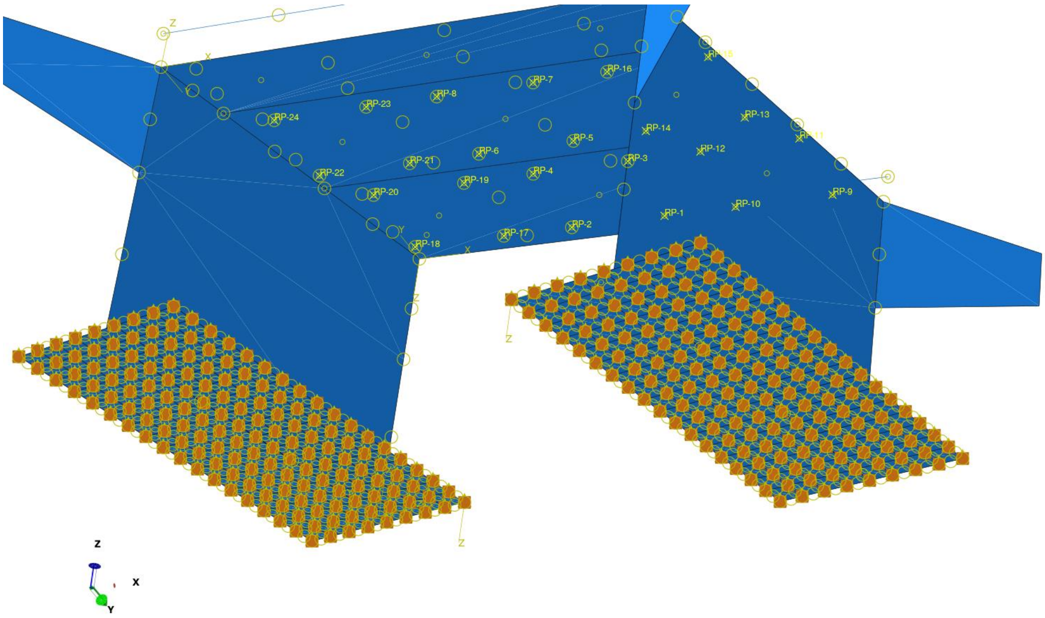

Figure 7 Spring connections between soil and base slab.

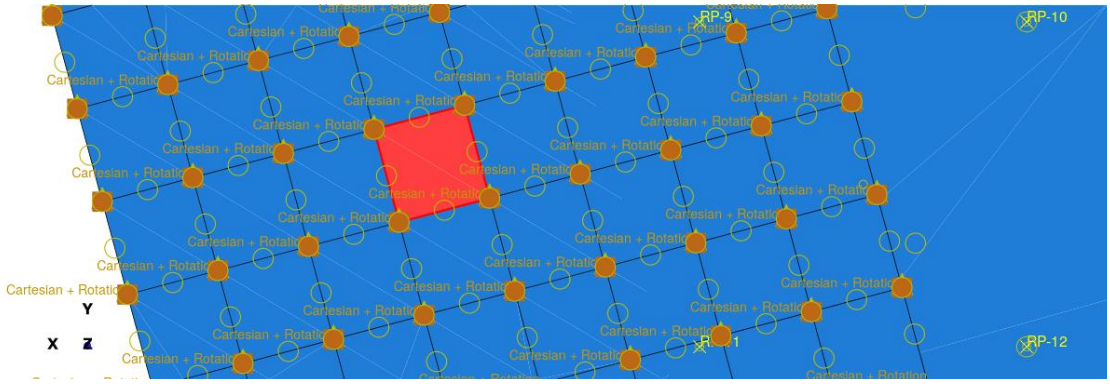

Figure 8 Partition of base slab and placement of springs at the partition's boundaries.

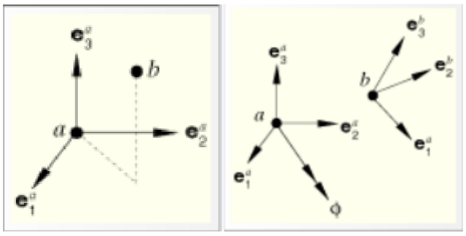

Figure 9 Cartesian connection translator type and rotational type

The connections were modeled as uncoupled linear elastic, with a Cartesian translation type, see Figure 9. In all three translation directions U1, U2, and U3 the connection elasticity is set to a spring stiffness. The spring stiffness is calculated from the modulus of subgrade reactions k_v, see Equation 1. The spring stiffness is then obtained by multiplying the modulus of subgrade reactions with the partition area to that spring, see colored area in Figure 8.

k_v depends on Young's modulus of the soil, E_g, and the Young's modulus of the foundation slab, E_{pl}.

$$k_v \approx \frac{1{,}3 \times E_g}{\frac{E_g}{E_{pl}}^{1/3}}$$

Equation 1

Equation 1 is a way of estimate the modulus of subgrade reactions k_v, by Anders Losberg (Ekström, 2017). Where E_g is Young's modulus of the soil and E_{pl} Young's modulus of the foundation slab. In this way it is possible to module the connection between the frame bridge and the soil just by stating Young's modulus of the soil and the foundation slab. E_{pl} is dependent on which type of concrete that was entered to the script, and $E_g$is dependent on which foundation type entered. From a journal article by Malkowski, Ostrsowski and Brodny the values for E_g was retrieved (Małkowski, Ostrowski, & Brodny, 2018).

4.4 **Preliminary design of frame bridges**

The structural design process of structural members aims to fulfil all the requirements that are set in the ultimate limit state and the serviceability limit state by Eurocode. By choosing dimensions and properties of concrete and reinforcement these requirements can often be satisfied in a variety of ways. During the design process it is important to even consider other aspects as environmental impact, economy and buildability.

According to the methodology for this project, the design phase will focus on predesign of frame bridges. The following chapters will specify the demands for design of the different structural parts of frame bridges and how this is done in the script. Demands from Eurocode as well as recommendations from STA experienced structural engineers will be presented.

4.5 **Loads**

In structural design, the loads acting on the structure, are divided in permanent and variable loads. Since this project is focused on preliminary design of frame bridges, only the most important loads are included. Loads as wind loads, snow load and fatigue loading are not included in the model. The influence of these loads was analyzed through the process and it was seen that their participation in the final results were low. However, these loads need to be accounted for in a final design process.

4.5.1 Permanent loads

Permanent loads in the model are self-weight and earth pressure load from the embankment. The self-weight is applied on the model by defining a gravity load.

The earth pressure load is defined as a hydrostatic pressure acting on the outer side of the frame legs and on the wing walls. The weight of the surrounding soil is set to $\gamma = 18\frac{kN}{m^2}$ and the earth pressure coefficient at rest $k_0 = 0.34$. The pressure at each side of the frame legs are calculated as $q = \gamma \cdot k_0 \cdot \Delta z$, where Δz is the varying depth of soil. i.e.

4.5.2 Variable loads

The variable loads implemented firstly in the model are temperature loads and traffic loads. A minimum and maximum temperature load are defined, as well as two gradient temperature loads. However, these loads were not considered in the end due to their low effect on the results, as seen in chapter 4.6.1

In Eurocode 1 several load models for vertical traffic loads are defined. In this project only "Load Model 1" was used. This load model was considered to be the most appropriate choice for a preliminary design of frame bridges. Eurocode states that Load Model 1 should be used for general and local verifications and that the model covers most of the effects of the traffic of lorries and cars.

