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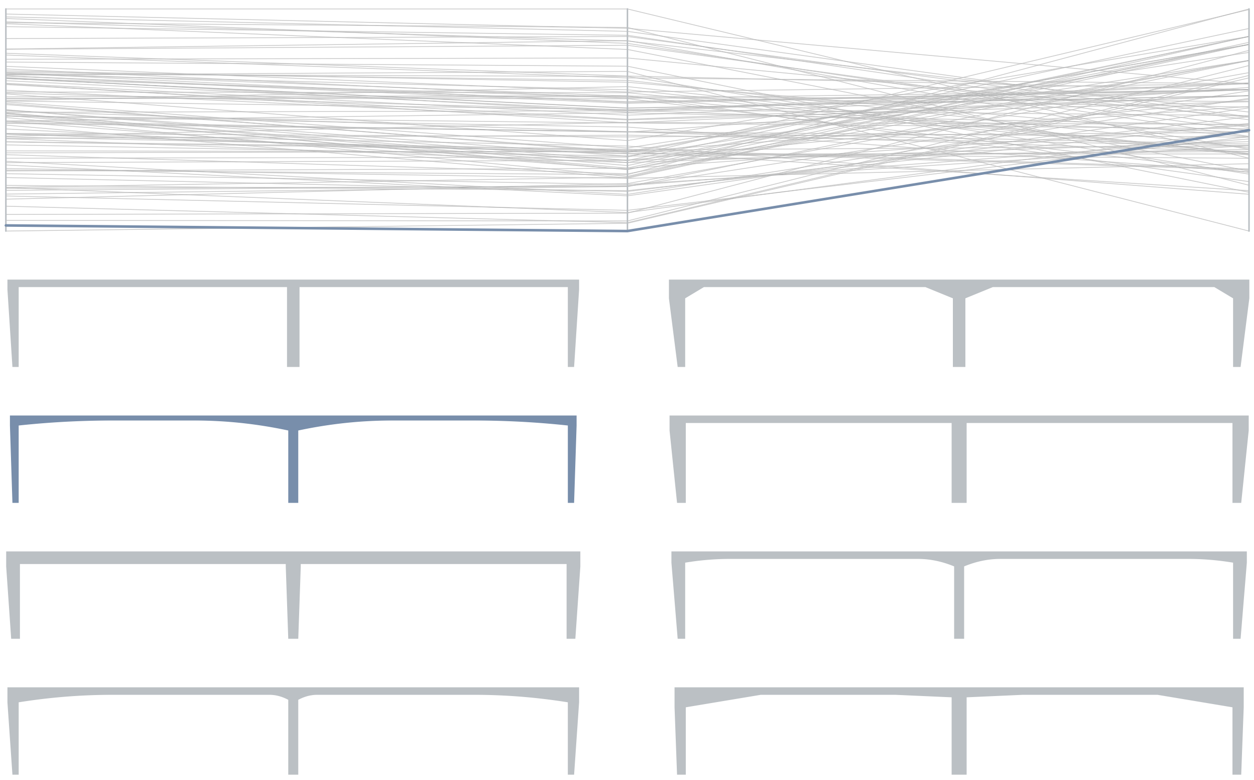

Integrating aesthetic considerations in set-based bridge design

A method for including qualitative values alongside quantitative objectives in early-stage concrete bridge design

Master's thesis in Structural Engineering and Building Technology

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CHALMERS UNIVERSITY OF TECHNOLOGY
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MASTER'S THESIS ACEX30

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Cover:
Conceptual illustration of the outcome of a set-based bridge design process, showing selected generated concrete bridge alternatives and a parallel coordinates plot of evaluated alternatives.

Department of Architecture and Civil Engineering
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ABSTRACT

Early-stage bridge design involves balancing several objectives, including cost, environmental impact, and aesthetic quality. Set-based design combined with parametric modeling can support this phase by generating and comparing many design alternatives. Previous applications have mainly focused on quantitative criteria, such as production cost and environmental impact, while aesthetic aspects are often assessed separately or given less systematic attention. This thesis investigated how aesthetic considerations can be incorporated as qualitative criteria within a set-based design process for concrete bridges.

The study was based on a literature study, consultations with professionals, and the development and assessment of a digital prototype. Aesthetic principles relevant to early-stage bridge design were identified and translated into criteria that could be handled within a computational model. The prototype was developed for a two-span concrete slab frame bridge and used to generate, filter, evaluate, and visualize design alternatives. The alternatives were assessed with respect to production cost, CO_2-equivalent emissions, and quantified aesthetic criteria. The aesthetic criteria were based on selected geometric relationships, such as proportions, symmetry, and variation of structural depth along the span.

The thesis proposes a set-based design method that considers qualitative values alongside quantitative objectives in early-stage concrete bridge design. The prototype assessment showed that the inclusion of aesthetic criteria added an additional evaluation dimension to the design space, making trade-offs between production cost, environmental impact, and selected aesthetic principles more visible. The proposed method should be understood as decision support rather than as an automatic design generator, supporting comparison, visual assessment, and professional judgment in early-stage design decisions.

Key words:
set-based design, bridge design, bridge aesthetics, qualitative criteria, parametric design, early-stage design

Integrering av estetiska aspekter i set-baserad brodesign
En metod för att inkludera kvalitativa värden tillsammans med kvantitativa mål i tidig broprojektering av betongbroar

Examensarbete inom masterprogrammet Konstruktionsteknik och Byggnadsteknologi

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SAMMANFATTNING

I tidiga skeden av broprojektering behöver flera mål vägas mot varandra, såsom kostnad, miljöpåverkan och estetisk kvalitet. Set-baserad design i kombination med parametrisk modellering kan stödja detta arbete genom att generera och jämföra ett stort antal designalternativ. Tidigare tillämpningar har främst fokuserat på kvantitativa kriterier, exempelvis produktionskostnad och miljöpåverkan, medan estetiska aspekter ofta bedöms separat eller behandlas mindre systematiskt. Detta examensarbete undersöker hur estetiska aspekter kan inkluderas som kvalitativa kriterier i en set-baserad designprocess för betongbroar.

Studien baserades på en litteraturstudie, samtal med yrkesverksamma samt utvecklingen och utvärdering av en digital prototyp. Estetiska principer relevanta för tidig broprojektering identifierades och översattes till kriterier som kunde hanteras i en beräkningsmodell. Prototypen utvecklades för en tvåspannig plattrambro i betong och användes för att generera, filtrera, utvärdera och visualisera designalternativ. Alternativen bedömdes med avseende på produktionskostnad, CO_2-ekvivalenta utsläpp och kvantifierade estetiska kriterier. De estetiska kriterierna baserades på utvalda geometriska samband, såsom proportioner, symmetri och variation av konstruktionshöjd längs spannet.

Examensarbetet föreslår en set-baserad designmetod som beaktar kvalitativa värden tillsammans med kvantitativa mål i tidig projektering av betongbroar. Prototypbedömningen visade att inkluderingen av estetiska kriterier tillförde en ytterligare utvärderingsdimension till designrymden, vilket gjorde avvägningar mellan produktionskostnad, miljöpåverkan och utvalda estetiska principer mer synliga. Den föreslagna metoden bör förstås som ett beslutsstöd snarare än en automatisk designgenerator, och kan stödja jämförelse, visuell bedömning och professionellt omdöme i tidiga skeden av projekteringen.

Nyckelord: set-baserad design, brodesign, broestetik, kvalitativa kriterier, parametrisk design, design i tidiga skeden

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Preface

This master's thesis was carried out at the Department of Architecture and Civil Engineering at Chalmers University of Technology during the spring of 2026. The thesis was developed in collaboration with WSP and the Swedish Transport Administration.

We would like to thank our examiner and supervisor Rasmus Rempling for valuable guidance, feedback, and enthusiasm throughout the project. We would also like to thank our supervisors at WSP, Malin Borgny and Daniel Ekström, and our supervisors at the Swedish Transport Administration, Mats Karlsson and Hans-Ola Öhrström, for their support, input, and engagement in the work.

We are also grateful to the other professionals within bridge design, infrastructure planning, architecture, and landscape architecture who contributed with insights through consultations and discussions. Their input was valuable for understanding current practice and the role of aesthetics in bridge design.

We would also like to thank our opponents Elisabeth Bruhn and Stina Durling for sharing the thesis process with us in a supportive way, and giving us valuable feedback and encouragement.

Finally, as this thesis marks the end of our educational journey at Chalmers, we would like to thank our families and friends for their support and encouragement throughout our studies.

Gothenburg, June 2026
Matilda Dahlgren
Ellen Nyholm

Notations

The abbreviations and symbols used in the report are listed below.

Abbreviations

3D	Three-Dimensional
AI	Artificial Intelligence
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
FEM	Finite Element Method
ILKA	Initial Landscape Analysis
LM1	Load Model 1
ML	Machine Learning
PBD	Point-Based Design
SBD	Set-Based Design
SLS	Serviceability Limit State
STA	Swedish Transport Administration (Trafikverket)
ULS	Ultimate Limit State

Roman upper case letters

$A(x)$	Aesthetic penalty score for design alternative x.
$A_{s,\text{max}}$	Maximum reinforcement area.
$A_{s,\text{min}}$	Minimum reinforcement area.
$A_{s,\text{req}}$	Required reinforcement area.
$C(x)$	Total production cost for design alternative x.
$C_m(x)$	Material cost for design alternative x.
$C_W(x)$	Cost of construction work for design alternative x.
D_{bd}	Structural depth of the bridge deck.
$D_{\text{bd,barrier}}$	Total visible depth including bridge deck and non-transparent railing or barrier.
$D_{\text{bd,fl}}$	Bridge deck depth at the frame leg.
$D_{\text{bd,ms}}$	Bridge deck depth at the mid-support.
$D_{\text{bd,span}}$	Bridge deck depth at midspan.
$D_{\text{fl,bot}}$	Frame leg thickness at the bottom.
$D_{\text{fl,top}}$	Frame leg thickness at the top.
D_{haunch}	Haunch depth.
D_{ms}	Governing mid-support thickness.
$D_{\text{ms,bot}}$	Mid-support thickness at the bottom.
$D_{\text{ms,top}}$	Mid-support thickness at the top.
D_{support}	Width of the support.
$E(x)$	Total CO_2-equivalent emissions for design alternative x.
$E_c(x)$	Total CO_2-equivalent emissions from concrete for design alternative x.
$E_r(x)$	Total CO_2-equivalent emissions from reinforcement for design alternative x.
$EI(x)$	Flexural stiffness along the bridge deck.
$F(x)$	Objective function.
$F_i(x)$	ith objective function.
$F_i^{\text{trans}}(x)$	Transformed ith objective function.
F_i°	Ideal point value for objective function i.
F_i^{max}	Maximum reference value for objective function i.
H	Bridge height from ground level to the deck.
L_{haunch}	Haunch length.
$L_{\text{haunch,fl}}$	Haunch length adjacent to the frame leg.
$L_{\text{haunch,ms}}$	Haunch length adjacent to the mid-support.
L_{span}	Span length.
M_{Ed}	Design bending moment.
$M_{\text{Ed,B}}$	Design bending moment at the mid-support.
M_{Rd}	Design bending resistance.
P_1	Slenderness ratio.
P_2	Height-to-span ratio.
P_3	Support-width-to-depth ratio.
P_4	Deck overhang proportion.
P_5	Haunch depth ratio.
P_6	Haunch length-to-span ratio.
Q_c	Total concrete volume.
Q_r	Total reinforcement weight.
$Q_{m,i}(x)$	Quantity of material i for design alternative x.

$T_W(x)$	Construction time for design alternative x.
U	Scalar utility function.
W	Bridge width. Also used for section modulus in the simplified mid-support check.

Roman lower case letters

b_{strip}	Analyzed strip width.
eq_c	CO_2-equivalent emission factor for concrete.
eq_r	CO_2-equivalent emission factor for reinforcement steel.
f_{cd}	Design compressive strength of concrete.
f_{yd}	Design yield strength of reinforcement.
$g_j(x)$	jth inequality constraint.
$h(x)$	Local cross-section height.
$h_k(x)$	kth equality constraint.
i	Index for design variables, objective functions, or material types, depending on context.
j	Index for inequality constraints.
k	Index for equality constraints. Also used for number of objective functions, depending on context.
n_g	Number of inequality constraints.
n_h	Number of equality constraints.
n_x	Number of design variables.
t_i	Transformed proportional penalty score for aesthetic criterion i.
t_{haunch}	Discrete penalty associated with the selected haunch geometry.
$t_{m,i}$	Unit construction time associated with material i.
w_i	Weighting coefficient associated with objective i.
x	Vector of design variables representing a design alternative.
x_i	ith design variable.
$\underline{x}_i$	Lower bound of the ith design variable.
$\overline{x}_i$	Upper bound of the ith design variable.
z	Internal lever arm.

Greek letters

δ_{max}	Maximum vertical deflection of the bridge deck.
ρ_{mc}	Concrete material cost.
ρ_{mr}	Reinforcement material cost.
$\rho_{m,i}$	Unit price of material i.
ρ_w	Labor cost per unit volume of concrete.

1 Introduction

1.1 Background

The early stage of bridge design involves evaluating alternative structural concepts and geometric configurations. Decisions made at this stage have a major influence on the outcome of a final concept. In this thesis, the early stage refers specifically to the land acquisition planning stage[1] as defined by the Swedish Transport Administration (STA). At this stage, the bridge location is identified, but the detailed geometry and structural configuration have not yet been established. Efficiency in this phase is therefore critical, as poor decisions may lead to increased economic costs, higher climate impact, reduced buildability, or lower overall quality of the structure (Ottosson, 2015).

In recent research, set-based design (SBD) combined with parametric modeling has been developed to support this decision-making in early planning and design stages (Mathern et al., 2018). This approach allows many feasible design alternatives to be generated simultaneously, making it possible to compare solutions based on quantitative criteria such as cost, CO_2 emissions and buildability (Bergenram & Ulander, 2023). This approach leads to a more transparent and structured design process and reduces the risk of excluding suitable solutions at an early stage.

Sustainability is a central motivation for improved decision support within early-stage bridge design. Sweden's climate policy framework states that the country shall reach net-zero greenhouse gas emissions by 2045 and thereafter achieve negative emissions (Naturvårdsverket, 2026). In parallel, the STA has established the long-term goal of climate-neutral infrastructure by 2040 and requires climate impact to be assessed from a life-cycle perspective during planning and procurement (Bengtsson, 2025). Previous research has also shown that set-based design can reduce both material cost and climate impact. For example, studies of soil-steel composite bridges have shown reductions of up to 20% in CO_2-equivalent emissions when comparing built bridges to optimal solutions identified using SBD (Lagerkvist et al., 2022).

Despite advances in recent research, the current set-based models mainly focus on measurable quantitative parameters. Qualitative aspects, such as architectural and aesthetic considerations, are typically assessed separately and often in a subjective way. Yet, these aspects play an important role in the selection process of design alternatives, especially in urban environments or areas subject to visual and contextual requirements. However, since these parameters are not integrated in the existing models, decision making still relies on separate tools and assessments, which limits the applicability of the set-based approach[2].

The research programme initiated by the STA, in collaboration with WSP and other partners, identifies a need for a data model that can evaluate alternative bridge solutions in a transparent way, not only with respect to quantitative parameters such as climate impact, cost and buildability, but also with regard to qualitative aspects such as form and architectural expression. There is therefore a need to further develop the existing set-based optimization model for bridges to investigate how aesthetic aspects can be systematically represented and assessed, and how they can complement current quanti-

[1] Swedish term used by th STA: *Väg- och järnvägsplan*

[2] Consultation with Senior Researcher Rasmus Rempling, Chalmers University of Technology.

tative evaluation criteria.

1.2 Purpose, aim and objectives

The purpose of this master's thesis was to investigate how aesthetic aspects can be incorporated as qualitative criteria within set-based and parametric design approaches for concrete bridges. The aim of the study was to contribute to improved decision support in early-stage bridge design by enabling aesthetic considerations to be addressed alongside quantitative criteria. This was pursued through the development and demonstration of a structured set-based design method for early-stage bridge design, exemplified by a digital prototype.

The objectives of the thesis were to:

- Identify key aesthetic attributes relevant to early-stage bridge design, based on literature and professional practice.
- Propose a structured method for incorporating aesthetic attributes as qualitative criteria within a set-based design process, alongside the quantitative criteria of production cost and CO_2 emissions, and discuss how the method can be used within the early-stage bridge planning process at the STA.
- Develop a digital prototype to exemplify the proposed set-based design method and demonstrate the integration of selected aesthetic considerations in early-stage bridge design.
- Analyze how the inclusion of aesthetic considerations influence the design space.

1.3 Scope and delimitations

Due to the limited time frame of the study, several delimitations were made. The proposed SBD method is intended for early-stage concrete bridge design, but the digital prototype was limited to one bridge type: a two-span concrete slab frame bridge. The prototype was based on a simplified case study, and the generated alternatives were limited by the selected design variables, input ranges, and geometric assumptions described in Chapter 3.

In the prototype, the aesthetic evaluation was limited to selected geometric attributes, such as proportions, symmetry, and variation of structural depth along the span. Other aesthetic aspects, such as material expression, detailing, color, lighting, and landscape integration, were not included in the prototype.

The structural verification within the prototype was simplified. It was used to filter out clearly infeasible design alternatives, but was not intended to replace detailed bridge design. More detailed structural analysis, reinforcement design, foundation design, and construction-related checks were outside the scope of the thesis.

The quantitative evaluation was limited to production cost and CO_2-equivalent emissions. Buildability was not implemented as an evaluation criterion, although it has been included in previous set-based bridge design studies. The cost and environmental impact calculations should be understood as simplified comparative estimates, not as complete project cost or life-cycle assessments.

The study focuses on how aesthetic considerations can be included in a set-based design process together with quantitative objectives. The discussion of bridge aesthetics is based on literature, guidelines, and professional consultations, while the application of the proposed method is mainly related to the planning and design process at the STA. The thesis does not aim to give a universal definition of bridge aesthetics.

1.4 Scientific approach

This thesis adopted an exploratory and computational scientific approach to investigate how aesthetic considerations can be incorporated into early-stage concrete bridge design. The work combined a literature study, professional consultations, development of a structured SBD method, and assessment through a digital prototype.

The literature study covered bridge aesthetics, the bridge planning process at the STA, relevant design methodologies, and optimization objectives for bridge design. Consultations with professionals involved in bridge planning and infrastructure projects were conducted to deepen the understanding of current practice and to support the formulation of assumptions used in the study.

Based on the frame of reference, selected aesthetic principles were translated into criteria that could be considered within a set-based design process together with quantitative objectives. A digital prototype was then developed to exemplify and assess the proposed method. The prototype was based on a simplified case study of a two-span concrete slab frame bridge and was used to generate, filter, evaluate, visualize, and compare design alternatives with respect to production cost, environmental impact, and quantified aesthetic criteria.

The prototype assessment was used to examine how the inclusion of aesthetic-related criteria influenced the design space and the trade-offs between different objectives. Based on the frame of reference and the prototype assessment, a proposed SBD method was formulated for how qualitative criteria can be considered alongside quantitative objectives in early-stage concrete bridge design.

1.5 Thesis outline

The thesis is structured as follows.

Chapter 1 introduces the background, purpose, aim and objectives, scope and delimitations, and scientific approach of the study.

Chapter 2 presents the frame of reference, including bridge aesthetics, the planning and design process at the STA, relevant design methodologies, and optimization objectives for bridge design.

Chapter 3 describes the development of the digital prototype, including the case study, design variables, constraints, objective functions, and visualization of generated alternatives.

Chapter 4 presents and discusses the results obtained from the digital prototype. The chapter focuses on how the generated alternatives performed with respect to production cost, environmental impact, and quantified aesthetic criteria.

Chapter 5 presents and discusses the proposed SBD method for integrating quantitative and qualitative criteria in early-stage concrete bridge design. The chapter describes how qualitative criteria can be represented, how alternatives are generated and evaluated, and how the method may support decision-making within the planning and design process at the STA.

Chapter 6 discusses the study from a broader perspective. The chapter focuses on the possibilities of qualitative assessment within a set-based design process, the influence of qualitative considerations on the design space, limitations of the proposed approach, and possible further development.

Chapter 7 presents the conclusions of the thesis. The chapter summarizes the main findings in relation to the purpose, aim, and objectives of the study.

2 Frame of reference

This chapter establishes the theoretical and contextual foundation for the study. In addition to a literature-based background, insights from consultations with professionals involved in bridge planning are included where relevant to clarify current practice and to support the interpretation and formulation of assumptions used in the subsequent chapters.

2.1 Bridge aesthetics

Bridges serve an important functional role within the built environment by enabling transportation and connectivity. At the same time, they are highly visible elements that often have a long-term visual impact on their surroundings (Ellison, 2026). Consequently, bridge design involves not only satisfying structural and functional requirements, but also considering how bridges are visually perceived and experienced by users and observers (Tang, 2018). This section presents the importance and classification of bridge aesthetics, aesthetic principles relevant for common concrete bridges in infrastructure contexts, and how the Swedish Transport Administration currently approaches aesthetics in bridge design projects.

2.1.1 The importance of aesthetic integration in bridge design

Aesthetic quality plays a fundamental role in how humans perceive and respond to the built environment (Pearce et al., 2016). Since bridges are primarily designed by engineers, engineering decisions strongly influence both structural performance and visual expression (Billington & Gottemoeller, 2000; Kulasuriya, 2005). The responsibility of bridge engineers therefore extends beyond structural analysis to also include aesthetic considerations.

However, aesthetics has traditionally not been a central topic within engineering education and is more commonly associated with architectural disciplines (Kulasuriya, 2005). A common mistake in bridge design is to treat aesthetics and structural design as separate processes, either by focusing solely on the most economical structural solution and addressing aesthetics afterwards, known as the engineer's pitfall, or by first deciding the visual appearance and then adapting the structure, often referred to as the architect's pitfall (Showers, 2011). Both approaches can lead to suboptimal results, as key design decisions are made too late in the process. An understanding of aesthetic principles and the integration of aesthetics early in the design process, together with structural and functional considerations, are therefore important for achieving well-balanced bridge solutions (Kulasuriya, 2005; Tang, 2018).

This balance is described by Billington and Gottemoeller (2000) as a form of structural art, where structural efficiency, cost, and visual quality are achieved simultaneously, and where the structural system itself defines the aesthetic expression of the bridge. Similarly, the Minnesota Department of Transportation (1995) describes design excellence in bridge design as the result of an integration of science, technology and artistic judgment, as illustrated in Figure 2.1. The three components represent different dimensions of the design process, which together shape the overall quality of the final solution. Science represents analytical knowledge grounded in mathematics, geometry, and structural mechanics. Technology contributes practical knowledge related to materials, construction methods, and economic constraints, that ensure feasibility and buildability. Artistic judgment, in turn, balances scientific and technical considerations by addressing visual quality, proportion, and contextual integration. Design excellence is thus not achieved through any single dimension, but through the balanced interaction of all three dimensions.

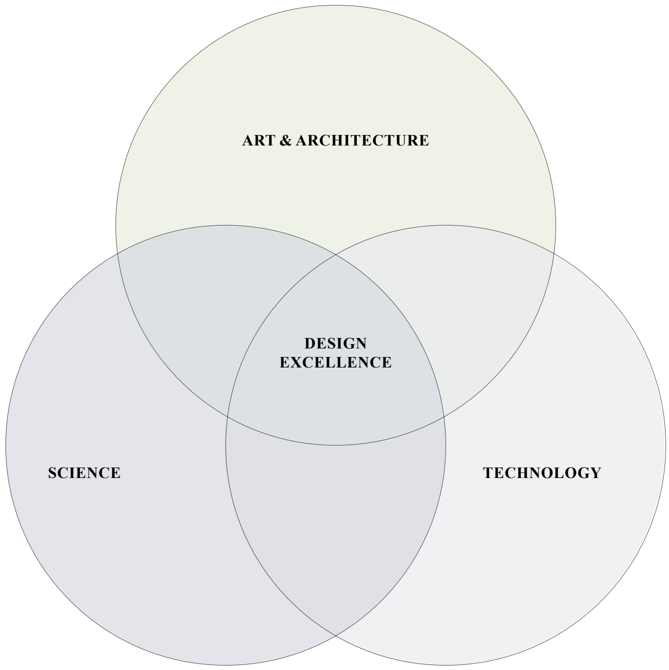

Figure 2.1: The three components of design excellence according to Minnesota Department of Transportation (1995).

2.1.2 Classification and determinants of bridge aesthetics

Bridge aesthetics can be interpreted through different design-related aspects that influence the visual perception of a bridge (Tang, 2018; Transport for NSW, 2023). Although judgments of what is considered beautiful or aesthetically pleasing are often regarded as subjective and grounded in individual perception (Graham, 2005), research has shown that aesthetic preferences often display consistent patterns across individuals, suggesting that they can be statistically unified through shared underlying principles (Danaci, 2012).

Bridges can therefore be classified and interpreted through different design-related perspectives, highlighting how various factors contribute to the visual expression of a bridge. The primary approaches to interpreting bridge aesthetics include:

- *Structural system and form*: Different structural systems contribute to distinct aesthetic expressions, where the structural system itself often becomes the dominant architectural feature of the bridge (Gerges, n.d.). Bridge types such as arch bridges, suspension bridges, and cable-stayed bridges are commonly associated with longer spans and often possess strong visual identities. In contrast, beam bridges and slab frame bridges are typically used for shorter spans and are generally characterized by simpler and more functional forms (Otak, 2024). The structural form of a bridge is fundamentally related to how forces are transferred through the structure, including axial forces, bending, and curvature (Tang, 2018).

The aesthetic expression of bridges is therefore closely connected to the structural system and the underlying force flow shaping the bridge geometry.

- *Functionality*: The function of a bridge plays a central role in determining its form and aesthetic character (Pipinato, 2021). For example, pedestrian and bicycle bridges often allow for greater architectural freedom and variation due to lower structural demands and their role within urban environments. In contrast, highway and railway bridges are typically more constrained by structural efficiency, safety requirements, and standardization.
- *Degree of distinctiveness*: Bridges can be categorized based on their degree of distinctiveness, ranging from landmark bridges to more standardized bridges (Maryland Department of Transportation, 2005). Landmark bridges are often associated with larger spans or special locations, where aesthetic expression and visual identity play a significant role in the overall design. Such bridges may also be developed through architectural competitions. In contrast, more standardized solutions designed for efficiency, economy, and constructability, often referred to as "workhorse bridges," typically have a lower degree of distinctiveness. These bridge types represent the majority of bridges in practice, where the aesthetic expression is generally more restrained and derived from proportion, detailing, and structural consistency rather than uniqueness.
- *Materials*: Material availability plays a fundamental role in shaping both the structural form and aesthetic expression of a bridge (Sundqvist, 2000). The most commonly used materials in bridge construction are concrete, steel, and wood, and the choice of material is a key determinant of the type of structural system that can be designed. Historically, the development of new materials has enabled new types of bridge structures and expanded the possibilities for design (Tang, 2018). For example, the introduction of steel allowed for longer spans and more slender and expressive forms. Thus, material availability not only determines what can be built, but also influences the level of aesthetic freedom in bridge design. As new materials continue to develop, new structural solutions and visual expressions may emerge.

Beyond these broader interpretive perspectives, guidelines on bridge aesthetics suggest that the visual perception of bridges can also be structured according to levels of importance, distinguishing between primary and secondary determinants, as shown in Table 2.1 (Maryland Department of Transportation, 2005; Showers, 2011). The primary determinants, ranked in order of importance, begin with (1) the overall structural form, as the geometry of the bridge is typically the first aspect perceived by observers. In particular, the vertical and horizontal geometry, as well as the bridge's relationship to its surrounding environment, are considered the most significant determinants of its appearance. This is followed by (2) the type and configuration of the superstructure, such as slab frame bridges, girder bridges and arch bridges, (3) support placement and span arrangement, (4) abutment placement, and (5) the shape or depth of the superstructure.

Secondary determinants include elements such as (6) support shape, (7) abutment shape, (8) parapet and railing details, (9) surface colors, textures and detailing, as well as (10) lighting, signage and landscaping (Maryland Department of Transportation, 2005; Showers, 2011). These are generally regarded as more detailed components that contribute to, but do not dominate, the overall visual impression of the bridge. While these secondary elements are often more directly associated with what is traditionally perceived as "bridge aesthetics," the primary determinants are nonetheless inherently aesthetic decisions, as they fundamentally define the overall appearance of the structure.

Table 2.1: Determinants of bridge aesthetic appearance, presented as five primary determinants that dominate the visual impression and five secondary determinants associated with more detailed aspects, structured in order of levels of importance (Maryland Department of Transportation, 2005; Showers, 2011)

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Determinants of Aesthetic Appearance	
Primary determinants	**Secondary determinants**
1. Horizontal and vertical geometry and relation to surroundings	6. Support shape
2. Superstructure type	7. Abutment shape
3. Support placement and span arrangement	8. Parapet and railing details
4. Abutment placement	9. Surface colors, textures and detailing
5. Superstructure shape	10. Lighting, signage and landscaping

2.1.3 Aesthetic principles for concrete bridges in infrastructure

The most common bridge types in Sweden are concrete slab frame bridges, slab bridges, and beam bridges, typically used for road and railway traffic (Hallberg, 2023; Janhunen, 2023). These bridge types are generally characterized by relatively simple and standardized structural systems optimized for constructability, durability, and cost efficiency. Despite their standardized nature, the aesthetic quality of these bridges remains important due to their widespread use and long service life. This section therefore focuses on aesthetic principles relevant to concrete bridges in infrastructure contexts, with particular emphasis on structural form, proportions, symmetry, and geometric composition.

2.1.3.1 Variation of superstructure depth along the span

The variation of superstructure depth along the span can significantly influence the visual expression of a bridge (Maryland Department of Transportation, 2005). The structural depth may either remain constant or vary along the span, as illustrated in Figure 2.2. Variations in structural depth are often percievd as more dynamic and elegant compared to bridges with constant-depth superstructures.

One example of varying structural depth is haunched girders, where the depth increases near the supports (Transport for NSW, 2023). This creates a smooth and gradual transition between the pier and the bridge deck, in contrast to constant-depth beams where the transition is more abrupt. Haunches can be found either tapered or as parabolic, where smooth curves are generally preferred for a more harmonious appearance. In addition to improving visual continuity, haunches adds to the structural efficiency by helping the bridge to withstand the increased bending forces that appears near the supports. Another example is having curved girder, making the whole bridge deck curved, giving an elegant look.

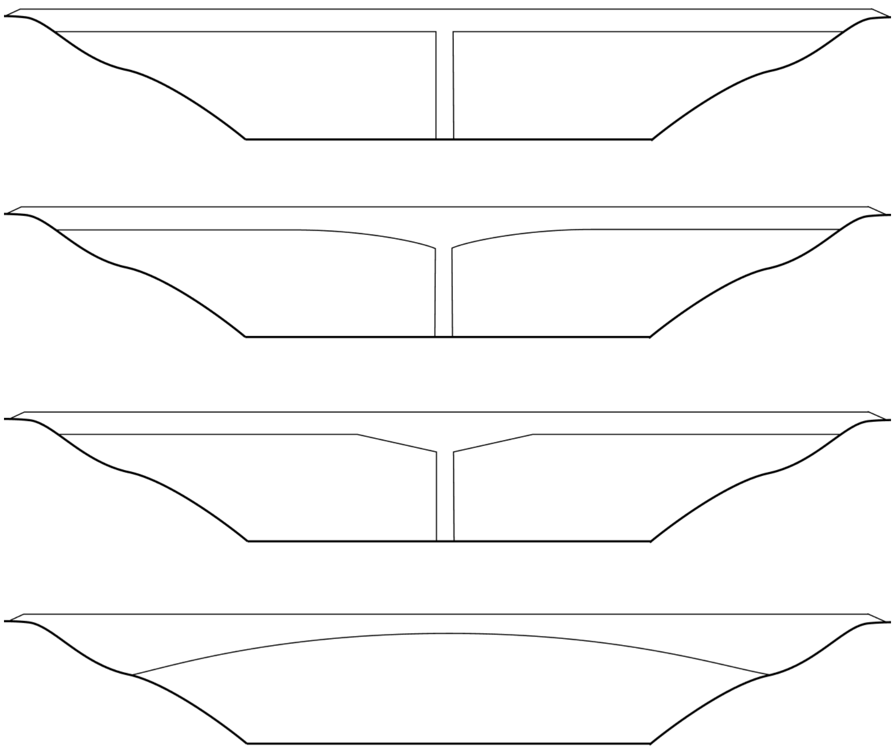


Figure 2.2: Illustration of the different girder elevation types considered in the study: constant depth (top), haunched girders: parabolic (second), and tapered (third), and complete curved (bottom).

2.1.3.2 Abutments

The connection between the bridge and the surrounding land has a considerable influence on how the bridge is perceived (Alberta Infrastructure and Transportation, 2005). If the supports are relatively close to the road beneath the bridge, the structure may appear more bulky and massive. In contrast, when the abutments are positioned further away from the road, the space beneath the bridge becomes more open, giving the structure a more slender appearance, as illustrated in Figure 2.3.

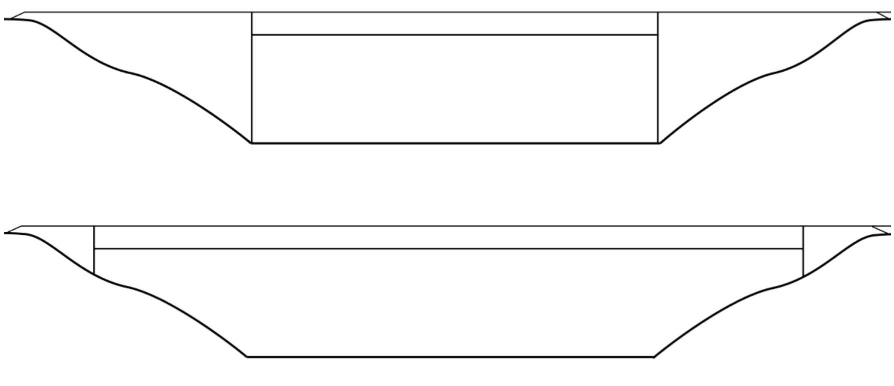


Figure 2.3: Illustration of different abutment configurations: abutments positioned close to the road, representing a common slab frame bridge configuration (top), and abutments positioned further away from the road (bottom).

In addition, if the bridge superstructure is continuous over the abutments, the bridge can appear more elegant as the shadow line of the superstructure reduces the visual dominance of the abutment (Transport for NSW, 2023). The abutment walls may also be slightly angled, which can reduce their visual mass and create a smoother transition between the bridge and the surrounding landscape. See Figure 2.4.

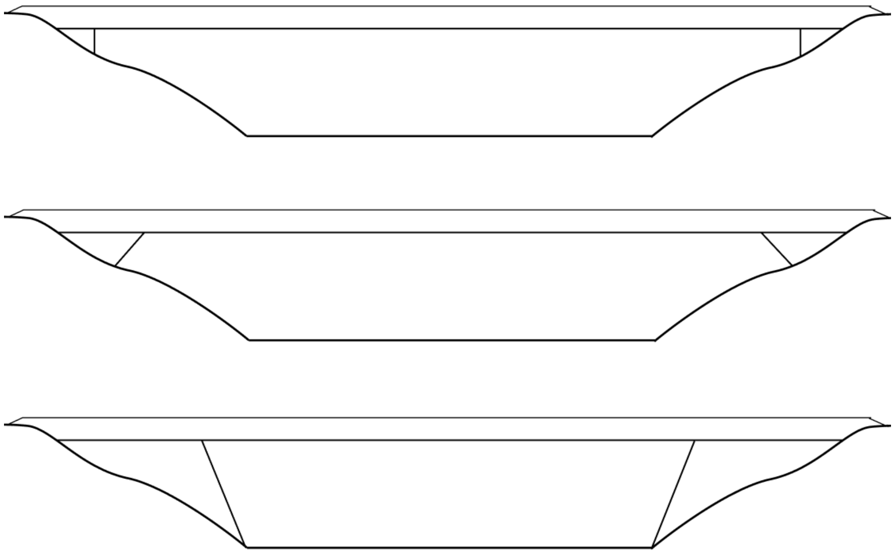


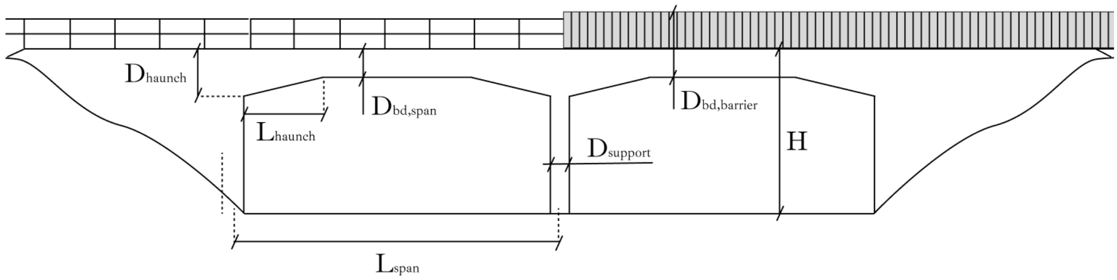
Figure 2.4: Illustration of different abutment configurations with continuous bridge superstructure considered in the study: supports positioned further away from the road (top), abutments positioned further away from the road and tilted inwards (middle), and abutments positioned closer to the road and tilted outwards (bottom).