Load Model 1 consist of two different parts, one for concentrated loads and one for uniformly distributed loads. The part for concentrated loads is called Tandem System (TS), which is a double-axle concentrated load system. In Table 3 values for the tandem system and for the uniformly distributed loads can be seen.

Table 3. Characteristic values for Load Model 1 in Eurocode

Load Modul 1		
Location	Tandem system	Distributed load
	Axle loads Qlk (kN)	qlk(qrk) kN/m^2
Lane Number 1	300	9
Lane Number 2	200	2,5
Lane Number 3	100	2,5
Other Lanes	0	2,5
Remaining area	0	2,5

These loads are placed in different combinations, trying to find the worst placement on the bridge. The loads are placed in different distribution lanes, illustrated in Figure 10, and with the Axle loads either placed at the middle of the bridge deck or close to the frame legs.

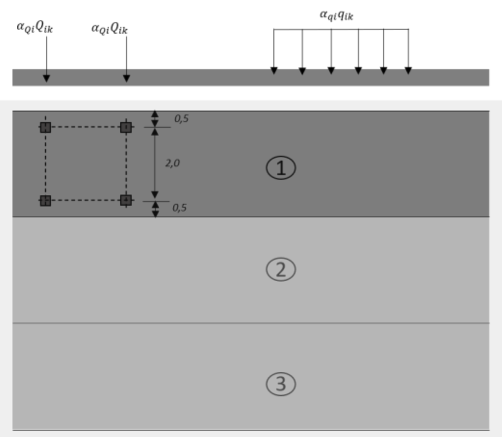

Figure 10 Application of Load Model 1 according to Eurocode

4.6 **Load combinations**

The different loads, defined in the model, need to be combined in all combinations in which it is likely that they can appear. Five different load cases from the Load Model 1 together with self-weight, earth pressure loads, and the temperature loads yielded in a total of 320 different load combinations.

However, since the objective of the script is to compare a large amount of bridges in preliminary design, a number of load combinations needed might be able to be reduced in order to save computational time. To investigate this, two separate studies were done. First one, a comparison of load actions, studied if the number of load combinations needed might be able to be reduced if the impact from some loads is shown to be small in relation to other loads.

Also, the design values of actions in ULS were studied in chapter 4.6.2.

4.6.1 Comparison of load actions

A study was done to investigate the range of impact the different loads contributed in relation to one another. The variable loads from traffic and the permanent self-weight were assumed to have such a large impact that they could not be neglected. Also, earth pressure from the embankment was assumed to play such a large role to resemble the behavior from a frame bridge, that it could not be neglected. However, the four different temperature loads were studied to investigate how large the impact from these loads are in comparison to the other loads.

For this purpose, a bridge model with dimensions of 16 m span, 7.5 m width and a height of 6 m was studied. This represents the most common dimensions for the studied bridges of the case study. The different loads were applied separately on this model and its impact where studied in relation to the other loads.

Data from the model was collected in a path, with 40 data points evenly distributed along the middle of the bridge deck. Since the sectional moment in the local longitudinal direction (SM1) is the driving force to produce the longitudinal reinforcement in the slab, this variable was extracted for all loads. Also, the normal force (SF1) in the slab was studied due to the large impact from temperature variations in concrete.

Looking at the sectional moment, SM1, the effects from the traffic load case (LC2) was significantly larger than from the temperature loads, see Figure 11. The sectional moment in every data point along the slab from the temperature loads, temp_low and temp_high, is fluctuating around just 1% and 2% of the sectional moment from the traffic load case. The difference is slightly larger for the gradient temperatures, but still as low as around 5% of the sectional moment from LC2.

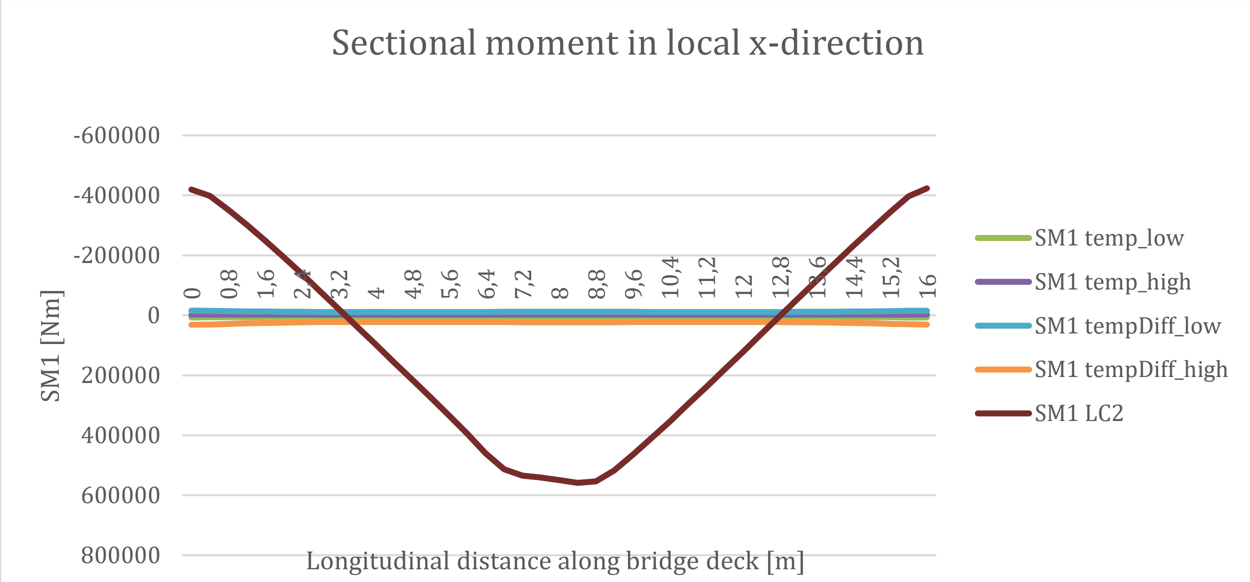

Figure 11, Sectional moment diagram in mid path of bridge deck

Regarding the impact of the normal force, SF1, the temperature does have a bigger impact on the structure than for the longitudinal sectional moment. As seen in Figure 12 the traffic load case, LC2, still yields the largest normal force in every section of the slab, but for especially the negative temperature load, temp_low, the normal force is roughly over 30% of the normal force from LC2 in some sections of the slab. However, this normal force from temp_low is in compression and has a favorable effect for the bending moment. The normal forces from the positive temperature and the gradient positive temperature loads are in tension, but the magnitude is smaller than 20 kN at its largest sections of the slab. Taking this magnitude into consideration and calculating the preliminary need of reinforcement bars for 20 kN, it gives a necessity of φ16 rebars with a separation of roughly 4 m. For a bridge deck of around 7.5 m width, it will maximum need two reinforcement bars of φ16. A neglectable number of bars in this context.