2.1.3.3 Support geometry

Several aspects may influence the aesthetic appearance of bridge supports, including cross-sectional geometry, tapering, spacing, and the relationship between the support and the superstructure (Transport for NSW, 2023). Rectangular, circular, elliptical, and tapered pier geometries may create different visual impressions depending on the surrounding context and bridge type. Rectangular supports with sharp edges may create a more rigid and structural appearance, while rounded or elliptical geometries are often perceived as softer and visually lighter. Tapered supports may contribute to a more refined and slender expression by visually emphasizing the transfer of forces toward the foundation.

2.1.3.4 Proportions

The proportions of a bridge have a significant influence on how its aesthetics are perceived. Proportion describes the relationship between different elements of a structure, including their relative sizes and how they relate to the whole (Minnesota Department of Transportation, 1995). These relationships contribute to the overall visual balance and coherence of the structure. However, achieving appropriate proportions alone does not guarantee a high aesthetic quality. As noted by Parke and Hewson (2022), proportional guidelines and formulae may help establish a sense of order, but they should not be seen as a substitute for the designer's own judgment and intuition. Instead, they should be used as supportive tools within a broader design process.



L_{span}	Span length	D_{haunch}	Haunch depth
$D_{\text{bd,span}}$	Bridge deck depth at midspan	L_{haunch}	Haunch length
$D_{\text{bd,barrier}}$	Visible deck depth incl. barrier	H	Bridge height above ground
D_{support}	Support thickness		

Figure 2.5: Proportions illustration of a slab frame bridge with geometric parameters used for proportional evaluation.

The following proportional relationships are commonly referenced in bridge aesthetic literature and design guidelines. Each describes a geometric ratio that has been associated with visual balance or structural expression in concrete bridge design. The parameters used are illustrated in Figure 2.5.

Slenderness ratio One of the most common proportional relationships in bridge design is the relationship between the span length L_{span} and the structural depth of the superstructure $D_{\text{bd,span}}$, commonly referred to as the *slenderness ratio* (Minnesota Department of Transportation, 1995). Higher slenderness ratios generally correspond to visually lighter and more elegant bridge structures, while lower ratios result in a heavier and more massive appearance. Design guidelines indicate that typical values range approximately between 5 and 35 (Transport for NSW, 2023). The perceived slenderness of the bridge is also influenced by the visual mass and height of the abutments (Minnesota Department of Transportation, 1995). Bridges with shallow and visually lighter abutments are typically associated with higher slenderness ratios (above 24), while bridges with deeper and visually heavier abutments, as for example seen in Figure 2.5, may require lower slenderness ratios (below 22) in order to achieve balanced overall proportions. The slenderness ratio is expressed in equation C.10 below.

$$P_1 = \frac{L_{\text{span}}}{D_{\text{bd,span}}} \tag{2.1}$$

Bridge height to span ratio Another proportional relationship commonly considered is the ratio between the bridge height H and the span length L (Transport for NSW, 2023). This ratio is treated primarily as a contextual parameter rather than a form parameter, reflecting the principle that higher bridges typically require wider spans in order to avoid dense support arrangements and achieve better landscape integration. The ratio between height and span length is defined in equation 2.2. The span length should in general be designed longer than the height of the bridge.

$$P_2 = \frac{H}{L_{\text{span}}} \tag{2.2}$$

Once the ratio between span and vertical clearance, P_2, has been determined for the main span, it should, where possible, remain constant, such that any variation in structural height results in a proportional adjustment of the span lengths (Maryland Department of Transportation, 2005).

Support width proportion Another proportional relationship commonly considered is the ratio between the support width D_{support} and the superstructure depth D_{bd} (Transport for NSW, 2023). From an aesthetic perspective, the supports should not dominate the visual composition of the bridge. Instead, the primary visual emphasis should remain on the horizontal lines of the superstructure. Low ratios may result in supports that appear overly slender and visually unstable, while high ratios can create a heavy or bulky appearance.

For bridges with solid barriers or noise screens, proportions within the interval $0.25 < P_3 < 0.5$ are commonly considered visually balanced (Minnesota Department of Transportation, 1995). In cases where the bridge deck is designed with a more transparent barrier, such as a railing or parapet, the perceived depth of the superstructure is reduced. This may require slightly larger support proportions, typically within the interval $0.5 < P_3 < 0.67$. The support width proportion is defined in Equation C.11.

$$P_3 = \frac{D_{\text{support}}}{D_{\text{bd,barrier}}} \quad \text{or} \quad P_3 = \frac{D_{\text{support}}}{D_{\text{bd,span}}} \tag{2.3}$$

Deck overhang proportion For girder bridge cross-sections, several proportional relationships associated with the deck overhang geometry are commonly considered, as illustrated in Figure 2.6. The proportion between the overhang length C and the overhang deck thickness A is commonly recommended to remain within the range 2–4 (Minnesota Department of Transportation, 1995). Similarly, the relationship between the exposed girder depth D and the overhang thickness A is also recommended to remain within the range 2–4. In addition, the proportions should generally satisfy $C > D$ and $C > B/2$, where B represents the width of the bridge deck underside. The proportional relationships are defined in Equation 2.4.

$$P_{4,1} = \frac{C}{A} \quad \text{and} \quad P_{4,2} = \frac{D}{A} \tag{2.4}$$

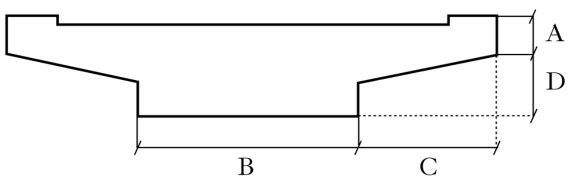


Figure 2.6: Illustration of deck overhang geometry and proportional relationships for girder bridge cross-sections.

In addition to the proportional relationships of the deck overhang itself, deck overhangs may also influence the perceived slenderness described by Equation C.10 (Minnesota Department of Transportation, 1995). The overhang creates shadows on the supporting beam, visually emphasizing the thinner upper element and contributing to a lighter structural appearance.

Haunch depth proportion When using haunches, the depth ratio between the support and midspan should be considered. The haunch depth is generally recommended to remain below approximately twice the midspan depth (Minnesota Department of Transportation, 1995). Values within the interval $1.33 \leq P_5 \leq 2.0$ are commonly considered to provide balanced proportions. The proportion is defined in Equation 2.5.

$$P_5 = \frac{D_{\text{haunch}}}{D_{\text{bd,span}}} \tag{2.5}$$

Haunch length proportion To achieve a balanced design, haunches should be proportionate to the span length and avoid short or abrupt transitions (Maryland Department of Transportation, 2005). Gradual tapers are generally perceived as more graceful and structurally expressive than short haunches (Transport for NSW, 2023). The proportion between the haunch length and the span length is defined in Equation 2.6. Values within the interval $0.10 \leq P_6 \leq 0.40$ are generally considered appropriate, while proportions around $P_6 \approx 0.33$ are often regarded as visually favorable.

$$P_6 = \frac{L_{\text{haunch}}}{L_{\text{span}}} \tag{2.6}$$

Proportions related to support arrangements The spacing and number of supports may also affect the perceived simplicity and visual clarity of the (Minnesota Department of Transportation, 1995). Closely spaced supports may create a visually heavy or cluttered appearance, while fewer and more slender supports may contribute to a lighter and more elegant structural expression.

2.1.3.5 Symmetry

Symmetry plays an important role in the visual perception of bridges, as symmetrical compositions are often perceived as more balanced, stable, and aesthetically pleasing (Transport for NSW, 2023). Figure 2.7 illustrates an example of asymmetry in bridge design. It shows asymmetry caused by different visual mass and geometry of the abutments, where the left side appears more heavy and the right side more open. More symmetrical arrangements are generally considered to contribute to a more balanced overall composition.

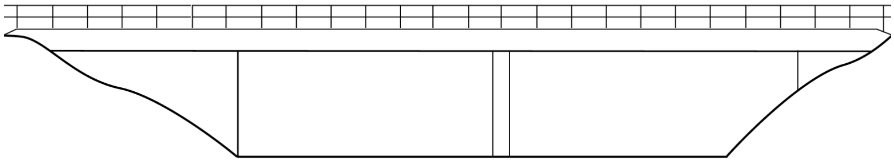


Figure 2.7: Example of asymmetry in bridge design, asymmetrical abutment geometry and visual mass.

More symmetrical support and abutment configurations are illustrated in Figure 2.4. Symmetry may not always be achievable at all sites. In some cases, asymmetry may also be effective when responding to site conditions or functional requirements, provided that an overall visual balance is maintained.

2.1.3.6 Additional parameters affecting aesthetic perception

In addition to geometric proportions and symmetry, several other parameters may influence the aesthetic perception of a bridge. These include material selection, surface treatment, parapets, joints, lighting, noise barriers, and the integration of artistic or architectural elements (Transport for NSW, 2023). Although such parameters may enhance the visual expression of a bridge, the primary aesthetic impression is still largely determined by the overall structural form and proportions (Tang, 2018).

Figure 2.8 illustrates the progression from the fundamental structural form of a slab frame bridge to the inclusion of abutment walls and finally additional detailing elements such as railings, brick-designed abutments, and street lighting. While the overall structural geometry remains unchanged, the additional detailing elements influence the architectural expression and visual character of the bridge. The comparison also illustrates the distinction between early-stage structural design and later stages of architectural refinement and detailing within the bridge design process.

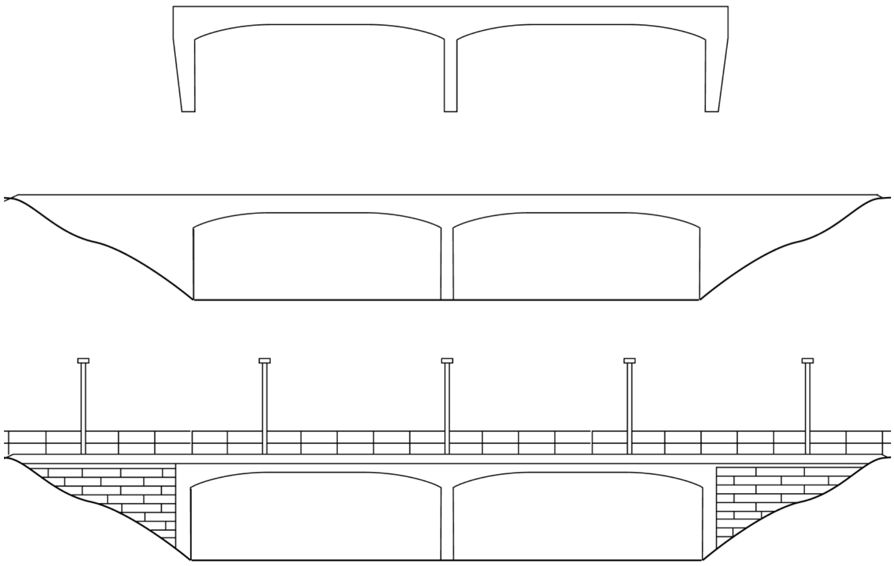


Figure 2.8: Comparison between a bridge configuration showing the primary structural form used for structural analysis (top), the same bridge including abutment walls (middle), and the bridge with additional detailing elements such as railings, brick-designed abutments, and street lighting (bottom).

2.1.4 The Swedish Transport Administration's approach to aesthetics

The Swedish Transport Administration (STA) has a *Design Manual for Road and Railway Projects*[1] (hereafter referred to as the Design Manual; Trafikverket (2024)). In this

[1]Swedish term used by the STA: *Gestaltningshandbok för arkitektur i väg- och järnvägsprojekt*

manual, aesthetics is defined as "the study of the perception of beauty" (own translation, p. 89). Within the STA, aesthetics is not treated as an isolated visual concern, but as an integral part of infrastructure quality, influencing how road and railway projects are perceived, accepted, and integrated into their surroundings. Aesthetics is embedded within the broader concept of *gestaltning*[2], which encompasses not only visual appearance, but also spatial coherence, scale, adaptation to context, and how the structure is experienced in relation to its surroundings.

2.1.4.1 Aesthetics as qualitative judgment

A recurring theme in the Design Manual is that aesthetic quality depends on the specific context. Rather than prescribing universal forms, the guidelines emphasize adaptation to landscape, surrounding infrastructure, and cultural setting (Trafikverket, 2024).

Many decisions that affect the aesthetic quality of a bridge are made in the early stages, when the geometric layout, structural system, and overall form are defined. Later stages usually refine these qualities rather than define them from the beginning (Trafikverket, 2024). This means that aesthetic considerations need to be addressed early, before design changes become more costly and time-consuming.

Although the Design Manual provides guidance and examples, it does not propose quantitative methods for evaluating aesthetics. Instead, aesthetic assessment is framed as a qualitative and professional judgment, informed by experience and contextual understanding. The manual often uses reference projects and illustrative examples to communicate desirable aesthetic outcomes.

2.1.4.2 Turning aesthetic intentions into measurable requirements

The Design Manual states that overarching aesthetic ambitions should be "concretized into measurable requirements" (Trafikverket, 2024, own translation, p. 54). This should not be understood as a complete quantification of aesthetics. Instead, qualitative goals are translated into clear and verifiable design requirements, making it possible to assess whether a proposed solution follows the intended aesthetic principles. In this context, 'measurable' should not necessarily be interpreted as numerically quantifiable, but rather as requirements that can be assessed in a transparent and consistent manner. An example of such a requirement could be that a bridge should not obstruct the horizon when viewed from a specific location. Although this criterion is not expressed numerically, it can still be evaluated in a clear and systematic way.

Within the STA, such aesthetic ambitions are typically formulated through project-specific architectural programs[3] developed during the early planning stages of infrastructure projects. The architectural design requirements can also be included as part of technical design documents for structures[4]. The planning and design process at the STA, including the relevant project documents, is described in more detail in Section 2.2. These documents specify desired characteristics related to form, landscape integration, or visual impact, and serve as guidance during subsequent project phases.[5]

[2] Swedish term, often referred to as *architectural intentions* within this thesis.
[3] Swedish term used by the STA: *Gestaltningsprogram*
[4] Swedish term used by the STA: *PM Byggnadsverk*
[5] Consultation with landscape architect involved in infrastructure planning at the STA, February 2026.

In some projects the STA uses *design classes*[6] within the architectural programme, to systematize different bridges within a larger infrastructure project (COWI, 2022). This classification structure clarifies priorities and defines different levels of aesthetic ambition for different parts of the project. The categorization is based on a contextual analysis, including a landscape analysis and an assessment of the facility's impact from a viewer and traveler perspective. By structuring the aesthetic ambition in this way, the approach illustrates how qualitative design intentions can be formalized within a project without being fully quantified. Instead, aesthetic considerations are defined differently depending on the context and the visibility of the site.

At the same time, this type of classification can create a tension between standardization and adaptation to local conditions. While predefined ambition levels can make project management more systematic, according to consultations, they may also make aesthetic quality easier to adjust or lower when cost becomes the main priority. In contrast, aesthetic intentions that are closely connected to the specific site and project goals may be more difficult to de-prioritize, since they are clearly linked to local conditions.[7]

Alongside classification systems, structured evaluation methods have also been explored within the STA, such as the use of reference groups in early design stages to assess perceived quality and attractiveness.[8] These approaches show that aesthetic judgment can be organized and discussed in a systematic way without being fully expressed in numbers. Instead of reducing aesthetics to numerical values, such methods support structured comparison and collective evaluation, highlighting the importance of early design decisions for long-term spatial quality.

2.2 Planning and design process at the Swedish Transport Administration

Infrastructure projects within the the Swedish Transport Administration (STA) follow a structured and iterative process consisting of several stages from early problem identification to implementation (Tyréns AB, 2018).

2.2.1 Overview of the planning and design process at the STA

The overall process can be divided into five main stages, from early feasibility studies to detailed design and construction, as illustrated in Figure 2.9 (Tyréns AB, 2018).

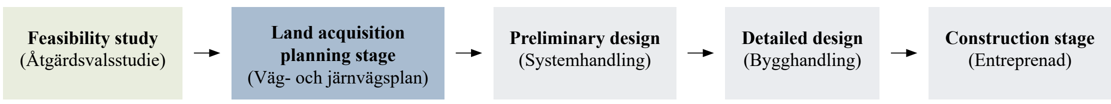


Figure 2.9: Overview of planning process at the Swedish transport administration.

The process begins with a feasibility study[9], which focuses on identifying and understanding the transport-related problem in a broad and system-oriented context (Trafikverket, 2021). Within this stage, the STA applies a four-step principle as a general method-

[6] Swedish term: *gestaltningsklasser*
[7] Consultation with architect involved in bridge and infrastructure projects at the STA, February 2026.
[8] Consultation with architect involved in bridge and infrastructure projects at the STA, February 2026.
[9] Swedish term used by the STA: *Åtgärdsvalsstudie*

ological approach to support more efficient and sustainable decision-making, which is shown in Figure 2.10. The principle first evaluates whether a problem can be solved without physical interventions in the infrastructure system, for example by influencing transport demand or travel behavior. If such measures are insufficient, the second step considers how the existing infrastructure can be optimized, such as through improved traffic management. If optimization is not adequate, the third step involves limited reconstruction or upgrading of the existing infrastructure. Only when all these steps are insufficient does the fourth step, new construction, become relevant, usually involving significant investments and physical interventions.

Figure 2.10: Feasibility study – four-step principle

If the feasibility study demonstrates that new construction or major reconstruction is required, the land acquisition planning stage[10] begins (Tyréns AB, 2018) . This process is regulated by Swedish legislation and ultimately leads to a legally binding document road or railway plan. The process is iterative and involves a gradual refinement of the project from early concepts to a finalized proposal. Throughout the process, the plan evolves through four formal stages, which produce an Initial consultation document, Consultation stage document, Review document and approval document.