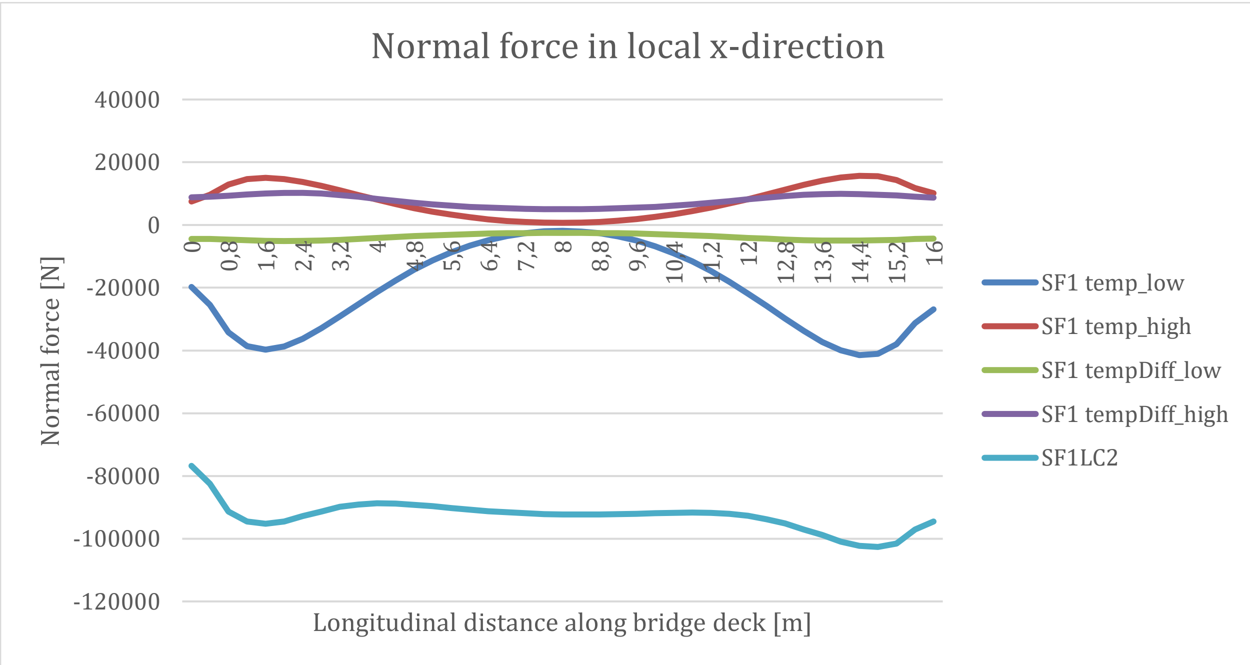

Figure 12, Normal force distribution along bridge deck

When taking the small impact on both the sectional moment and the normal force into consideration, it is safe to say that all temperature loads can be neglected in the load combinations for the preliminary design stage.

4.6.2 Comparison of expression 6.10a and 6.10b

The design values for the loads are chosen regarding to the Swedish national annex, TSFS 2018:57, of Eurocode SS-EN-1990.

The expressions 6.10a and 6.10b in TSFS 2018:57 should both be used in load combinations. Both expressions 6.10a and 6.10b were studied in a comparison in the same way as in chapter 4.6.1, with the same reference bridge of 16 m span, 7,5 m width and 6 m height. The comparison was carried out with the same data points in the same path of the bridge deck as in chapter 4.6.1. The load combination for the sectional moments, SM1, for the permanent loads self-weight and earth-pressure and the leading variable load of the traffic load case, LC2, was carried out with the design values for both 6.10a and 6.10b. The values in every point in the path are plotted in Figure 13.

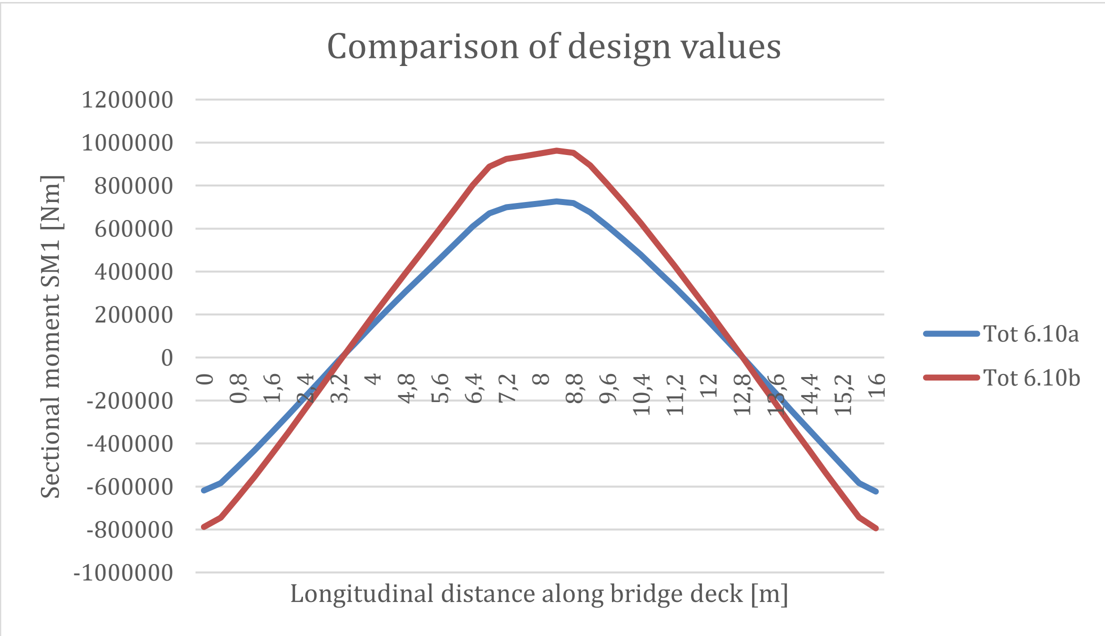

Figure 13. Comparison of design values of expressions 6.10a and 6.10b

The comparison shows that the final design values for the load were around 30% higher in every point of the bridge deck for the expression 6.10b. It will then be safe to only use the expression 6.10b in the load combinations of ULS, and then reduce the number of needed load combinations to half.

4.6.3 Load combinations used in the study

With temperature loads and expression 6.10a neglected, a final set of load combinations was created, see Figure 14. This yielded 10 different load combinations for each bridge model, which helped on saving computer time allowing to compare a bigger set of data faster.

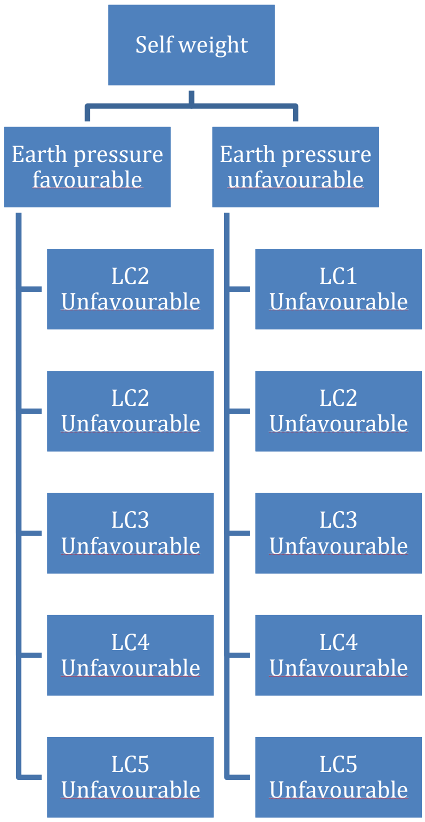

Figure 14 Final set of load combinations

4.7 Bending reinforcement

The needed resisting moments and design conditions, for both the bridge deck and the frame legs, were calculated according to Björn Engström (Engström, 2011). Longitudinal and transverse top and bottom reinforcement were calculated as follow:

$$m_{ry} = m_y + |m_{xy}| \qquad m'_{ry} = m'_y + |m_{xy}|$$
$$m_{rx} = m_x + |m_{xy}| \qquad m'_{rx} = m'_x + |m_{xy}|$$