During the land acquisition planning stage, several core tasks are carried out (Tyréns AB, 2018) . These include the investigation of alternative locations and design solutions, environmental assessments, and the progressive development of technical design. A central component in this stage is stakeholder consultation[11], where the STA consults with authorities, municipalities, organizations, and the public. In parallel, a preliminary design[12] is continually developed and refined, providing a basis for decisions throughout each stage of the land acquisition plan. (Tyréns AB, 2018).

After the planning stages have been completed and the Approval document[13] has been approved and gained legal force, the project moves into a more detailed design phase (Tyréns AB, 2018) . At this stage, the focus shifts from evaluating alternatives to developing detailed drawings and technical solutions based on the chosen design established during the planning process. This involves refining the selected alignment and layout into a preliminary design, with more technical specifications, calculations and analyses required for construction.

Based on this work, a detailed design[14] is prepared (Tyréns AB, 2018) . These documents contain detailed drawings of the approved design, along with technical descriptions, material specifications, and instructions for execution. In this sense the detailed design translates the selected solution from the planning stage into a form that can be directly implemented.

[10]Swedish term used by the STA: *Väg- och järnvägsplan*
[11]Swedish term used by the STA: *Samråd*
[12]Swedish term used by the STA: *Systemhandling*
[13]Swedish term used by the STA: *Fastställelsehandling*
[14]Swedish term used by the STA: *Bygghandling*

Once the detailed design documents are finalized, the project enters the final stage, construction, where the infrastructure is built based on the approved design and technical specifications developed throughout the previous stages (Tyréns AB, 2018) .

2.2.2 Integration of architectural and aesthetic considerations

Architectural and aesthetic considerations are primarily integrated during the land acquisition planning stage (Trafikverket, 2024). The overall objective at this stage is to determine both where and how the structure will be built. The land aquisition planning stage contains several steps, illustrated in Figure 2.11.

In the early phases of this stage, aesthetic considerations are introduced through analysis of the site and context, as well as reviewing existing material from previous studies and projects (Trafikverket, 2024). This includes understanding of the landscape and how different user groups may percieve and interact with the infrastructure. The outcome of this phase is Architectural intentions, which define the overall ambitions and goals for the project and Initial landscape analysis (ILKA).

During the next stage, the consultation stage, aesthetics considerations are further developed by generating ideas and through further exploring and comparing different solutions (Trafikverket, 2024). The level of detail is intentionally kept relatively low, as the focus is on comparing overall concepts rather than final solutions. During the localization investigation, aesthetic aspects are considered in relation, aesthetic aspects are assessed in relation to the broader urban context, including the need for structures such as bridges. The outcome of this stage is results in documents such as the Architectural programme for location, the preliminary architectural programme, and the landscape analysis.

Once a main alternative has been selected, the design is gradually refined with increasing detail (Trafikverket, 2024). The focus shifts towards feasibility and constructability, but previously defined aesthetic intentions continue to guide the design and are consolidated in the final architectural programme.

Although these architectural programmes provide a comprehensive description of the intended design, they do not have legal status and are therefore not formally binding (Trafikverket, 2024). As a result, aesthetic ambitions may occasionally be reconsidered during procurement or later project stages if alternative solutions are proposed that offer significant cost savings. This reflects a common challenge in infrastructure projects, where economic and technical considerations may ultimately take precedence over initially stated design intentions.[15] However, it is important that the implemented design remains consistent with what has been communicated during the planning process, particularly in earlier consultation stages (Trafikverket, 2024).

[15]Consultations with an architect and a bridge engineering specialist involved in bridge design and infrastructure projects at the STA, February–March 2026. The observation is also supported by consultations with a civil engineer specializing in bridge and infrastructure at a consultancy firm collaborating with the STA, February 2026.

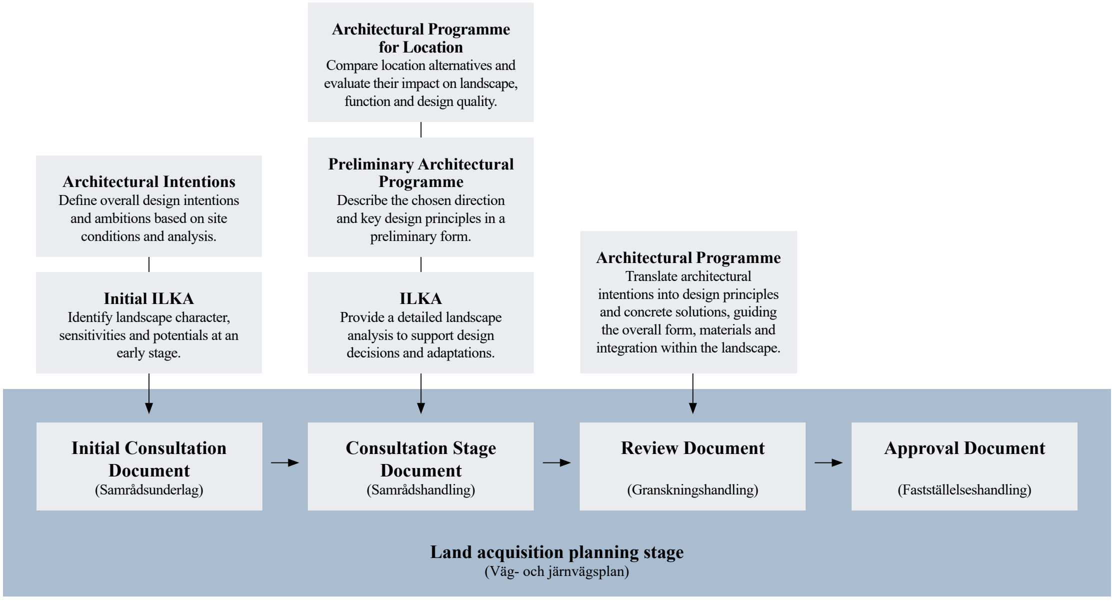


Figure 2.11: Architectural design contribution within the land acquisition planning stage.

2.2.3 Importance of early-stage decisions

Decisions made during the early stages of a project have a major influence on the final outcome. The MacLeamy curve, illustrated in Figure 2.12, shows how the ability to influence a design project changes throughout the design process (The American Institute of Architects, 2007). During the early stages, the freedom to explore and modify design alternatives is high, while the cost of implementing changes remains relatively low. As the project progresses, design flexibility gradually decreases, whereas the cost of modifications increases significantly. Consequently, early-stage decisions play a critical role in shaping the final design outcome.

Professional consultations indicate that many design decisions with long-term aesthetic consequences are made during the earliest planning stages, when the overall alignment, structural system, and main geometry of the infrastructure are defined.[16] Later design phases tend to focus more on refinement and technical detailing rather than fundamental form decisions. Several practitioners further emphasized that aesthetic considerations are often difficult to introduce during later stages of the process, as structural solutions and economic constraints have already been largely established. [17] Early exploration of multiple design alternatives is therefore considered particularly valuable when aesthetic considerations are to be integrated alongside technical and economic criteria.

[16]Consultation with landscape architect involved in infrastructure planning at the STA, February 2026.

[17]Consultations with professionals involved in bridge planning and infrastructure projects, February 2026.

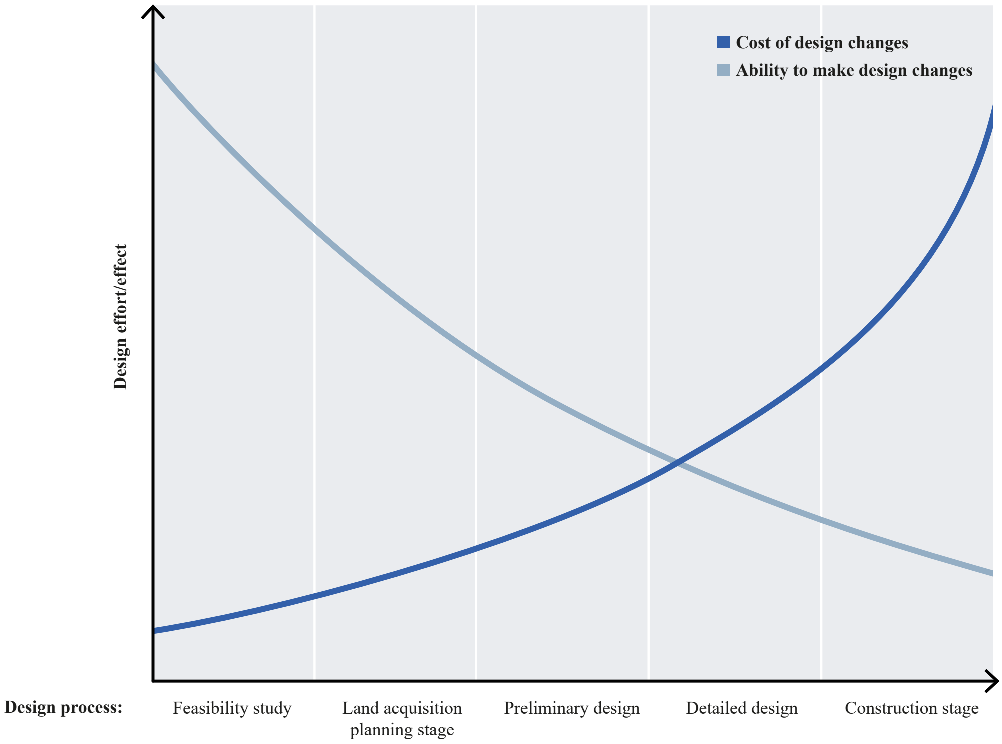


Figure 2.12: Macleamy curve illustrating the cost and design alternatives throughout the process. Adapted from and inspired by The American Institute of Architects (2007).

2.3 Design methodologies

This section introduces design methodologies and digital approaches relevant to this study. It first contrasts point-based and set-based design, as this distinction forms the methodological basis for the proposed approach. Computational and parametric design are then presented as tools for generating and managing multiple design alternatives within a set-based design process. Finally, parametric optimization, design space exploration, and the use of artificial intelligence and machine learning are discussed in relation to the evaluation of quantitative and qualitative criteria.

2.3.1 Point-based design

Point-based design (PBD) represents the conventional approach to engineering design. In this approach, a limited number of alternatives are generated and one preferred solution is selected early in the process, which is then refined further throughout the project (Parrish et al., 2007). This approach can be efficient when the design requirements and project conditions are clear. However, in early-stage projects characterized by incomplete information and evolving criteria, early commitment to a single concept may reduce flexibility and restrict the ability to accommodate new requirements (Mathern et al., 2018; Parrish et al., 2007). Mathern et al. (2018) further argue that because of this, the PBD approach contributes to challenges in addressing sustainability goals and diverse stakeholder demands within civil engineering projects.

2.3.2 Set-based design

The concept of set-based design (SBD) was developed in the 1990s within the car manufacturing industry. It was initially referred to as *the second Toyota paradox* (Ward et al., 1995), and is viewed as a key ingredient of Toyota's economic success (Parrish et al., 2007). In contrast to PBD, SBD does not rely on selecting one preferred solution at an early stage. Instead, it maintains a broad range of possible design alternatives, which are developed and evaluated in parallel (Parrish et al., 2007). Rather than choosing a single concept too early, SBD works by defining a broad design space of possible solutions and gradually removing alternatives that do not meet the required criteria (Sobek II et al., 1999). As more information and constraints are added, the design space is progressively narrowed down.

Within structural engineering, SBD has been introduced as a method for handling complex design problems involving multiple evaluation criteria and uncertainty in early project stages (Mathern et al., 2018; Parrish et al., 2007). A systematic literature review by Castañeda et al. (2023) shows that the use of SBD in construction projects is associated with several recurring benefits. The most frequently reported are more transparent decision-making processes, improved collaboration in decision-making, and better communication among designers. According to the authors, these benefits are linked to the fact that SBD evaluates several alternatives in relation to project requirements, which supports more explicit comparison of options and encourages interaction between design disciplines. The review also highlights important difficulties related to implementation, particularly inadequate organizational structures for adopting SBD, lack of staff experience, and resistance to change in organizations.

Mathern et al. (2018) demonstrate how SBD can be combined with parametric modeling to systematically generate and evaluate large numbers of structural alternatives. In this context, SBD should not be understood as a detailed optimization method in itself, but as a structured framework for design space exploration and preliminary decision-making. Within this framework, computational methods can be used to define, generate, evaluate, and compare multiple design alternatives.

2.3.2.1 Design spaces within SBD

The way design spaces are formulated may vary depending on the objectives and evaluation criteria of a specific study or project. Previous work by Bergenram and Ulander (2023) structured the implementation of a set-based multi-criteria optimization algorithm for a single span slab frame bridge into a sequence of four design spaces, denoted Design Spaces *A*–*D*. This methodology is illustrated in Figure 2.13.

Design Space *A* represents the most inclusive set and contains all conceivable design alternatives within the modeling framework, regardless of feasibility or predefined geometric limitations. Design Space *B* is defined by applying the governing input parameters selected for the study, such as span length and overall geometry. Within this space, both feasible and infeasible solutions may still be present. Design Space *C* consists of the subset of Design Space *B* that satisfies structural verification requirements, evaluated through ULS and SLS checks. The feasible alternatives in Design Space *C* are then evaluated according to the selected objective functions. In the study by Bergenram and Ulander (2023), this final evaluation resulted in Design Space *D*, defined as the set of optimized solutions with the lowest objective function values among the feasible alternatives. Their selected objectives included investment cost, environmental impact, and buildability.

The transition from Design Space *A* to *D* illustrates how SBD supports the transparent and traceable reduction of alternatives while retaining a broad set of parallel design solutions throughout the design process.

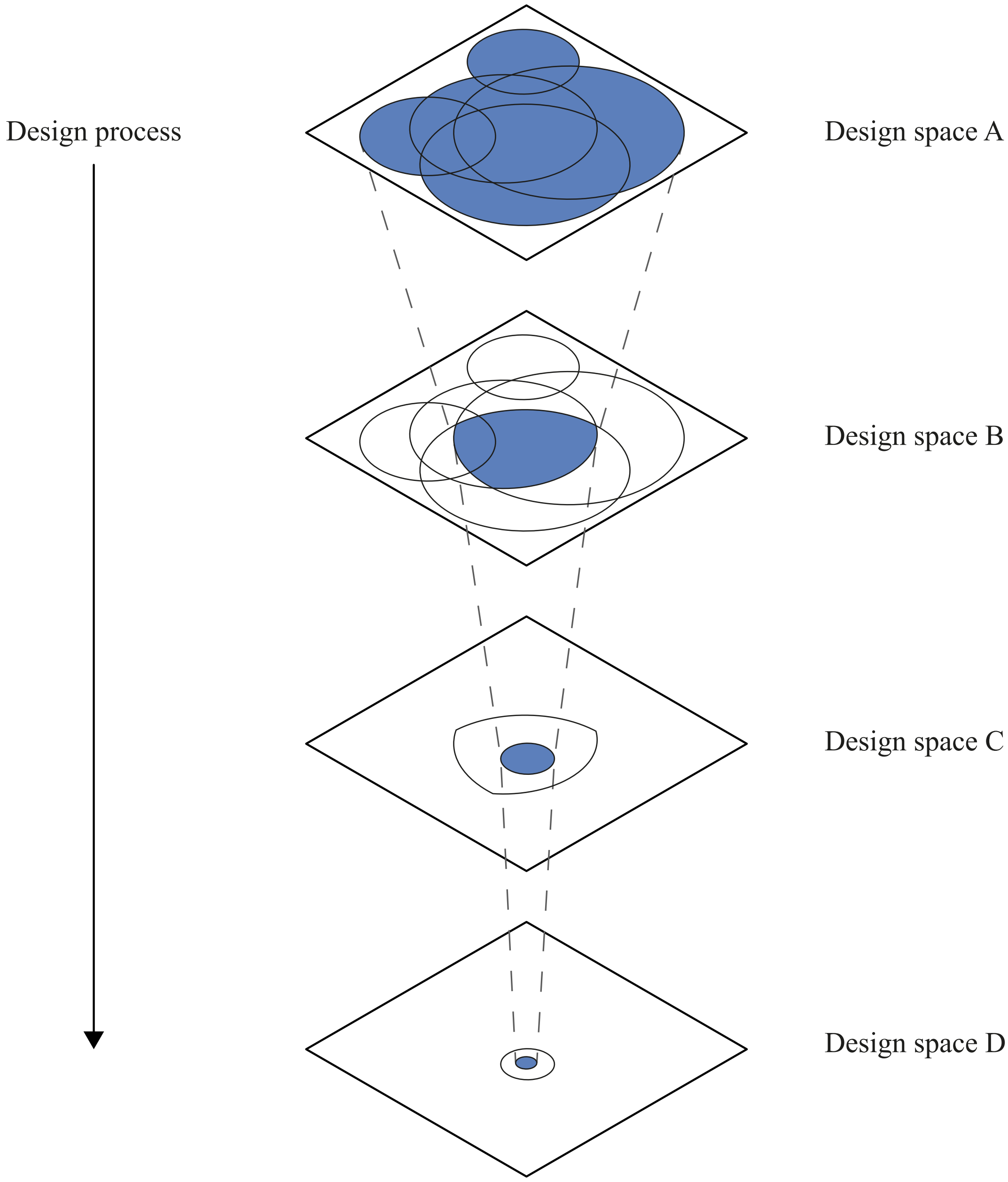


Figure 2.13: Conceptual illustration of a set-based design process, showing the progressive narrowing of solution spaces during the design process. Inspired by and adapted from Bergenram and Ulander (2023) and Sobek II et al. (1999).

2.3.3 Computational and parametric design

Computational design can be understood both as a structured way of approaching design problems through computational thinking and as a collection of digital methods and tools that support this approach (Yu et al., 2021). Within this framework, parametric design refers to a modeling approach in which geometry, performance, and constraints are defined through different parameters and their relationships (Girardet & Boton, 2021; Lee & Ostwald, 2020). By establishing relationships between parameters, a change in input values immediately leads to a different result. This makes parametric design a flexible tool, allowing quick and systematic generation of multiple design alternatives. Parametric modeling is therefore particularly useful in early-stage design, where many aspects of the problem are uncertain and where exploring a broad range of alternatives is more valuable than refining a single solution.

2.3.4 Parametric optimization

Parametric optimization can be viewed as a further development of parametric design, in which the parameters and their relationships are not only used to generate alternative designs, but also to evaluate and improve them with respect to different performance criteria.