With design condition:

$$m_r \leq f_{yd} A_s z$$

$$A_s \geq \frac{m_r}{f_{yd} z}$$

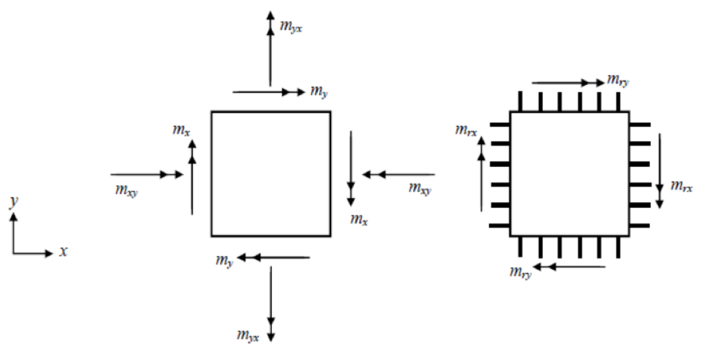

Figure 15 Definition of reinforcement moments. From (Engström, 2011)

The resisting moments are determined from the sectional forces obtained from analysis in the script. The sectional longitudinal moment SM1 from the analysis, corresponds to m_x or m'_x. If SM1 is positive, the longitudinal bottom reinforcement m_{rx} is calculated as SM1 + SM3, where SM3 is the twisting moment, corresponding to $|m_{xy}|$. If SM1 is negative, the longitudinal top reinforcement m'_{rx} is calculated as SM1 + SM3.

The transverse top and bottom reinforcement are calculated in the same way, but with SM2 instead of SM1 obtained from the analysis.

The calculated reinforcement moments are then distributed in transverse direction of the slab. The distribution width for the reinforcement moment was chosen to 20% of the span length, closest to the upper and lower sides of the slab, and to 60% of the span length in mid strip of the slab. These widths are an estimation, that was made after consultation with former bridge designers. Eurocode gives no guidelines or recommendations in how to distribute the reinforcement moment. However, Plos, Pacoste and Johansson (2016) states that for slabs, the distribution widths only have minor influence on the response in ULS.

In nodes, were the calculated reinforcement area A_s were less than the minimum reinforcement, the reinforcement area was set to the minimum reinforcement. Minimum reinforcement was calculated according to Eurocode 2.

4.8 Shear reinforcement

The check, if and where shear reinforcement is required, were done according to EN-1992-1 6.2.2. The design value for shear resistance of concrete, $V_{Rd,\,c}$, were compared to the design value of the applied shear force, V_{Ed}. In regions of the slab or frame legs where $V_{Ed} \leq V_{Rd,c}$, no shear reinforcement is needed. If $V_{Ed} > V_{Rd,c}$, sufficient shear reinforcement was provided according to EN-1992-1 6.2.3.

The definition of the design value of the applied shear force, V_{Ed}, in the script, were done according to (Plos et al., 2016)

$$V_{Ed,i} = \sqrt{SF4_i^{\,2} + SF5_i^{\,2}}$$

Where $SF4_i$ and $SF5_i$ are the transverse shear force per unit width in local x and y direction in every section point *i*.

4.8.1 Shear capacity in bridge deck slab

When designing a bridge deck slab with regard to shear force capacity, the point loads from the traffic often generates high peaks of shear force close to the point loads. In order to not over design the shear reinforcement, these peaks of shear force can be spread in the slab. This chapter declares how this was taken care of in the design tool.

Firstly, SF4 and SF5 were retrieved in two longitudinal paths along the bridge deck slab. One path in middle of the slab and one path close to the slab edge, both paths positioned right under the point loads. At section points of every 0.5 m transverse paths were then established. In every transverse path, the shear force for the section point, was spread transverse according to Boverket (2004) section 6.5.4.

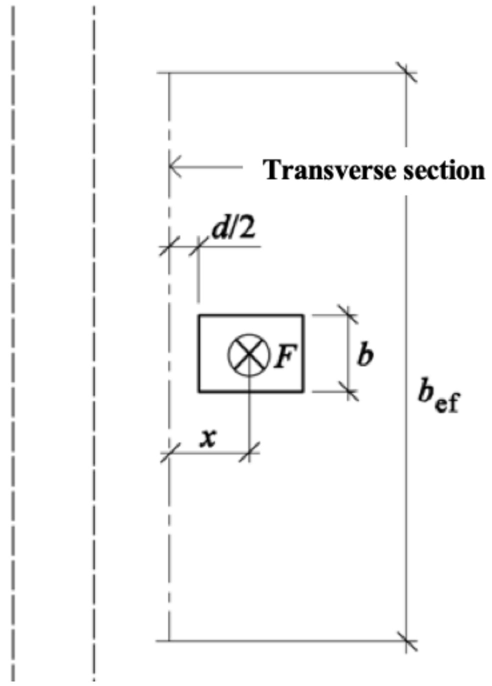

Figure 16 Effective width, bef, were shear force can be spread (Boverket, 2004)

The shear force can be spread along an effective width, b_{ef}, see Figure 16. Where b is the width of the closest point load, x is the distance between load center and the section point and d is the effective height of the slab. The effective width can then be calculated as the biggest value as below:

$$b_{ef} = \begin{cases} 7d + b + t \\ 10d + 1{,}3x \end{cases}$$

Where t is the thickness of the road surfacing.

Figure 17 illustrates how shear force in the bridge deck slab was spread in the design tool. The curve in the figure shows the transverse shear force along a transverse path in the slab. Within the distance of the effective width from the section point, the shear force can be calculated as the area under the curve.

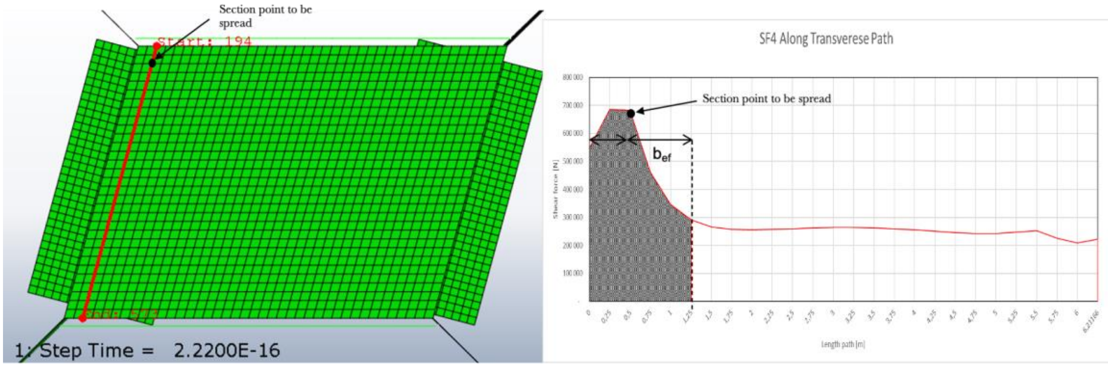

Figure 17. Spread of section point in model

For parts in the slab where $V_{Ed} > V_{Rd,c}$, design of shear reinforcement was done according to EN-1992-1 6.2.3.

4.8.2 Shear capacity in frame legs

The only external force acting on the frame legs are the earth pressure. The shear capacity is therefore mostly dependent of the size off the earth pressure force, with some impact from the bending of the bridge deck. The check of shear capacity in the script was therefore less complex than for the bridge deck slab.

Transverse shear forces, SF4 and SF5, were therefore retrieved only at three longitudinal paths in every frame leg. No point load was acting on the frame legs, so no further calculations needed to be done as in the bridge deck. The calculated shear reinforcement volume per meter width, was in this case distributed in the same way as for the bending reinforcement.

The amount of needed shear reinforcement was, as expected, much lower than for the bridge deck slab. Thickness of the frame legs had the largest influence whether shear reinforcement was needed or not. The results also showed that the skewed angle of the bridge also had a large impact on symmetry of needed shear reinforcement in the frame legs.

4.9 Reinforcement in rest of the bridge

The reinforcement for the wing walls was estimated with a fixed rebar diameter, $\phi = 16$ mm, and spacing, s = 100 mm. Same approach was done on the foundation slabs, with a fixed rebar diameter, $\phi = 20$ mm, and spacing s = 100 mm in global y-direction and s = 200 mm in global x-direction.

The dimensions and reinforcement of the edge beam was taken from the Swedish Transport Administrations requirements for building of bridges in Sweden (Trafikverket, 2016).

4.10 **Deflection**

Demands on deflection for bridges are not specified in Eurocode. Instead the Swedish Transport Administration, requires that the vertical deflection in a bridge should not exceed 1/400 of the theoretical span length, when loaded with the traffic load.

The deflection in the FE model is retrieved from several paths. The highest deflection is then checked against the demand of 1/400 of the span length.

4.11 **Running of script**

To make sure that an error in one or a few analyses would not make the running of thousands of bridges crash, a try and except statement in the python script was implemented. Normally when an error occurs in python, it will stop the script and generate an error message. If this is happening when running several bridge-analysis the script will end at the error and the remaining bridges will never be executed.

However, when using the try and error statement, it will make the script try the code for every bridge and if an error is raised, the except block will be performed. Instead of crashing and display an error, the script will wright an error message in the result file and then move on to the next bridge. By doing this, it is possible to run a script with as many bridges as desired without having to start over if some error in the analysis happens.

5 RESULTS AND DISCUSSION

In the beginning of the project two objectives were defined to be able to achieve the purpose to develop, document and implement a design routine based on SBD. The first objective was to identify and compile sustainability and buildability evaluation criteria, for evaluation of a set of frame bridges in a preliminary design stage. The second objective was to develop a script, based on SBD, that enables an automated and iterative structural preliminary design of frame bridges.
In this chapter, results and discussion of both these objectives are presented. Also, results and discussion on how to work with a large dataset from a SBD process is presented, and how geometric parameters affect the choice of frame bridge. As well as how the implementation of SBD of frame bridges can be carried out in an infrastructure project.

5.1 Final set of evaluation criteria for frame bridges

In Chapter 3.3 several evaluation criteria within buildability and sustainability were identified. These criteria were based on enhancing buildability and sustainability within a civil engineering project in general. However, one of the projects objectives was to compile some criteria for evaluation in a preliminary design of frame bridges. The compiled lists, in Chapter 3, needed to be narrowed to a couple of criteria that could be used in the design tool to weight different frame bridges against each other.

To determine the final set of evaluation criteria, two parameters were decisive. First, every criterion was discussed in interviews about how big impact it would have on the building of frame bridges. And secondly if the criteria were possible to implement in the design tool in a realistic way or not.

5.1.1 Buildability

For the buildability criteria, presented in Table 1, criteria number BF1 to BF4 are all of great importance for archiving good buildability in a project.

- BF1: Early involvement of contractor
- BF2: Workplace organization
- BF3: Available space on construction site
- BF4: Production planning
- BF5: Production methods

However, in most projects these factors are decided in the conceptual project plan phase. Often before a contractor or the designer for the final design is involved. Though the benefits of which type of contracting should be stated. As for “Early Involvement of Contractor”, it is possible to increase construction knowledge during the design process, in contrast to more traditional contracting where often the contractor is involved at the end of the design phase. To conclude, BF1 to BF4 are essential in the feasibility study and decisions on these criteria are in the majority of cases made in this phase. In other words, these decisions frame the design process and thereby also the possible number of alternatives. Thus, BF1 to BF4 are essential for the development of a design script, as proposed in this project.

Criteria BF5, “Production Method” has several factors regarding reinforcement and concrete options. Peter Simonsson (2011a) is recommending to integrate production knowledge in to the design. Considering constraints of the use for different production methods will provide experience in the design team, both for workers and managers.

One factor to consider regarding production method, is the use of prefabricated reinforcement. Prefabrication of reinforcement will help the on-site worker to better working positions. Placing of traditional reinforcement on site is often performed in a bad ergonomic way. Using rebar carpets or rebar cages provides the opportunity to a more controlled working environment and a more sustainable working position. This can decrease the number of physically demanding working positions. Also, the construction time can be reduced if using rebar carpets or cages. When using rebar carpets, the time spent on fixing reinforcement on site can be reduced with as much as 80% (Simonsson, 2011).

Faster construction time and a more ergonomic working environment are also advantages if using Self Compacting concrete (SCC) over traditional concrete. Number of workers needed for casting is significantly lower using SCC. It is possible to save up to 65% of casting time compared to casting with traditional concrete (Simonsson, 2011).

All the mentioned production methods will increase buildability for all civil engineering projects. When building frame bridges, it will not affect this more or less. However, in an interview with Per Arvidsson and Peter Johansson, they emphasized that the use of standardization of bridge dimensions and “Left or reuse concrete form system” would increase the production and buildability when constructing several frame bridges. The production time will increase significantly if it’s possible to standardize sections of the bridge and at the same time reuse the concrete form system. If some dimensions, for instance base slab, bridge deck and wing walls, are standardized for several bridges in one project, it is possible to reuse and transfer the same concrete form system along several bridges. This will save production time, material use and enhance the buildability.

When constructing several frame bridges in a project, it is important to encourage design repeatability by identifying construction parts that could be standardized. In same manner, grouping of bridge types should be done during tender and not by geographical areas, which is most the common way. The designer should design for repetition into the construction, when designing bridge spans, foundation sizes and support structures (Simonsson, 2011).

Nevertheless, for a designer, the criteria in Table 1 considering production method, standardization and design of structures is important to consider when designing concrete structures in a civil engineering project to enhance buildability. As well as when constructing several frame bridges, and then also consider extra to standardize dimensions and design for reuse of concrete form systems.

However, none of these criteria are considered reasonable to be built into the script that was developed. The main reason for this is that the buildability criteria are hard or impossible to quantify.

5.1.2 Sustainability

In opposite to the buildability criteria, several of the sustainability criteria are easily quantified. If it is possible to quantify the criteria it is rather easy to implement them in a script to assess different options.

For one of the three pillars of sustainability, the social criteria, the aspects are mainly not part of the designer's process. Most of social criteria need to be adopted very early on in the Feasibility study and the Process for land acquisition plan. Often long before a contractor or structural designer are involved. A contractor or designer have therefore very small opportunities to affect the social criteria. Therefore, no social aspects were considered in the development of the design script.