To further describe a parametric optimization, three fundamental components must be defined: design variables, objective functions, and constraints (Martins & Ning, 2021).

- *Design variables* are the parameters that can be changed during the optimization process. They define the possible design alternatives within the design space. The variables can be represented as a vector:

$$x = [x_1, x_2, \ldots, x_{n_x}] \tag{2.7}$$

  where n_x is the number of variables. Each vector x represents a specific design solution.

- *Objective functions* describe the performance of a design and define what should be minimized or maximized. An objective function depends on the design variables and can be written as $F(x)$. An optimization problem can have one or several objectives, the later further described in Section 2.3.4.1.

- *Constraints* define the limitations that the design must satisfy. These may represent physical laws, structural requirements, or practical restrictions. Constraints restrict the feasible design space and ensure that only acceptable solutions are considered. Constraints can be formulated either as equality constraints, $h_k(x) = 0$, which enforce an exact relationship, or as inequality constraints, $g_j(x) \leq 0$, which restrict the design to remain within specified limits.

Together, the design variables, objective functions, and constraints define the mathematical formulation of the optimization problem. The design variables determine the possible solutions, the objective functions evaluate the performance of each solution, and the constraints define which solutions are feasible. The goal of the optimization process is therefore to identify the values of the design variables that optimize the objective function while satisfying all constraints (Martins & Ning, 2021). In contrast to manual exploration of parameter variations, algorithmic optimization methods systematically search the design space to find such solutions in an efficient and structured manner.

In its general form, a single-objective optimization problem can be written as (Martins & Ning, 2021):

$$\begin{array}{lll} \text{minimize} & F(x) & \\ \text{by varying} & \underline{x}_i \leq x_i \leq \bar{x}_i, & i = 1, \ldots, n_x \\ \text{subject to} & g_j(x) \leq 0, & j = 1, \ldots, n_g \\ & h_k(x) = 0, & k = 1, \ldots, n_h \end{array} \tag{2.8}$$

where

- $x = [x_1, x_2, \ldots, x_{n_x}]$ is the vector of design variables,
- $\underline{x}_i$ and $\overline{x}_i$ are the lower and upper bounds of the ith design variable,
- $F(x)$ is the objective function,
- $g_j(x)$ denotes the jth inequality constraint,
- $h_k(x)$ denotes the kth equality constraint,
- n_x is the number of design variables,
- n_g is the number of inequality constraints,
- n_h is the number of equality constraints.

2.3.4.1 Multi-objective optimization

In structural engineering applications, optimization is often formulated as a multi-objective problem, where several potentially conflicting objectives must be considered simultaneously. Typical objectives can be to minimize cost and CO_2 emissions while at the same time maintaining structural safety. Such problems typically involve trade-offs between different objectives, where improvements in one may lead to compromises in another (Mathern et al., 2021).

Multi-objective optimization does not necessarily yield a single optimal solution, but rather a set of alternatives representing different balances between competing criteria. There are different ways to approach a multi-objective problem, but a common way is to classify the quality of individual solutions in terms of *Pareto optimality* (Miettinen, 1998). A solution is said to be Pareto optimal if no other feasible solution exists that improves at least one objective without simultaneously worsening at least one other objective (Marler & Arora, 2004). The set of corresponding objective values for these solutions forms the *Pareto front*, which illustrates the trade-offs between competing objectives. The concept of Pareto optimality is illustrated in Figure 2.14, which also shows the *ideal point*, representing a theoretical solution with the lowest possible value of all objectives simultaneously. In practice, such a solution does not usually exist within the feasible design space.

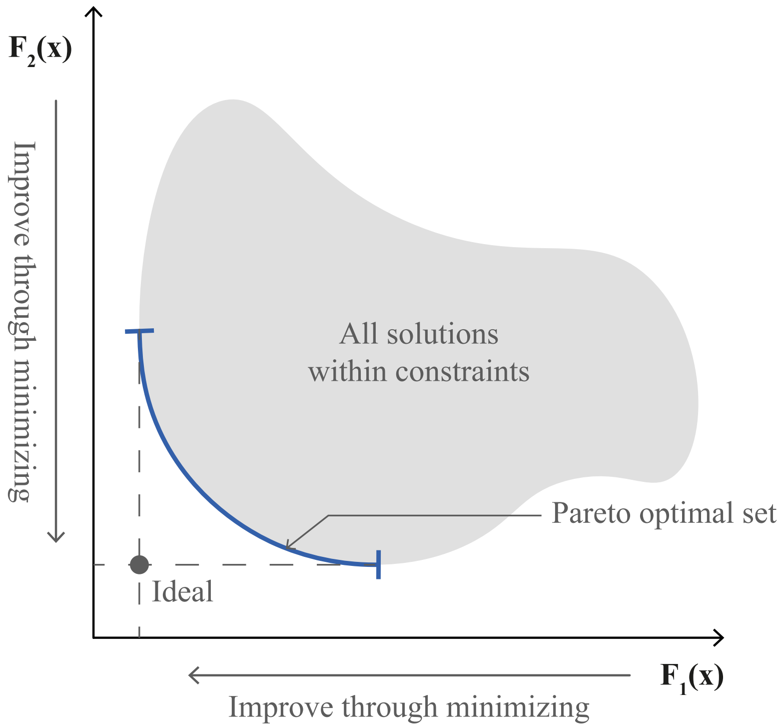


Figure 2.14: Pareto optimal solutions for the objective functions $F_1(x)$ and $F_2(x)$. The blue line represents the Pareto front. The illustration is inspired by and adapted from Miettinen (1998).

One common approach to multi-objective optimization is the *weighted sum method*, in which each objective function is assigned a weighting factor and combined into a single scalar utility function, also referred to as a global criterion function. This approach transforms the multi-objective problem into a single-objective formulation, which can be solved using conventional optimization techniques (Marler & Arora, 2004). The weighted sum method can be mathematically expressed according to Equation 2.9:

$$U = \sum_{i=1}^{k} w_i \cdot F_i(x) \tag{2.9}$$

where

- U is the scalar utility (global criterion) function,
- k is the number of objective functions,
- $F_i(x)$ is the ith objective function,
- x is the vector of design variables,
- w_i is the weighting coefficient associated with objective i.

For positive weighting coefficients, which is the common case, the minimum of Equation 2.9 is Pareto optimal. The weighting coefficients are often normalized such that the total sum equals one (Martins & Ning, 2021):

$$\sum_{i=1}^{k} w_i = 1 \tag{2.10}$$

Since the original objective functions may be expressed in different units and differ in numerical magnitude, it can be advantageous to transform them before applying scalarization methods such as the weighted sum method. This is particularly important when preferences are assigned in advance through weighting coefficients, since differences in scale may otherwise affect the intended influence of the weights (Marler & Arora, 2004).

One way to address this issue is to recalculate the objective functions to the same unit. Bergenram and Ulander (2023) present an example of this approach, in which investment cost, environmental impact, and buildability are all represented in terms of a cost. In their study, environmental impact is expressed as an environmental cost, while buildability is represented through labour- and production-related costs. This makes the three objectives comparable through a common unit.

Another solution is to make all objective functions dimensionless, for example through normalization. According to Marler and Arora (2004), a robust normalization approach is given by Equation 2.11:

$$F_i^{\text{trans}}(x) = \frac{F_i(x) - F_i^{\circ}}{F_i^{\max} - F_i^{\circ}} \tag{2.11}$$

where

- $F_i^{\text{trans}}(x)$ is the transformed objective function i,
- $F_i(x)$ is the original objective function i,
- F_i° is the ideal point value for objective function i,
- $F_i^{\max}$ is the maximum reference value for objective function i.

Here, the ideal point is the same as that introduced above in relation to Pareto optimality. The maximum reference value may be determined in different ways, for example from Pareto-set vertices or from an absolute maximum value, if such a value exists (Marler & Arora, 2004). In practice, the ideal point value and the maximum reference value may be complicated to compute, and an approximation may therefore be used. The transformation in Equation 2.11 generally yields values between zero and one, depending on how the ideal point and the maximum reference value are determined.

The solution that Equation 2.9 gives is Pareto optimal. However, this does not mean that all Pareto-optimal solutions can be found using the weighted sum method. In particular, when the optimization problem is non-convex, certain Pareto-efficient solutions cannot be identified through this formulation. The weighted sum method can therefore guarantee that a solution is Pareto optimal, but it cannot guarantee that all possible Pareto-optimal solutions are explored (Marler & Arora, 2004). Depending on the problem, other solution methods can provide a more representative and well-distributed approximation of the Pareto front, although this generally comes at the cost of increased complexity. Examples include the *ε-constraint method*, the *normal boundary intersection* method, and *evolutionary algorithms* (Martins & Ning, 2021).

2.3.5 Design space exploration beyond optimization

Although a computational model can generate solutions to a multi-objective optimization problem, the resulting alternatives cannot be interpreted as objective truths. The outcome depends on how the objectives are formulated and weighted against each other. For example, the relative importance assigned to cost, environmental impact, or aesthetics reflects value-based judgments rather than purely technical facts. In multi-objective problems, trade-offs are unavoidable. Optimization techniques can identify Pareto-optimal solutions to multi-objective problems (as described in Section 2.3.4.1), but they cannot determine which trade-off is most appropriate in a given context. Such decisions ultimately require human interpretation and professional judgment. Miettinen (1998) defines a *decision maker* as a person, or a group of persons, with good insight into the problem who can express preferences between the different solutions. The author also emphasizes that the decision maker typically carries the responsibility for selecting the final solution.

Previous research has shown that parametric design environments can promote design creativity, showing a link between the number of generated variations and the emergence of unforeseen results that support design creativity and new ideas (Lee & Ostwald, 2020; Yu et al., 2021). However, other studies note that parametric approaches may also constrain creativity, as fixed rules and predefined parameters can limit the range of possible solutions (Yu et al., 2021).

Additional limitations become evident when qualitative values are included. Optimization methods are well suited for objectives that can be expressed as numerical functions, but qualitative aspects are generally more difficult to formalize in an objective numerical way. Aesthetics is one example of such a value, as discussed in Section 2.1. As noted by Machwe et al. (2005), qualitative criteria such as aesthetics cannot always be represented as a fixed set of numerical parameters. In such situations, a strictly numerical formulation may reduce complex design questions to overly simplified terms.

Several researchers argue that parametric and computational design tools should be understood as support for design space exploration and decision-making, rather than as replacements for human judgment and intuition (Balmer et al., 2024; Lee & Ostwald, 2020; Machwe et al., 2005; Mathern et al., 2021; Yu et al., 2021). For example, Balmer et al. (2024) show that computational design tools can support early-stage exploration by making relationships between design variables and performance criteria more transparent, even if the evaluation itself remains centered on quantitative objectives. Similarly, Mathern et al. (2021) describe multi-objective optimization as a way to generate and visualize sets of trade-off solutions for a decision maker, rather than as a procedure for automatically identifying one single optimal solution.

2.3.6 Use of artificial intelligence and machine learning for quantitative and qualitative evaluation

A further development in computational design for supporting design exploration is the use of artificial intelligence (AI) and machine learning (ML). In this context, AI is used as a broad term for intelligent computational support, while ML refers more specifically to methods that learn patterns from data or user evaluations.

When design alternatives are evaluated using quantitative performance criteria, ML models can be used to learn relationships between design variables and structural performance, which enables faster evaluation of alternatives and generation of new designs. Balmer et al. (2024) present such an approach. Their study develops a type of generative model that is trained on a large data set of alternative designs for pedestrian bridges and their structural performance. The model is used both to predict structural behavior and generate new design alternatives based on specified performance targets. However, the study is primarily based on quantifiable criteria, such as cost, structural utilization, internal forces and displacements. As discussed in Section 2.3.5, the study emphasizes the need to also apply human judgment when using the model, especially regarding qualitative aspects, that the AI does not evaluate. The model should be used as a co-pilot for design space exploration rather than replacing human judgment.

Other studies indicate that AI and ML can also be used to incorporate qualitative evaluation into the computational process. Machwe et al. (2005) describe an approach in which subjective aesthetic preferences are incorporated into an interactive computational algorithm. In this setup, the designer visually assesses generated alternatives and thereby guides the numerical representation of aesthetic preferences. After an initial phase of user evaluations, a machine learning agent infers these preferences and can continue the search process with reduced direct input from the designer. In this case, qualitative values are not used only as informal subjective judgments, but are translated into forms that the computational system can process. Machwe et al. (2005) combine two types of input: simple rule-based aesthetic criteria and numerical evaluations given by the user. The rule-based part includes features such as symmetry of support placement, slenderness ratio, and uniformity in the thickness of supports and span sections. At the same time, the user assigns a fitness value to generated alternatives, which gives the system additional information about what is considered aesthetically preferable. In this way, subjective judgment is incorporated in the algorithm, through transforming it into numerical input.

2.4 Bridge design optimization objectives

Objective functions define how design alternatives are evaluated and compared within parametric optimization and set-based design. In early-stage bridge design, such objectives should represent performance aspects that are relevant for decision-making.

Previous studies on set-based and parametric bridge design have commonly included quantitative objectives such as production cost and environmental impact. Hansson and Tacking (2024) summarize previous research on set-based bridge design and apply objective functions for production cost and environmental impact in the evaluation of bridge alternatives.

In addition to these quantitative objectives, qualitative aspects such as aesthetic quality may also influence early-stage design decisions. While aesthetics cannot be fully captured through numerical parameters, selected aesthetic principles can be related to geometric properties and considered as quantifiable criteria. The following sections present production cost, environmental impact, and quantifiable aesthetic criteria as objectives relevant for early-stage bridge design optimization.

2.4.1 Production cost

As an economic objective, production cost is defined as the sum of material cost and construction work cost. Following Mathern et al. (2021), the production cost of a design alternative can be expressed as follows:

$$C(x) = C_m(x) + C_W(x) \tag{2.12}$$

$$C_m(x) = \sum_i \rho_{m,i} \cdot Q_{m,i}(x) \tag{2.13}$$

$$C_W(x) = \rho_W \cdot T_W(x) \tag{2.14}$$

$$T_W(x) = \sum_i t_{m,i} \cdot Q_{m,i}(x) \tag{2.15}$$

where

- $C(x)$ is the total production cost,
- $C_m(x)$ is the material cost,
- $C_W(x)$ is the cost of construction work,
- $T_W(x)$ is the construction time
- x is the vector of design variables representing a specific bridge design alternative,
- $\rho_{m,i}$ is the unit price of material i,
- $Q_{m,i}(x)$ is the quantity of material i for design alternative x,
- ρ_W is the unit labor cost,
- $t_{m,i}$ is the unit construction time associated with material i.

2.4.2 Environmental impact

Regarding environmental impact, the study by Hansson and Tacking (2024) follows the procedure presented by Solat Yavari et al. (2017) in their paper about environmental impact optimization of reinforced concrete slab frame bridges; Environmental impact is expressed as the total CO_2-equivalent emissions associated with the quantities of concrete and reinforcement required for a given bridge design alternative (Solat Yavari et al., 2017):

$$E(x) = E_r(x) + E_c(x) \tag{2.16}$$

$$E_c(x) = eq_c \cdot Q_c(x) \tag{2.17}$$

$$E_r(x) = 1.4 \cdot eq_r \cdot Q_r(x) \tag{2.18}$$

where

- $E(x)$ is the total CO_2-eq [kg],
- $E_c(x)$ is the total CO_2-eq emissions from concrete [kg],
- $E_r(x)$ is the total CO_2-eq emissions from reinforcement [kg],
- x is the vector of design variables representing a specific bridge design alternative,
- eq_c and eq_r are the CO_2-eq emission factors for concrete and reinforcement steel, respectively [kg CO_2-eq/kg material],

- $Q_c(x)$ and $Q_r(x)$ are the quantities of concrete and reinforcement steel, respectively.

A factor of 1.4 is applied to the reinforcement quantity in order to account for anchorage and additional reinforcement material use due to design details, following Solat Yavari et al. (2017).

2.4.3 Quantifiable aesthetic criteria

As discussed in Section 2.1, aesthetic quality in bridge design is context-dependent and cannot be fully captured through numerical parameters alone. However, several aesthetic aspects that are relevant in early-stage bridge design can be related to geometric properties, such as proportions, symmetry, and the variation of structural depth along the span.

Within the literature reviewed in this thesis, no directly applicable reference was identified in which aesthetic criteria are formulated as objective functions within a set-based design framework for concrete bridges. The quantified aesthetic criteria used in this thesis are therefore proposed as a new approach, based on the aesthetic principles discussed in Section 2.1 and the design methodologies described in Section 2.3. The implementation of the quantified aesthetic criteria is presented in Section 3.5.3. The role of non-quantifiable aesthetic judgment within the proposed SBD method, as well as the limitations of representing aesthetic quality through quantifiable criteria, are further discussed in Chapter 5 and 6.

3 Prototype development

The digital prototype was implemented in Python. Some of the results were visualized directly in Python, and some were imported into Grasshopper and Excel for visualization. The prototype was developed for a two-span slab frame bridge, based on a case study provided by the STA. The case study was used to define the scope of the prototype, including the selected bridge typology, simplified geometric assumptions, and relevant input data. It thereby served as a representative reference case for the implementation. Some simplifications where made regarding the geometry of the case study. For example, in the real bridge project, the roadway alignment is curved in plan, whereas the prototype assumes a straight alignment. Due to the simplifications introduced both regarding geometry and in general in the prototype model, the generated alternatives were compared only with each other within the model framework, rather than directly with the actual cost or performance of the real bridge project. However, one alternative representing the case study was included in the generated solution set to enable comparison with the reference geometry under the same modeling assumptions. The input data of the simplified case study is presented in Table 3.3.

3.1 Prototype framework

The structuring of design spaces in the implementation of the present study builds on the framework proposed by Bergenram and Ulander (2023), as described in Section 2.3.2.1, but is adapted to fit the objectives of the present work.

As in the referenced study, the initial design generation defines Design Space *A* as the complete combinatorial set of bridge alternatives that can be generated within the parametric model. However, this design space is only theoretical, since not all possible combinations are explicitly retained in the implemented prototype.

Design Space *B* is defined by applying project-specific input parameters and boundary conditions relevant to the selected bridge typology. In the present prototype, the implemented code begins with this design space, defining the input data and generating the design alternatives based on them.

Design Space *C* is obtained by removing solutions that do not satisfy the constraints, in this case the structural verification requirements. In the present study, a simplified structural filtering procedure was introduced in order to ensure that the remaining solutions were structurally feasible. This is further explained in Section 3.4.