From the identified criteria in Table 2, two criteria, one from Environment and one from Economy, were selected to delimit and to investigate how these criteria can be optimized in an iterative design process:

- Material cost (Economy)
- CO_2 -equivalent (Environment)

These two criteria were implemented in the design script. Both material cost and CO_2 -equivalent are quantified from the use of material amount. In an interview with Kristine Ek, she stated that the quantitative sustainability criteria are directly affected by the type of material and amount of material use. The two selected sustainability criteria are quantified from EPD documentations and then implemented in the design script. The script calculates the needed amount of concrete and steel for every bridge analyzed, and then quantifies the criteria:

Concrete C35/45:

- Material Cost = 1 985 [SEK/m^3] (Mathern et al., 2020)
- Material CO_2 - equivalent = 388 [Kg CO_2e/m^3] (Svensk Betong, 2017)

Reinforcement steel:

- Material Cost = 14 400 [SEK/ton] (Mathern et al., 2020)
- Material CO_2 - equivalent = 370 [Kg CO_2-e/ton] (Celsa Steel Service AS, 2015)

5.2 The developed script

Most of the time, in this project, has been focused on the design tool. The objective was to develop a script, based on SBD concept, that performs a preliminary design of frame bridges. The script needed to be able to execute this in an automated and iterative way, so that a large amount of bridges could be designed and analyzed.

In Chapter 4 the build-up of the design tool and its different parts is presented. In this chapter the result from the script is presented and how the evaluation criteria from Chapter 5.1 is implemented.

As presented in Chapter 4, the script performs a preliminary design of bending and shear reinforcement in ULS according to Eurocode. In SLS the script checks if the demands of deflection from the Swedish road administration are fulfilled or not. Due to limited time and complexity, no other checks were implemented. No checks for crack width in SLS, for example, were performed. This needs to be done in a final design later.

In the very top of the script, the user or designer, states which parameters of geometry, material and ground conditions that should vary or be fixed. Number of variations for every parameter is also stated. The script combines all the parameters and calculates how many bridges that should be designed and analyzed. For every bridge, the geometry is built and an FEA analysis is performed. From the analysis, the needed amount of bending reinforcement, shear reinforcement and concrete are calculated. The evaluation criteria, specified in Chapter 5.1, are then implemented and quantified from the needed amount of material. The total cost and C02-equvilant from the whole model are then calculated and written to a separate result document.

In Table 4 to Table 7, examples from the result document are showed. Results from three bridges analyzed in the script is presented. The script generates not only results of the total cost and C02- equivalent, but it also specifies how much bending or shear reinforcement is needed for specific parts of the model. In this way it is possible to see for example how the transverse top reinforcement in the bridge deck is changing when the skewed angle or leg thickness is changed between different models. This can help the designer to understand which parameters are of most importance when finding the most optimal bridge to design.

Table 4. Result of cost and CO_2 in some models

Bridge/Model:	Cost and CO_2, whole model					
	Total cost [SEK]	Total CO_2 [Kg CO_2 e]	Reinforcement Total cost [SEK]	Reinforcement CO_2 [kg CO_2e]	Concrete Total cost [SEK]	Concrete CO_2[kg CO_2e]
Frame-Bridge_0599	609 956	76 829	249 730	6 417	360 226	70 412
Frame-Bridge_0600	674 866	85 429	273 809	7 035	401 058	78 393
Frame-Bridge_0601	367 571	46 088	151 734	3 899	215 838	42 189

Table 5. Dimensions of some models from the result

Bridge/Model:	Dimensions						
	Span Length [m]	Width Bridge Deck [m]	Thickness Bridge Deck [m]	Height Left Frame Leg [m]	Height Right Frame Leg [m]	Thickness Frame Legs [m]	Skewed angle [degree]
Frame-Bridge_0599	11	7,5	0,2	6	6	1	60
Frame-Bridge_0600	11	7,5	0,2	6	6	1,2	60
Frame-Bridge_0601	11	7,5	0,3	6	6	0,2	60

Table 6. Reinforcement volume of some models in the results

Bridge/Model:	Shear Reinforcement		Bending Reinforcement, Bridge Deck [m^3]			
	Bridge Deck [m^3]	Frame Legs [m^3]	Longitudinal Top Reinforcement	Longitudinal Bottom Reinforcement	Transverse Top Reinforcement	Transverse Bottom Reinforcement
Frame-Bridge_0599	0,243	0,002	0,218	0,23	0,126	0,114
Frame-Bridge_0600	0,243	0,002	0,219	0,229	0,127	0,114
Frame-Bridge_0601	0,141	0,043	0,113	0,325	0,085	0,151

Table 7. Deflection demands and calculation time for some models in the results

Bridge/Model:	Foundation	Concrete class	Maximum Deflection [m]	Deflection Demand (L/400) [m]	Deflection Demand OK?	Time When Analysis Completed
Frame-Bridge_0599	Slab on bedrock	C35/45	-0,093	0,028	Deflection NOT ok	03:29:07
Frame-Bridge_0600	Slab on bedrock	C35/45	-0,092	0,028	Deflection NOT ok	03:31:01
Frame-Bridge_0601	Slab on bedrock	C35/45	-0,058	0,028	Deflection NOT ok	03:32:55

In Table 4 to Table 7 none of the bridges in the example fulfilled the requirements of deflection. The dimensions presented in Table 5 reveals that, for frame bridge number 599, the thickness of the bridge deck is only 0.2 m with a span length of 11 m. This might seem as overdoing the process, when including dimensions that most designers would understand are a bad option. But this is a part of the concept of SBD. The definition of SBD states that a wide set of design alternatives should be generated and then narrow it down to a suitable solution. Also, computational time analyzing one option is often less than a minute. Compare to traditional design approaches a preliminary design option takes far more time analyzing.

The design concept and visualization of how the script generates results can be seen in Figure 18. The figure plots 396 analyzed bridges that are of the same span length, width of bridge deck, height of frame legs and foundations and material conditions. The bridges are plotted against the CO_2-equivilant and material cost. The yellow dots are bridges that did not fulfill the deflection requirement's and are therefore sorted out. To find the most optimal solution for a bridge with these fixed variables and as low material cost and CO_2-equivilant as possible, number of bridges should obviously be narrowed down to those in lower left corner that fulfills the requirement for deflection. But it is not as simple as, that the bridge with lowest material cost and CO_2-equivilant in Figure 18 is the most optimal bridge. By the means of SBD, the varying parameters should be varied finer within the parameters of those bridges with the lowest material cost and CO_2- equivalent.

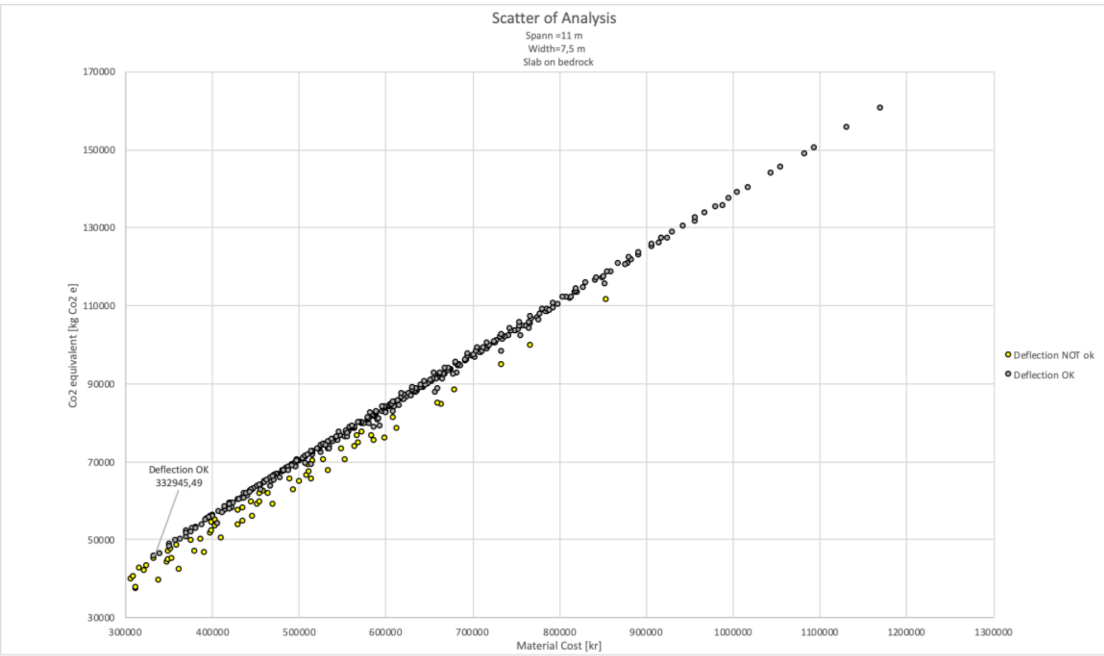

Figure 18 Set of 396 bridges. Same span length, width of bridge deck, height of frame legs and foundation conditions. Varying thickness of bridge deck, thickness of frame legs and skewed angle.

One problem when generating the result was the available computer capacity. When running a script that was executing several bridges, the analyze of every bridge got exceptional slow after a few hundred executions were completed. For the first hundred bridges the average running time for the script, for one bridge to be completed, was about 45 seconds. But after that, the running time just got slower and slower for about every hundred-bridge completed. As seen in Table 8 the script printed the time for every completed bridge in the result file. During the hundred executed bridges between bridge number 100 and bridge number 200, the average computer calculation time was 51 seconds per bridge. When executing the bridges between the last two bridges in Table 8, average computer calculation time was more than tripled.

Table 8. Example of running times of analysis

Bridge/Model:	Foundation	Concrete class	Maximum Deflection [m]	Deflection Demand (L/400) [m]	Deflection Demand OK?	Time When Analysis Completed
Frame-Bridge_0100	Slab on bedrock	C35/45	-0,003	0,026	Deflection OK	16:02:42
Frame-Bridge_0200	Slab on bedrock	C35/45	-0,089	0,026	Deflection NOT ok	17:27:47
Frame-Bridge_0650	Slab on bedrock	C35/45	-0,002	0,028	Deflection OK	05:09:31
Frame-Bridge_0750	Slab on bedrock	C35/45	-0,005	0,028	Deflection OK	09:43:43

Running the script directly from the Windows CMD without opening Brigade's graphical user interface did reduce the computational time a bit. But not enough to generate as many bridges as first intended. Therefore, the number of bridges analyzed needed to be reduced in this project. The use of a computer cluster would allow to shorten the time required for the analyses. However, due to lack of time, this was never implemented in the project.

5.3 Parametrization with decision tree

As seen in previous sub chapters, the result from a SBD tool can generate a huge amount of unique bridges. The management and analysis of this amount of data is challenging. One method is to use a statistical computer program to understand which parameters in a large dataset that influence a certain result the most.

Chapter 5.1 concluded that the final evaluation criteria, to be implemented in the design tool, were material cost and material CO_2-equivalent. The design tool generated a large amount of bridges, evaluated from these criteria, as seen in Chapter 5.2. To find relations in the dataset and try to find those parameters that influences the result of CO_2-equivalent or material cost criteria, so called "decision trees" were built.

These decision trees were created with an algorithm from program language R ("R-project," 2020). The algorithm is searching through predetermined parameters and try to split the dataset in these parameters in several steps. The algorithm tries to find the parameters that influence a certain result the most.

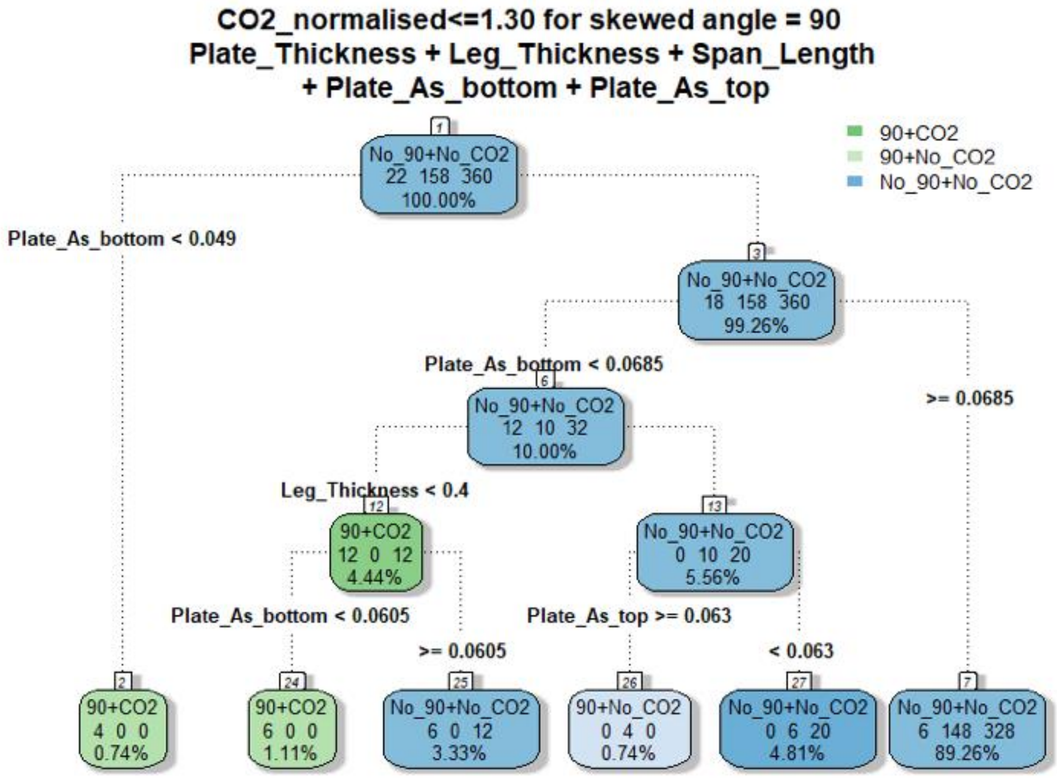

Figure 19 Decision tree from R with normalized CO_2-equivalent less than 1.3 and skewed angle 90 degree. Every colored box are nodes and white box over every node is the numbering of the node.

Figure 19 shows an example from a decision tree built with R. In this case, the algorithm tries to find those parameters that influence the skewed angle and a normalized CO_2-equivalent, in a part of the extracted data from the design tool, 540 different bridges.

In this dataset of 540 bridges, the skewed angle is either 90, 75 or 60 degrees. The bridge deck thickness, frame leg thickness and span length are some of the varying input parameters in the design tool. With these parameters, the amount of top and bottom reinforcement where calculated in the design tool. The CO_2-equivalent for every bridge was also calculated and normalized.

In the decision tree, seen in Figure 19, two pre-determined targets are set as input: Normalized CO_2-equivalent $\leq$ 1.3 and skewed angle = 90 degree. "Splitting parameters" are set as bridge deck thickness, frame leg thickness, span length, top- and bottom reinforcement. Meaning that the algorithm will try to split those parameters in the dataset, that either fulfills or not fulfills the target of both skewed angle = 90 degree and normalized CO_2-equivalent $\leq$ 1.3.