In contrast to the previous implementation, Design Space *D* is not treated as a strict filtering step where only a small number of optimized solutions remain. Instead, the feasible alternatives in Design Space *C* are evaluated with respect to production cost, environmental impact, and quantified aesthetic criteria. The weighted sum method is then used to rank the feasible alternatives and identify selected high-performing solutions for comparison and visualization. However, the full set of feasible alternatives is still retained as part of the decision-support material, enabling visual comparison, professional judgment, and consideration of non-quantifiable aspects.

3.2 Design variables and fixed input data

As described in Section 2.3.4, design variables are parameters that vary during the computational process. In the prototype, these variables define the generated design alternatives, while fixed input parameters remain constant for all alternatives.

Figure 3.1 illustrates the dimensions included in the prototype, and Table 3.1 and 3.2 states the input data leading to the prototype output presented in Chapter 4. The design space was explored and refined throughout the development process, and the values presented in the tables represent the final input data used for the prototype assessment.

As shown in Figure 3.1, the depth of the bridge deck is always constant over the span for all alternatives, apart from the haunches. Furthermore, all generated bridge alternatives are symmetrical with respect to the middle support, meaning that the same dimensions are applied to both spans.

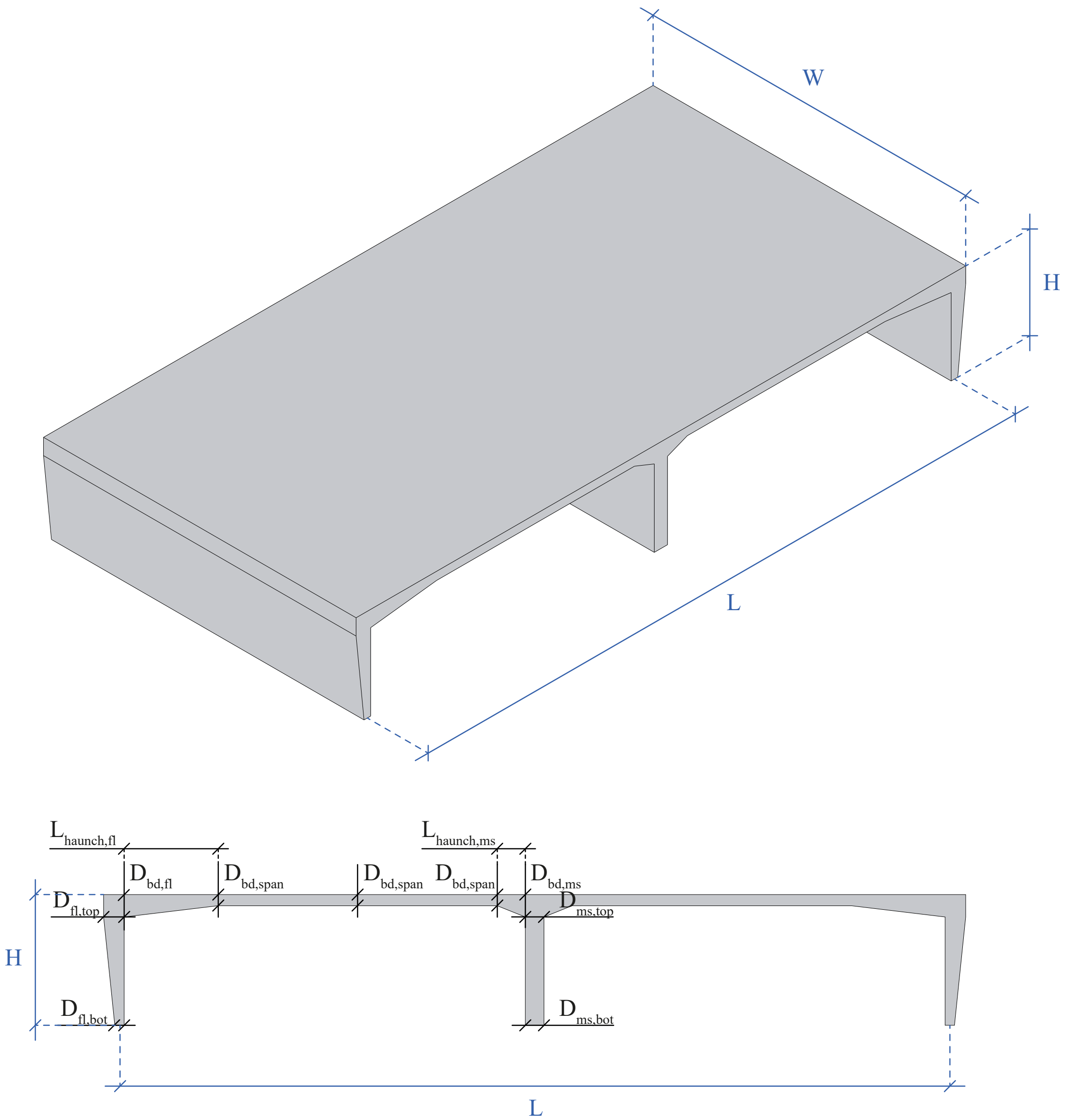


Figure 3.1: Isometric drawing and elevation view of s bridge, with dimensional design variables shown in black and fixed dimensional parameters shown in blue.

Table 3.1: Fixed input parameters.

Fixed design parameter	Value
Total theoretical span length, L [mm]	44460
Height of bridge, H [mm]	7000
Width of bridge, W [mm]	23670
Concrete class	C35/45

Table 3.2: Design variables and their discrete values.

Design variable	Values
$D_{fl,bot}$ [mm]	500, 700, 900
$D_{fl,top}$ [mm]	700, 900, 1100, 1300
$D_{ms,bot}$ [mm]	600, 800, 1000, 1200
$D_{ms,top}$ [mm]	600, 800, 1000, 1200
$D_{bd,fl}$ [mm]	800, 1000, 1200, 1400, 1600
$D_{bd,span}$ [mm]	400, 600, 800, 1000
$D_{bd,ms}$ [mm]	800, 1000, 1200, 1400, 1600
$L_{haunch,fl}$ [mm]	1500, 3000, 4500, 5000, 6000, 7500
$L_{haunch,ms}$ [mm]	1500, 3000, 4500, 6000, 7500
Haunch type	Constant depth, Tapered, Parabolic

The design variable values of the simplified case study bridge are presented in Table 3.3. This geometry is also the one illustrated in Figure 3.1.

Table 3.3: Design variable values for the simplified case study bridge.

Design variable	Values
$D_{fl,bot}$ [mm]	500
$D_{fl,top}$ [mm]	1100
$D_{ms,bot}$ [mm]	1000
$D_{ms,top}$ [mm]	1000
$D_{bd,fl}$ [mm]	1200
$D_{bd,span}$ [mm]	600
$D_{bd,ms}$ [mm]	1200
$L_{haunch,fl}$ [mm]	5000
$L_{haunch,ms}$ [mm]	1500
Haunch type	Tapered

3.3 Generation of design alternatives

The design alternatives were generated by systematically combining the different design variables within their predefined ranges. To avoid generating unrealistic or unsuitable solutions, additional restrictions were applied during this process. For example, alternatives in which the bridge deck is thicker at midspan than at the supports were excluded, since such configurations are not considered reasonable from either a structural or an aesthetic perspective. The design alternatives generated make up Design Space *B*.

3.4 Structural constraints

In the model, a simplified structural check was implemented to verify the structural feasibility of each design alternative. The check consists of three parts: a serviceability limit state (SLS) deflection check of the bridge deck, an ultimate limit state (ULS) reinforcement check of the bridge deck, and a simplified ULS bending moment check of the mid-support section. No separate structural check was performed for the frame legs, as this was considered outside the scope of the simplified model. The feasible alternatives obtained through this structural check make up design space *C*. The governing equations and parameters used in the structural checks are summarized in Appendix B.

3.4.1 Finite element model

The structural response of the bridge was evaluated using a two-dimensional finite element (FE) frame model, implemented in Python. The model consists of beam-column frame elements representing the bridge deck, frame legs and mid-support, with fixed boundary conditions at the base of the frame legs and mid-support, restraining all translational and rotational degrees of freedom. Each node has three degrees of freedom, translation in x, translation in y and rotation. The flexural stiffness EI(x) of each deck element was calculated based on the local cross-section height h(x), accounting for the varying geometry along the span due to the haunch. The loads considered were:

- Traffic loads according to Load Model 1 (LM1), including a uniformly distributed load and axle loads
- Self-weight of the bridge deck

3.4.2 Serviceability limit state check of bridge deck

The maximum vertical deflection of the bridge deck was evaluated using the nodal displacements obtained from the FE model. The calculated deflection was compared against the serviceability criterion presented in Equation 3.1. Design alternatives exceeding this limit were excluded from the design space.

$$\delta_{\text{max}} \leq \frac{L_{\text{span}}}{400} \tag{3.1}$$

- δ_{max} is the maximum vertical deflection of the bridge deck
- L_{span} is the span length.

3.4.3 Ultimate limit state check of bridge deck

A simplified ULS bending check was performed for the bridge deck by separating positive and negative bending moments from the FE model. Positive bending moments cause tension in the bottom fibre, requiring bottom reinforcement, while negative bending moments cause tension in the top fibre, requiring top reinforcement. The design was considered acceptable if the required reinforcement satisfied the following criterion at all points along the deck:

$$A_{s,\text{min}} \leq A_{s,\text{req}} \leq A_{s,\text{max}} \tag{3.2}$$

where

- $A_{s,\text{min}}$ is the minimum reinforcement

- $A_{s,\max}$ is the lesser of the maximum reinforcement ratio limit and a practical upper limit set for the model

The required reinforcement area per unit width was calculated as:

$$A_{s,req} = \frac{M_{Ed}}{f_{yd} \cdot z} \tag{3.3}$$

where

- M_{Ed} is the design bending moment per unit width
- f_{yd} is the design yield strength of the reinforcement
- $z = 0.9h(x)$ is the approximate internal lever arm for simplified calculation

3.4.4 Ultimate limit state check of mid-support

The mid-support was checked against a simplified unreinforced bending capacity. The design bending moment $M_{Ed,B}$ was taken from the FE model at the mid-support. Design alternatives where $M_{Ed,B} > M_{Rd}$ were removed from the design space. This check is conservative, as it does not account for reinforcement in the mid-support section. The bending capacity was calculated as:

$$M_{Rd} = f_{cd} \cdot W = f_{cd} \cdot \frac{b_{strip} \cdot D_{ms}^2}{6} \tag{3.4}$$

where

- f_{cd} is the design compressive strength of concrete
- b_{strip} is the analysed strip width, equal to 1000 mm
- $D_{ms} = \min(D_{ms,bot},\ D_{ms,top})$ is the governing thickness of the mid-support, where $D_{ms,bot}$ is the thickness at the base and $D_{ms,top}$ is the thickness at the connection to the bridge deck

3.5 Evaluation of feasible design alternatives towards objectives

The evaluation of feasible design alternatives was formulated using multiple objective functions and follows the framework for multi-objective optimization presented in Section 2.3.4. After the infeasible alternatives had been removed through structural and geometric constraint filtering, the remaining feasible alternatives in Design Space *C* were evaluated with respect to the selected objectives: production cost, environmental impact, and quantified aesthetic criteria. The theoretical background for these objectives is presented in Section 2.4, while the present section describes how they are represented and combined in the prototype.

In earlier related studies, such as Bergenram and Ulander (2023), different objectives were expressed in a common cost-based unit in order to enable a combined evaluation. In the present study, such an approach was not considered appropriate, since the quantified aesthetic criteria do not have a clear or meaningful cost-based interpretation. Instead, the objective functions were transformed into dimensionless quantities through normalization, following Equation 2.11. This made it possible to compare and combine the objective functions despite differences in unit and numerical magnitude.

3.5.1 Production cost

The production cost objective follows the framework presented in Section 2.4.1. In the present study, the production cost $C(x)$ was estimated as the sum of material costs for concrete and reinforcement, and labour costs for concrete work:

$$C(x) = \rho_{mc} \cdot Q_c + \frac{\rho_{mr}}{1000} \cdot Q_r + \rho_w \cdot Q_c \tag{3.5}$$

where

- ρ_{mc} is the concrete material cost [SEK/m^3]
- Q_c is the total concrete volume [m^3]
- ρ_{mr} is the reinforcement cost [SEK/ton]
- Q_r is the total reinforcement weight [kg]
- ρ_w is the labour cost per unit volume of concrete [SEK/m^3]

For bridges with parabolic haunches, an additional fabrication cost was included to account for the increased formwork complexity, as described in Section 2.4.1. The cost parameters used in the model are summarized in Appendix C.1.

3.5.2 Environmental impact

The environmental impact objective follows the framework presented in Section 2.4.2. In the present study, the environmental impact $E(x)$ was estimated as the sum of CO_2-eq emissions from concrete and reinforcement production:

$$E(x) = eq_c \cdot Q_c + \frac{eq_r}{1000} \cdot Q_r \tag{3.6}$$

where

- eq_c is the CO_2-eq emission factor for concrete [kg CO_2-eq/m^3]
- eq_r is the CO_2-eq emission factor for reinforcement steel [kg CO_2-eq/ton]
- Q_c is the total concrete volume [m^3]
- Q_r is the total reinforcement weight [kg]

Emission factors are summarized in Appendix C.2.

3.5.3 Quantified aesthetic criteria

As discussed in Section 2.4.3, no directly applicable reference was identified in which aesthetic criteria are formulated as objective functions within a set-based design framework for concrete bridges. The implementation presented in this section was therefore developed within the present study, based on the aesthetic principles identified in Section 2.1.

Aesthetic quality was not treated as a purely numerical property within this study. However, it was partly parameterized through quantifiable design attributes. These attributes represents proportions and geometric relationships that, according to previous literature and professional practice, influence the perceived visual quality of bridges. Within this section, the parametrized criteria are discussed. The non-quantifiable aspects of bridge aesthetics were not included in the numerical objective function, but can still be assessed within the broader SBD method through visual comparison and professional judgment. This is further discussed in Chapter 5 and 6.

Within the prototype, the quantified aesthetic evaluation was based on two main components:

- Proportional relationships (numerical parameter)
- Variation of superstructure depth - haunch geometries (predefined design option, numericalized)

The proportional relationships were implemented as continuous evaluation parameters based on geometric ratios identified in the reviewed bridge aesthetic literature, while the haunch geometry was included as a categorical parameter representing different overall geometric expressions of the bridge superstructure.

The proportional relationships included in the prototype evaluation framework are summarized in Table 3.4. The ideal proportional values were primarily based on recommendations identified in the reviewed bridge aesthetic literature and design guidelines presented in Chapter 2.1.

The minimum and maximum bounds were initially derived from the reviewed literature, representing approximate lower and upper limits for visually acceptable proportions. However, during the implementation and testing of the prototype, several generated bridge alternatives exceeded the recommended proportional ranges while still representing visually distinguishable geometric solutions. To improve the discriminatory capability of the evaluation framework, certain minimum and maximum bounds were therefore extended beyond the guideline recommendations. This reduced the number of alternatives receiving identical maximum penalty scores and enabled larger proportional deviations to be differentiated within the optimization process.

Table 3.4: Aesthetic proportional relationships reviewed in the study and implemented in the prototype evaluation framework.

Parameter	Min	Ideal	Max
$P_1 = \frac{L_{\text{span}}}{D_{\text{bd,span}}}$	5.0	17.0	60.0
$P_3 = \frac{D_{\text{support}}}{D_{\text{bd,span}}}$	0.4	0.55	3.0
$P_5 = \frac{D_{\text{haunch}}}{D_{\text{bd,span}}}$	1.0	1.5	4.0
$P_6 = \frac{L_{\text{haunch}}}{L_{\text{span}}}$	0.05	0.33	0.50

Several other proportions were mentioned in Chapter 2.1 but were not included in the model. The height-to-span ratio P_2 was not included since the bridge height remained constant within the case study. Similarly, the overhang-related proportions P_4 were excluded, as the prototype focused on slab frame bridges rather than girder bridge cross-sections.

For the haunch-related parameters, separate evaluations were performed for the haunch adjacent to the frame leg and the haunch at the middle support. This resulted in the proportional parameters $P_{5,\text{fl}}$, $P_{5,\text{ms}}$, $P_{6,\text{fl}}$, and $P_{6,\text{ms}}$.

The implemented proportional relationships differ depending on bridge geometry. Since constant-depth bridge alternatives do not contain haunches, only the proportional parameters P_1 and P_3 were included in their aesthetic evaluation. For tapered and parabolic alternatives, all implemented proportional relationships were evaluated.

In addition to the proportional relationships, a categorical penalty related to haunch geometry was included in the aesthetic evaluation. Since this parameter does not represent a continuous proportional relationship, no minimum or maximum bounds were defined. Instead, discrete penalty values were assigned based on the selected haunch geometry, where parabolic haunches received the lowest penalty score, tapered haunches an intermediate score, and constant-depth configurations the highest penalty score, as presented in Table 3.5.

Table 3.5: Discrete aesthetic penalty values assigned to the evaluated haunch geometries.

Haunch type	Aesthetic penalty score
Constant depth	1.0
Tapered	0.5
Parabolic	0.0

Each design alternative was assigned an overall aesthetic penalty score, denoted $A(x)$, representing the weighted sum of transformed proportional deviations. Lower values therefore indicate solutions closer to the defined ideal proportions, while higher values indicate larger deviations from the preferred aesthetic relationships. This formulation makes the aesthetic objective compatible with the production cost and environmental impact objectives, since all three objectives are expressed such that lower values are preferred.

The proportional parameters were transformed using the normalization method presented in Equation 2.11, while the overall aesthetic score was calculated using the weighted sum method presented in Equation 2.9. Equal weighting was assigned to all proportional relationships included for each bridge configuration.

For constant-depth bridge alternatives, the aesthetic penalty score was calculated according to Equation 3.7.

$$A(x) = w_{1,s}t_1 + w_{3,s}t_3 + w_{h,s}t_{haunch} \tag{3.7}$$

For tapered and parabolic bridge alternatives, the aesthetic penalty score was calculated according to Equation 3.8.

$$A(x) = w_1t_1 + w_3t_3 + w_{5,l}t_{5,l} + w_{5,r}t_{5,r} + w_{6,l}t_{6,l} + w_{6,r}t_{6,r} + w_ht_{haunch} \tag{3.8}$$

where t_i represents the transformed proportional penalty scores and t_{haunch} represents the discrete penalty associated with the selected haunch geometry.