The first top node, in Figure 19, includes the whole dataset of 540 bridges, and shows that the largest amount does not fulfill the target of 90 degree and CO_2-equivalent $\leq$ 1.3. Below this node, the algorithm splits the dataset in the different parameters that influence the probability of fulfilling the target. As seen, it splits the set however the bottom reinforcement is or is not less than 0.049 m3. There are four bridges, seen in node number 2, in the dataset that fulfils both targets and at the same time have less bottom reinforcement than 0.049 m3. Next to this node, number 24, the algorithm captures another six bridges that fulfills both targets, but with different parameter splits.

The key in the two nodes, number 2 and 24, are that the two zeros indicates that the algorithm did not find any bridges with the two other possible outcomes. Either fulfilling one of the targets or not fulfilling none of the targets.

These results show that if a traditional design of frame bridges is done, regarding to these parameters on the left side, the probability of fulfilling the targets of skewed angle = 90 degree and normalized CO_2-equivalent ≤ 1.3 is much higher than if a design is done regarding the split on the right side of the tree. As another example, it can be seen in node 25, that the algorithm finds six bridges that fulfills the target and has bottom reinforcement ≥ 0.0605. But if a design is done with that parameter in a traditional design the probability is higher that the outcome does not fulfill the target. It is still possible that the design does fulfill the target, just a smaller chance.

However, it should be stated that the dataset outcome from the fulfilled target in node 2 and 24 in Figure 19, are too small to do a prediction based on only this. A larger dataset that passes the targets are needed to use the result as directly predictions. But it is possible to say, that the split parameters shown here, are important to focus on, when doing a traditional design and aiming on fulfilling these targets.

Building a decision tree can be done in several other ways than showed here. The starting dataset needs to be larger, other targets needs to be elaborated with and more splitting parameters are needed, to do better predictions. But using a decision tree can be a tool for the designer to elaborate which parameters are of most importance to fulfill certain targets in a bridge design process.

5.4 Implementation of Set-Based Design

In order to investigate how SBD of frame bridges can be implemented in an infrastructure project, a case study was done. The 270 km planed high-speed railway project, between Umeå and Luleå, were studied. In the project, called North Botnia Line, several frame bridges are planned to be built.

As mentioned in Chapter 2, the tender procedure of contractors will be in package with group of bridges. The STA says that it will be a sort of turnkey contract, with expectations that the contractor can find their own cost-effective solutions for the bridges. Therefore, the client wants to introduce incentives in the bridge contracts, that motivates the contractor to find solutions that are as effective as possible and keeps the cost low.

This could be a perfect opportunity to introduce SBD in a contract. The client has the possibility to also set up goals for sustainability. If the contractor then can bring solutions that makes the whole project more sustainable, inncentives in the contract might give more profit to the contractor.

The design tool shown in this thesis can be used for this purpose. In a large project like North Botnia Line and with a SBD tool, it is possible to find one bridge solution that fulfills the need of several bridges in a group of bridges.

Table 9 shows needed span length for several bridges in the North Botnia Line project. As an example, it might be that all these bridges are for road traffic crossing over the railway. With more or less the same widths and heights of the bridge needed.

Table 9. Span lengths needed for bridges in North Bothnia Line project

SPAN LENGTH [m]	GROUP
6	Group 1, span greater than 8.5 m
6	
7	
8,5	
9,5	Group 2, span greater than 11 m
10	
10	
10	
10,5	
11	
11	
12	Group 3, span greater than 15 m
12	
12,5	
14	
14	
15	
17	Group 4, span greater than 19 m
17	
17	
17	
18	
18	
19	

Using the same results from the design tool as presented in Chapter 5.2, it is possible to find a preliminary bridge design that covers the need of group 2 in Table 9. First identify the dimensions and parameters of the bridges in Figure 18 that has the lowest material cost and CO_2-equivalent. On the basis of SBD, these parameters should then be refined, to narrowing it down to the best solution possible.

By finding one bridge design that covers the need of several bridges in a project, makes it possible to standardize large part of the production and develop towards an industrializing building of frame bridges. This would make it possible to reduce the planning cost, when one preliminary bridge design is done instead of several separated processes. Also, when standardizing the production, the need of transportation can be reduced and the enhancing of buildability increases.

At the same time, analysis of how much this approach gains or losses in cost and environmental impact needs to be done. It is possible to increase profit and decrease the environmental impact in certain areas. But it needs to be in contrast to that some bridges will be over designed. More building material will be required, for some bridges, compared to if that bridge would have been optimized in a traditional way. However, the total waste of material, in a SBD process, might be lower if the whole project, with maybe over hundred bridges, is considered. This is not considered in this thesis though.

6 CONCLUSIONS

The aim of this thesis was to develop a SBD tool for preliminary design of frame bridges. Part of the aim was also to identify evaluation criteria within buildability and sustainability, that could be implemented in the SBD tool.

The developed design tool can be considered to function as intended. The design tool can perform an iterative, SBD of frame bridges. The design tool should be seen as a tool for the structural designer, in a preliminary design phase, that can generate a wider range of design alternatives, than a traditional design approach would do. However, a detailed design of the chosen alternative is required, as several simplifications of some calculations and checks have been done.

The work done on compiling evaluation criteria within buildability and sustainability brought a better understanding for the subject's importance as a structural engineer. The designer needs to consider early on in the process, which criteria is of most importance to enhance buildability and sustainability in the project. It is also of importance that the designer understands how the choices made during the design, will affect the buildability and sustainability during and after the construction.

However, the intention of implementing buildability in the design tool turned out to be more difficult than expected. Further work is needed on this subject.

To find relations in the large set of results generated by the design tool, a parametrization with the programing language R was carried out. The outcome from this separate study could not show any exact predictions in the relations of the parameters. Though, if the script in R can be developed and results verified, there is great potential in implementing this in the SBD tool. If so, it is possible to make the design tool evaluate the results. The design tool can automatically find the most important parameters to achieve a certainty result. Then refine these parameters on the basis of SBD, to find the most optimal solution.

Interviews with several people in the industry showed that the implementation of a more iterative and standardized production is well suited for frame bridges. If more work is done to implement SBD in large infrastructure projects and the client groups the bridges in the tender, the contractor can industrialize the construction of several bridges. As seen in Chapter 5.4, the contractor can perform one design that covers the need of several bridges in a project. Hence, there is great potential for the building industry to get a more sustainable and cost-effective building of bridges.

7 FURTHER DEVELOPMENT

More work is needed on both developing the design tool and investigating more evaluation criteria, to achieve a more thorough Set-Based design routine for frame bridges.

Other sustainability criteria than material cost and material CO_2-equivilat should be further investigated and implemented in the design tool, to get a wider perspective on sustainability. As mentioned earlier, no buildability criteria where implemented in the design tool. More work is needed on this subject.

To achieve a larger number of bridges in the results the script should be developed so that it can be run in a cluster computer. Also, other demands from Eurocode should be implemented in the script to get a more accurate design and to be able to sort out the design options that will not pass a final design.

A more in-depth study of how to implement a SBD tool in an infrastructure project, should be carried out. As well as investigating the consequences of implementing a SBD tool. How much of planning cost or CO_2can be saved if one design is carried out for several bridges? Instead of designing every bridge separate.

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