Furthermore, the following assumptions were adopted for the aesthetic evaluation framework:

- The abutments were assumed to be positioned relatively close to the road, corresponding to the slab frame bridge configuration used in the case study.
- No noise barriers were assumed, and the bridge railing was therefore treated as visually transparent.
- No explicit restrictions related to vertical clearance beneath the bridge were included in the proportional evaluation. In the real case study project, this was a govering factor for design. However, this was not included in the prototype, since the aim was to explore the aesthetic objectives.

3.5.4 Normalization of objective functions and summed evaluation

To enable comparison between objective functions with different units and numerical ranges, the objective values were transformed into dimensionless quantities through normalization according to Equation 2.11. The normalization was performed using fixed ideal-point values, minimum and maximum reference values. The ideal-point value represents the most favorable objective value, while the minimum and maximum reference value represents an under and upper reference level, see section A.4 in Appendix. These reference values were kept constant throughout the analysis to ensure comparability between different iterations and model runs. If the ideal-point value or the maximum reference value were allowed to vary between runs, the resulting normalized objective values would not be directly comparable.

After normalization, the objective functions were combined using the weighted sum method described in Section 2.3.4.1. In this way, each feasible design alternative was assigned a scalar utility value representing its overall performance with respect to the selected objectives and the chosen weighting coefficients. The weighting coefficients were used to reflect the relative importance assigned to the different objectives in the evaluation. For the output presented in Chapter 4, the weighting coefficients were set to $\frac{1}{3}$, meaning all three objective functions were assigned equal importance.

The weighted sum method was selected because it provides a simple and transparent way of combining multiple objectives within the prototype developed in this thesis. Given the discrete and constrained nature of the design space, the Pareto front cannot be assumed to be convex. Therefore, the weighted sum method cannot guarantee that all Pareto-optimal solutions are identified. However, the method was considered sufficient for the purpose of ranking and comparing feasible alternatives within the scope of the study.

3.5.5 Algorithmic choice

Following the normalization and weighted sum process, the bridge alternative with the lowest weighted sum value of the three objectives was selected as the algorithmic choice within the prototype framework. The algorithmic choice therefore represents the bridge alternative with the most balanced overall performance according to the selected objectives and evaluation method. The algorithmic choice should be interpreted as a decision-support outcome within the set-based design framework and does not necessarily represent the overall best solution within the explored design space.

3.6 Prototype output and visualization

The feasible design alternatives generated by the prototype were visualized through tables, diagrams and geometric models. The evaluation results were presented using Python and Excel, while the bridge geometries were exported as coordinates to Rhino/-Grasshopper for 3D modeling.

Regarding the evaluation results, the main output from the algorithm is how each design alternative performs with respect to the objective functions, i.e. production cost, environmental impact, and aesthetic penalty score. Most of these results were visualized directly in Python using different types of diagrams and tables. Some data were also exported to a CSV file and imported into Excel, where additional diagrams were produced. Different methods of visualization were tested in order to explore different ways of presenting the results, and the selected visualizations are presented in Chapter 4.

The geometry coordinates were also exported to a CSV file, which was imported into and linked to a Grasshopper script. The script was automatically updated when the Python script was run and the CSV file was overwritten. The 3D model generation is shown in Figure 3.2.

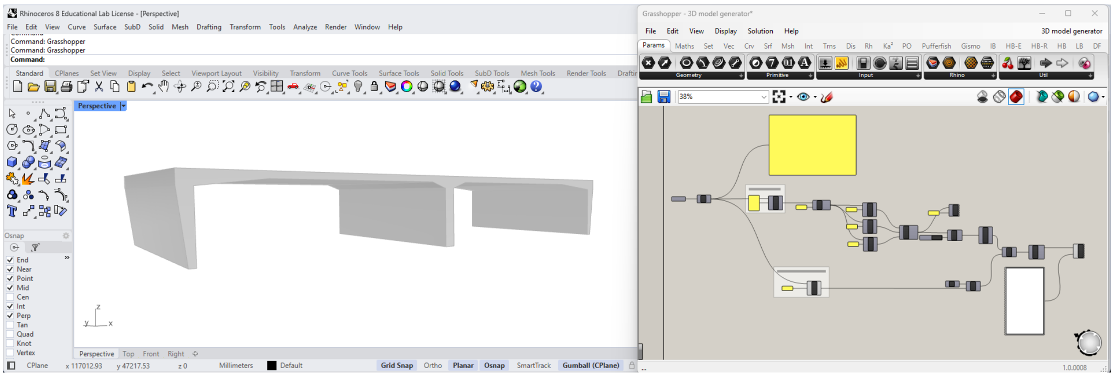


Figure 3.2: Screenshot of 3D model generation workflow in Rhino and Grasshopper.

During the 3D model generation, the representation of the haunch geometry became important. A constant depth bridge deck or a tapered haunch could be described using straight line segments, whereas a parabolic haunch required a curved representation. In an exact geometric model, this would correspond to representing the parabolic shape with a *spline*, which is a smooth curve defined by control points. To keep the Grasshopper script as simple and robust as possible, the parabolic haunch was instead approximated using a polyline with straight line segments, and a large number of points. In the present implementation, 30 points were used. This made it possible to use the same overall modeling procedure for all generated alternatives, regardless of whether the bridge deck had constant depth, tapered haunches, or parabolic haunches. Figure 3.3 illustrates the difference between a spline and its polyline approximation. The spline can represent the curved shape more exactly with fewer control points. However, with a sufficiently high number of points, the visual difference becomes small for the type of geometry considered in this study.

This approximation was adopted as a practical modeling choice. Although a spline gives a more exact geometric representation, the polyline approximation allowed all alternatives to be handled within the same simple Grasshopper workflow. Another possible approach would have been to create a more advanced Grasshopper script, in which

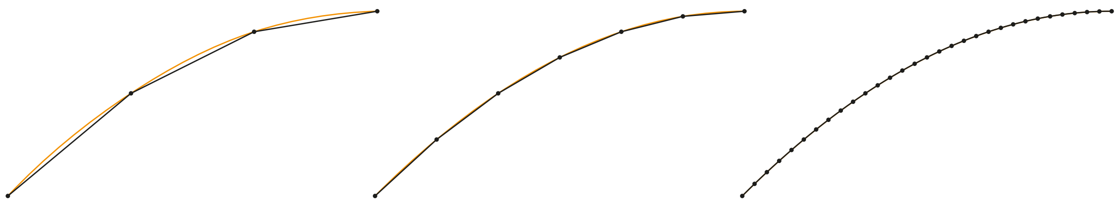


Figure 3.3: Illustration of the difference between a polyline with straight line segments and a spline, with different numbers of control points. The polyline is shown in black and the spline in orange.

different design alternatives are modeled in different ways, for example by using a *stream filter* component to route different geometry types through different modeling branches. This is possible, but it leads to a more complex computation. At the same time, a spline-based model may be lighter than an approximated polyline model, since the same curved shape can be represented with less geometric information. There is therefore a trade-off between keeping the modeling procedure simple and keeping the generated geometry as exact and efficient as possible.

To further support the exploration and interpretation of results, an interactive visualization tool was developed using Streamlit, a Python-based framework for building web applications. The tool allows the designer to interactively explore the evaluated design alternatives, illustrated in Figure 3.4

The tool provides the following functionality:

- Selection of a starting solution from predefined alternatives, such as the algorithmic choice, lowest cost, or case study.
- Selecting solutions based on interactive modification of the bridge geometry, where the user can design the bridge based geometries present in the evaluated design space.
- Automatic lookup of if the selected /modified design exists in the design space.
- Visualization of the bridge geometry and aesthetic proportions for the selected alternative.
- Display of objective function values including production cost, CO_2-eq emissions, aesthetic penalty score and weighted sum
- Positioning of the selected alternative in scatter plots and parallel coordinates diagrams, enabling direct comparison with the full design space.

If the modified geometry does not exist in the evaluated design space, for example because it failed the structural checks, the tool informs the designer accordingly.

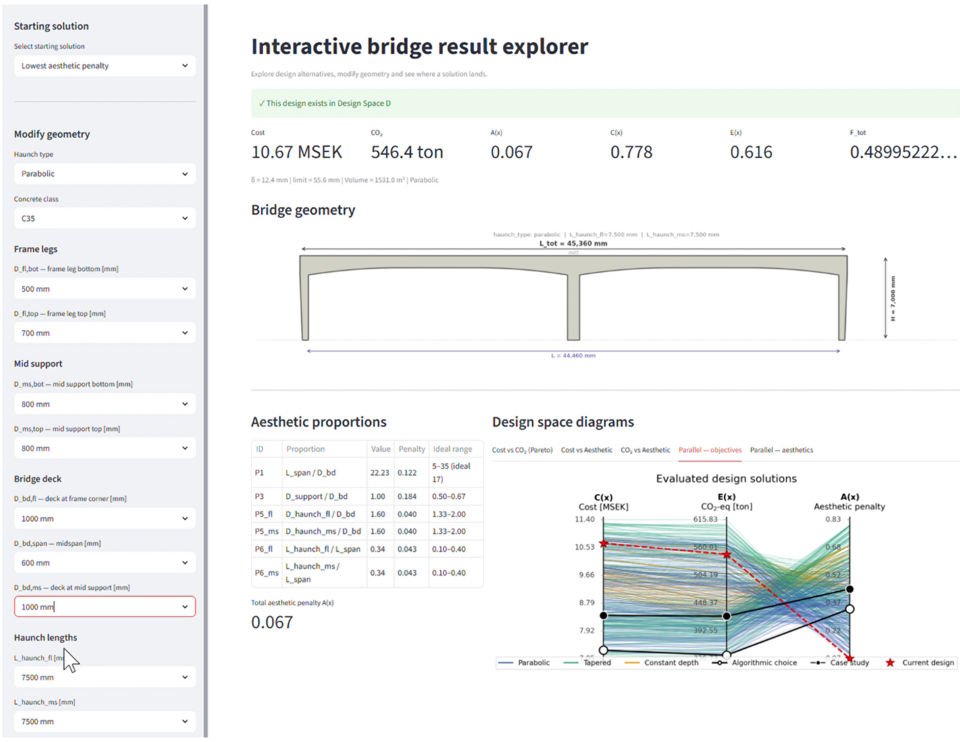


Figure 3.4: Interactive mode of results using streamlit application to python.

4 Prototype assessment

This chapter presents the evaluated bridge design alternatives generated through the proposed set-based design framework. The assessment focuses on the feasible solutions remaining within Design Space D after completion of the simplified structural verification checks and subsequent optimization procedure.

Table 4.1 presents the number of generated design alternatives remaining after each stage of the design space reduction process. No additional filtering was performed in Design Space D. Instead, the feasible alternatives from Design Space C were evaluated and optimized according to the selected objective criteria.

Table 4.1: Number of design alternatives in each design space.

Design space	Number of design solutions
Design space B	900 900
Design space C	381 097
Design space D	381 097

Table 4.2 further presents the distribution of feasible design alternatives according to haunch geometry. The relatively even distribution between constant depth, tapered, and parabolic configurations indicates that all three haunch geometries remained feasible throughout the explored design space.

Table 4.2: Number of design alternatives per haunch type in Design Space D.

Haunch type	Number of design solutions
Constant depth	124 920
Tapered	130 330
Parabolic	125 847

4.1 Overview of evaluated design alternatives

Figure 4.1 presents all evaluated bridge design alternatives using a parallel coordinates plot. The figure visualizes the distribution of feasible alternatives across the three evaluated objectives: production cost, CO_2-eq emissions, and aesthetic penalty score.

Lower values for production cost and CO_2-eq emissions indicate improved quantitative performance, while lower aesthetic penalty scores indicate that the bridge alternative more closely follows the selected aesthetic proportion criteria and geometric relationships incorporated in the model.

The parallel coordinates plot indicates a relatively consistent relationship between production cost and CO_2-eq emissions, where lower production costs generally correspond to lower environmental impact. This is largely explained by the fact that both objectives are strongly influenced by the total concrete volume of the bridge.

In contrast, the aesthetic penalty score shows greater variation across the design alternatives. The figure indicates that alternatives with slightly higher production cost and environmental impact may achieve lower aesthetic penalty scores.

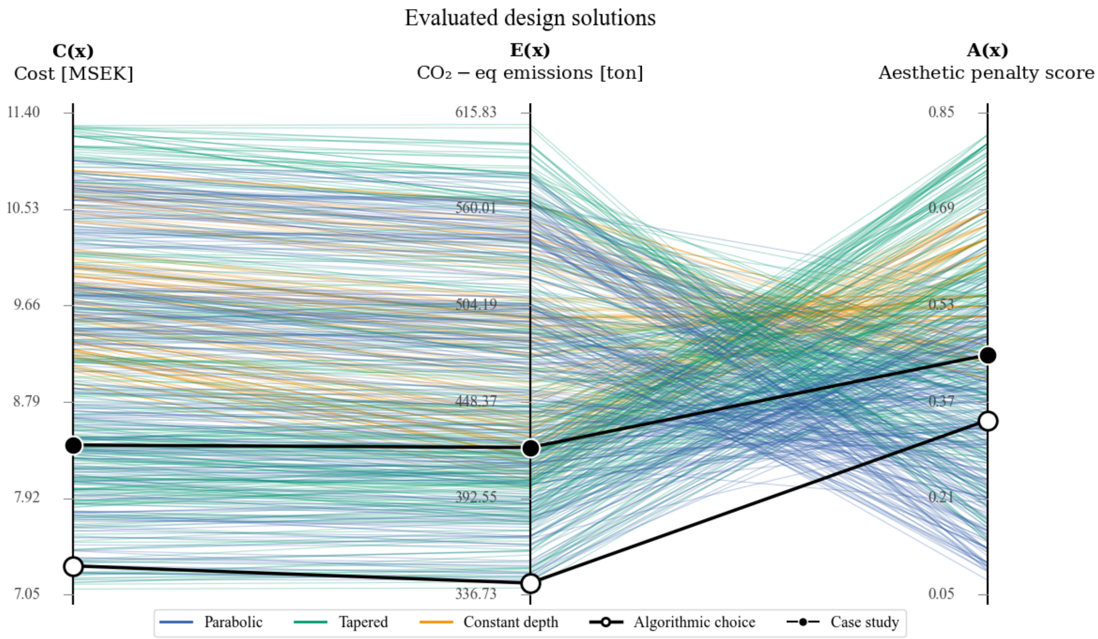


Figure 4.1: Parallel coordinates plot showing all evaluated bridge design alternatives color-coded according to the three haunch geometries: parabolic, tapered, and constant depth. The axes represent production cost, CO_2-equivalent emissions, and aesthetic penalty score. The reference test case and the algorithmic choice are also highlighted.

Many of the alternatives with the lowest production cost and CO_2-eq emissions are associated with tapered or parabolic haunch geometries. This is likely related to the increased structural efficiency achieved through variation of the superstructure depth, allowing for reduced bridge deck thickness in the midspan and consequently lower concrete volumes. Alternatives with constant bridge deck depth generally appear at higher ranges of quantitative objectives and also tend to recieve higher aesthetic penalty scores.

The algorithmic choice is positioned within the lower ranges of the production cost and CO_2-eq emission objectives, while its aesthetic penalty score is closer to the overall mean value. In comparison, the reference test case performs less favorably across all three evaluated objectives.

Overall, the figure demonstrates that no single alternative simultaneously minimizes all objectives, illustrating how the inclusion of aesthetic evaluation influences the overall design outcome within the explored design space.

4.2 Scatter plot visualization of relationships between evaluation criteria

To further analyze the generated design alternatives, scatter plots were used to visualize the relationships between pairs of evaluated objectives:

- CO_2-eq emissions and production cost,
- CO_2-eq emissions and aesthetic penalty score,
- Production cost and aesthetic penalty score.

The scatter plots provide additional insight into the distribution of feasible design alternatives and the relationships between the evaluated objectives within the explored design space.

4.2.1 CO_2-eq emissions vs. production cost

Figures 4.2, 4.3, and 4.4 present the relationship between CO_2-equivalent emissions and production cost for all evaluated design alternatives. The three figures represent the same design space, but use different color codings to support interpretation from multiple perspectives. Figure 4.2 shows the aesthetic penalty score, Figure 4.3 the haunch geometry, and Figure 4.4 the bridge deck thickness at midspan. In each figure, the Pareto-optimal solution obtained through two-objective Pareto optimization between production cost and CO_2-equivalent emissions is highlighted. For the explored design space in this study, only one Pareto-optimal solution was identified for this objective combination. Histograms along the axes further illustrate the distribution of alternatives for each objective.

The relationship between production cost and CO_2-equivalent emissions appears relatively linear across the explored design space, although with a certain spread of solutions around the general trend. Alternatives with lower production cost generally also exhibit lower environmental impact. This relationship can largely be explained by the fact that both the production cost estimation and the environmental impact calculations are strongly dependent on the total concrete volume of the bridge in the simplified structural check.

The Pareto-optimal solution is positioned close to the origin of the plots, where both production cost and CO_2-eq emissions are minimized simultaneously. The algorithmic choice is also located close to the Pareto-optimal solution, corresponding well with the observations from Figure 4.1, where the same solution was shown to lie within the lower ranges of both the production cost and environmental impact axes. This indicates that the algorithmic choice represents one of the more cost-efficient and environmentally favorable alternatives within the explored design space.

Figure 4.2 illustrates the distribution of the design alternatives with respect to aesthetic penalty score. The histogram indicates that relatively few alternatives achieve aesthetic penalty scores below 0.2, while the majority of solutions are concentrated above approximately 0.4. The figure further indicates that alternatives with lower aesthetic penalty scores are generally positioned further away from the Pareto-optimal solution for production cost and CO_2-eq emissions. This suggests that alternatives more closely aligned with the selected proportional and geometric aesthetic criteria may require slightly increased material usage compared to the most quantitatively optimized solutions. However, higher production cost and CO_2-equivalent emissions do not necessarily guarantee lower aesthetic penalty scores.

Figure 4.3 shows the same design space color-coded according to haunch geometry. The different haunch configurations are relatively evenly distributed throughout the plot. However, alternatives with constant bridge deck depth generally appear at higher production cost levels compared to tapered and parabolic haunch configurations and are also distributed over a narrower region of the design space. This is likely related to the more constrained geometric behavior of constant-depth alternatives compared to alternatives with varying superstructure depth.

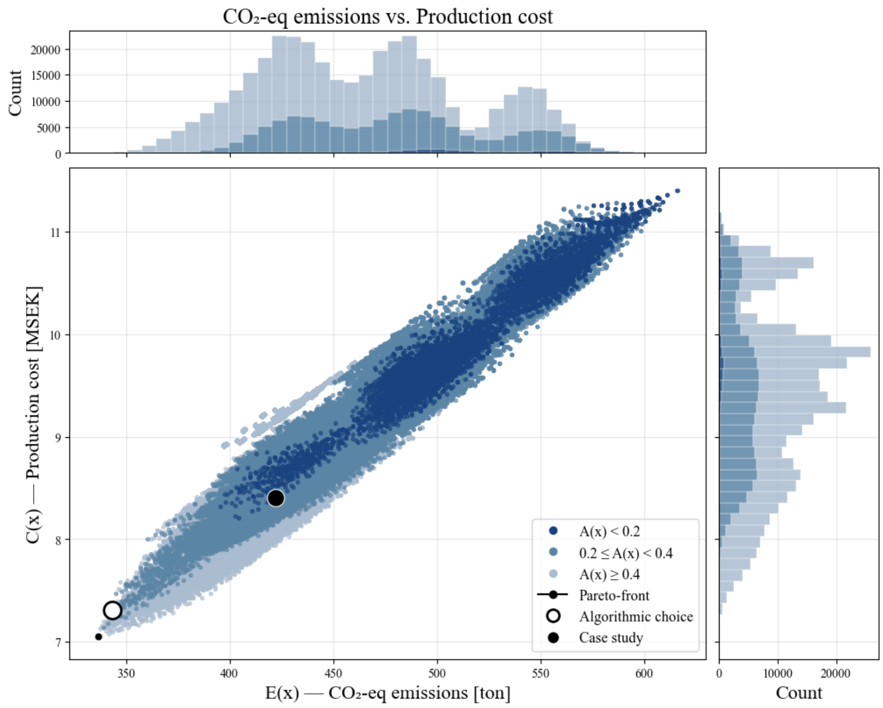


Figure 4.2: Scatter plot showing CO_2-equivalent emissions vs. production cost for all evaluated design alternatives. Colors indicate aesthetic penalty score, where lower values correspond to alternatives more closely aligned with the selected aesthetic criteria.

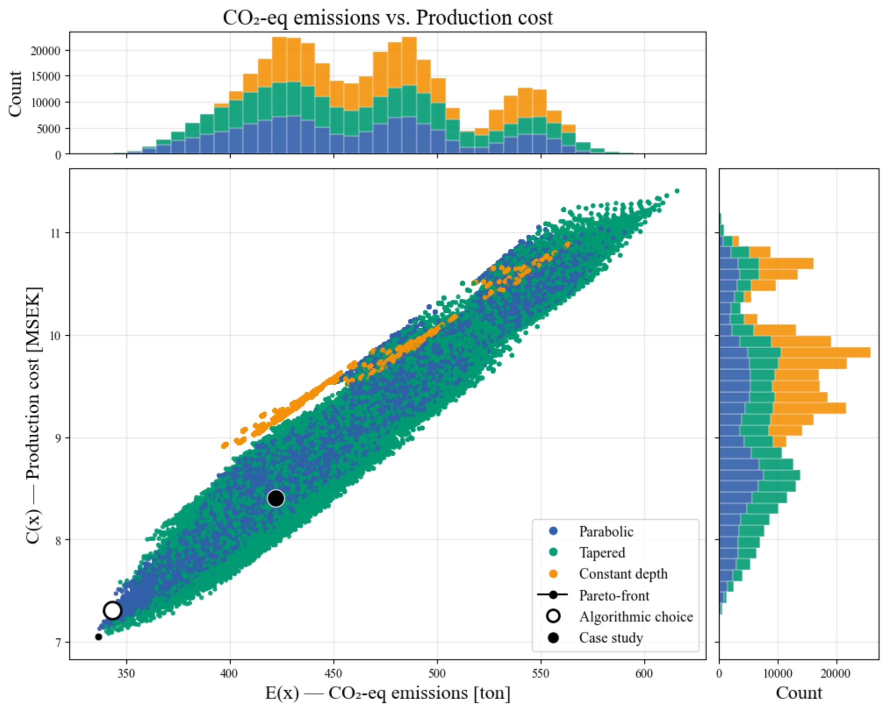


Figure 4.3: Scatter plot showing CO_2-equivalent emissions vs. production cost for all evaluated design alternatives. Colors indicate haunch geometry.

Figure 4.4 presents the distribution of alternatives according to bridge deck thickness at midspan, $D_{\text{bd,span}}$. The clustering visible in both the scatter plot and the histograms illustrates how the discrete bridge deck thickness values influence the distribution of solutions within the design space. Alternatives with bridge deck thicknesses of 600 mm and 800 mm constitute the majority of feasible solutions, while fewer alternatives are associated with thicknesses of 400 mm and 1000 mm. This distribution is mainly governed by the simplified structural verification checks, particularly the serviceability limit state deflection check and the ultimate limit state verification of the bridge deck.

The figure further indicates that thinner bridge deck sections generally correspond to lower production cost and CO_2-eq emissions, while thicker sections lead to increased values for both objectives due to the larger concrete volume.

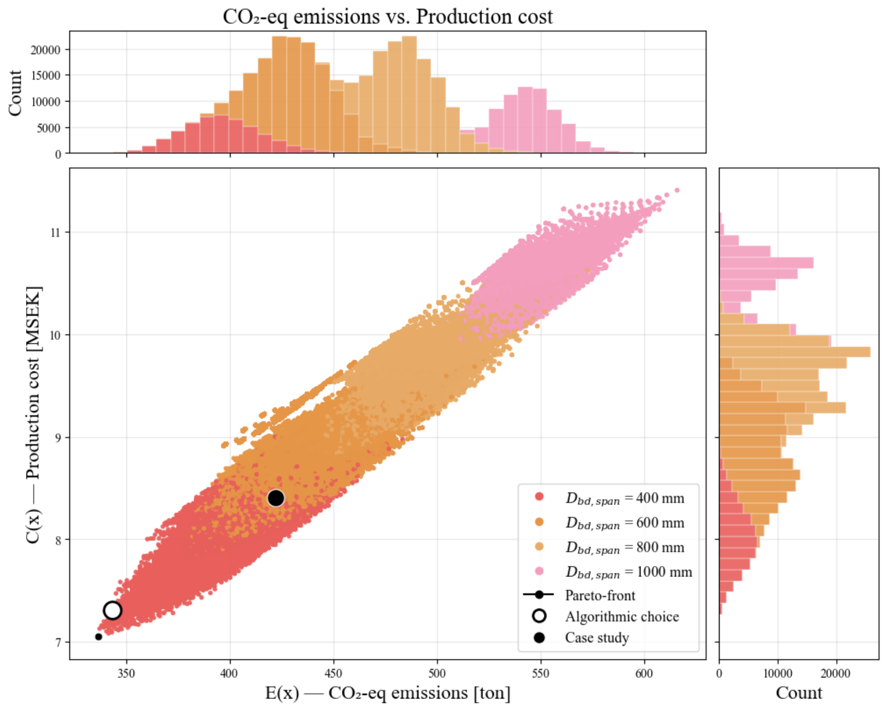


Figure 4.4: Scatter plot showing CO_2-equivalent emissions vs. production cost for all evaluated design alternatives. Colors indicate bridge deck thickness at midspan.

4.2.2 CO_2-equivalent emissions vs. aesthetic penalty score

Figure 4.5 illustrates the relationship between CO_2-equivalent emissions and aesthetic penalty score for all evaluated design alternatives. The figure shows a relatively wide distribution of solutions across the explored design space, indicating considerable variation between environmental performance and aesthetic evaluation.

In this objective combination, multiple Pareto-optimal solutions were identified, forming a Pareto front across the design space. The algorithmic choice is positioned directly on the Pareto front, indicating a balanced relationship between CO_2-eq emissions and aesthetic performance.

The figure further indicates that many of the solutions located on or close to the Pareto front are associated with parabolic haunch geometries. This suggests that parabolic superstructure depth variation may provide favorable conditions for simultaneously achieving lower aesthetic penalty scores and relatively low environmental impact.

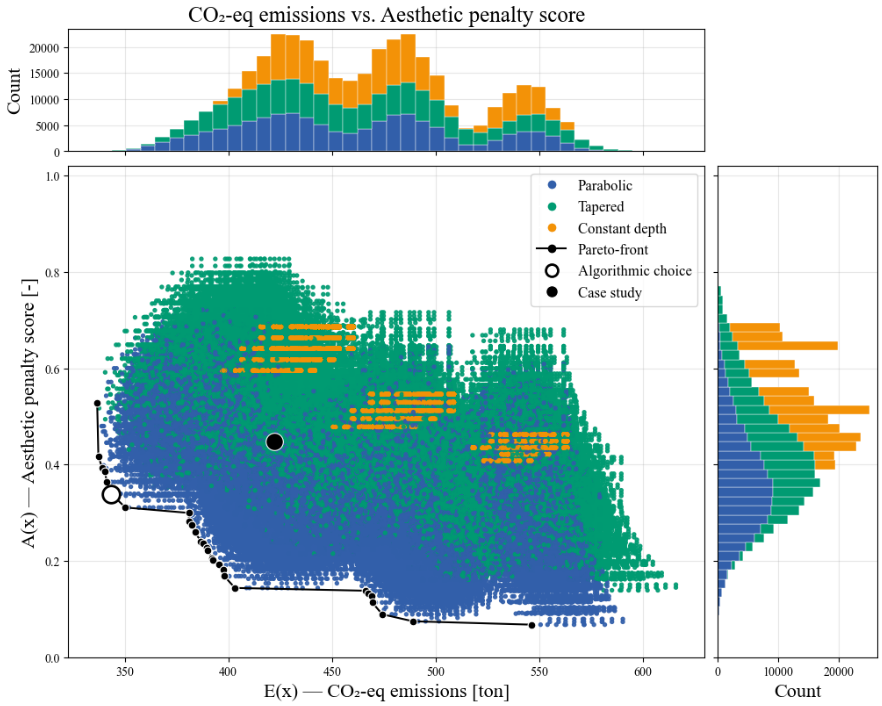


Figure 4.5: Scatter plot showing CO_2-equivalent emissions versus aesthetic penalty score for all evaluated design alternatives. Colors indicate haunch geometry.

4.2.3 Production cost vs. aesthetic penalty score

Figure 4.6 illustrates the relationship between production cost and aesthetic penalty score for all evaluated design alternatives. The overall distribution of solutions is similar to that observed in Figure 4.5, which presented the relationship between CO_2-eq emissions and aesthetic penalty score. This similarity is expected, since production cost and CO_2-eq emissions were previously shown to exhibit a relatively strong linear relationship across the explored design space.

The figure further indicates that alternatives with lower aesthetic penalty scores are generally associated with slightly higher production costs compared to the most cost-efficient solutions. Similar to the previous observations, many of the solutions located on or close to the Pareto front are associated with parabolic haunch geometries.

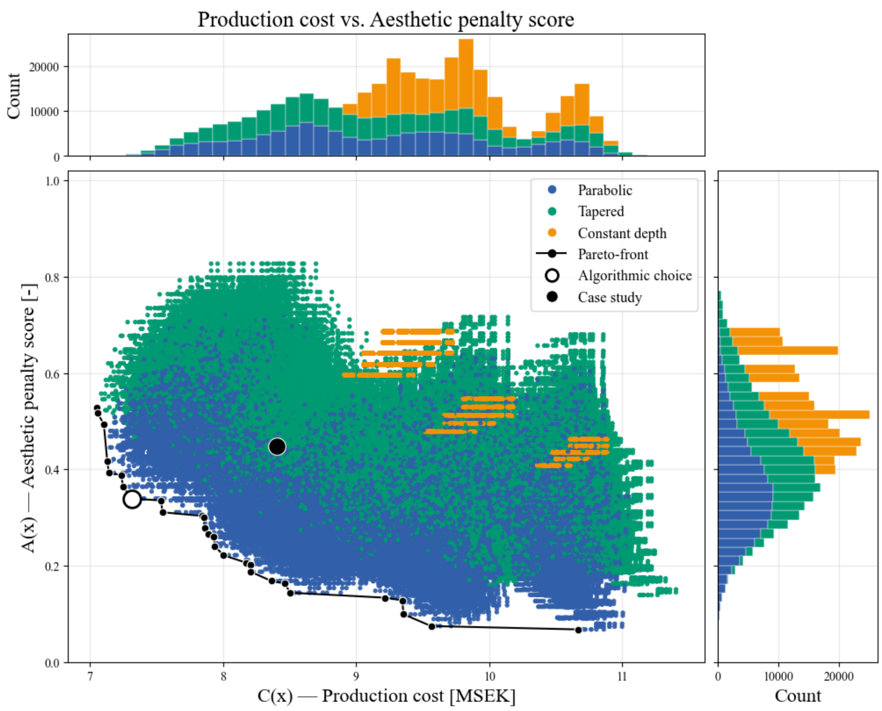


Figure 4.6: Scatter plot showing production cost versus aesthetic penalty score for all evaluated design alternatives. Colors indicate haunch geometry.

4.3 Evaluation of aesthetic proportions

Figure 4.7 presents a parallel coordinates plot showing the evaluated proportional relationships for all feasible bridge design alternatives. The first axis represents the total aesthetic penalty score, while the remaining axes illustrate the individual proportional criteria incorporated in the aesthetic evaluation framework. The geometric dimensions used for the proportional relationships are illustrated in Figure 3.1. The alternatives are color-coded according to haunch geometry.

The figure illustrates how the evaluated proportional relationships are distributed within the explored design space and how variations in geometric proportions contribute to the total aesthetic penalty score. It also enables comparisons between alternatives with low and high aesthetic penalty scores in relation to the selected proportional criteria. The light grey markers shown on each axis represent the recommended proportional values presented in Section 2.1.3.4.

The figure indicates that, among the evaluated proportional relationships, P3 is the only proportion for which none of the generated design alternatives satisfy the recommended target value, indicated by the light grey marker on the corresponding axis. Instead, all alternatives exceed the recommended value. Many solutions also achieve P3 values above 1.0, indicating that the width of the mid-support exceeds the bridge deck thickness for these alternatives.

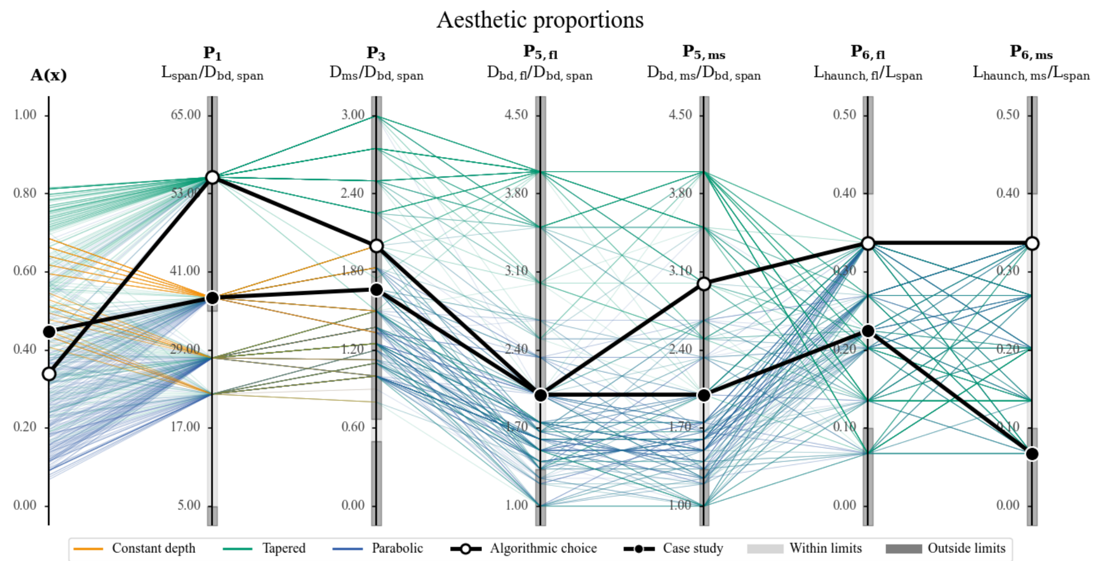
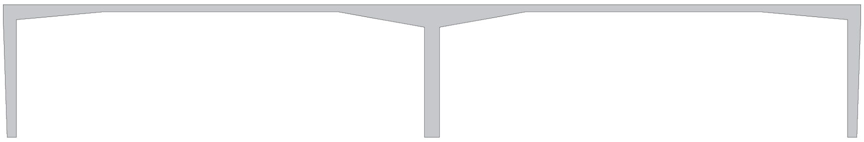


Figure 4.7: Parallel coordinates plot showing the evaluated proportional relationships for all feasible bridge design alternatives. The first axis represents the total aesthetic penalty score, while the remaining axes represent the individual proportional criteria included in the aesthetic evaluation framework. Colors indicate haunch geometry.

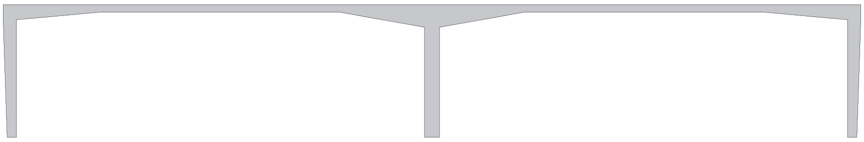
4.4 Selected bridge design alternatives

Figure 4.8 presents selected bridge design alternatives generated within the explored design space. The presented alternatives include the solutions with the lowest production cost, the lowest CO_2-equivalent emissions, the lowest aesthetic penalty score, the algorithmic choice obtained through the weighted evaluation method, and the selected case study bridge.

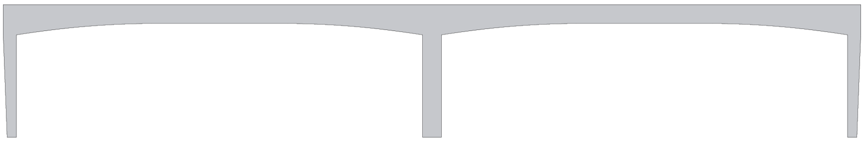
The figure provides a visual representation of how the generated bridge geometries differ between the evaluated alternatives. (KANSKE TA BORT) The purpose is not to determine aesthetic quality objectively, but rather to illustrate how the proposed framework can generate and evaluate alternative bridge configurations based on different performance criteria during early-stage bridge design.



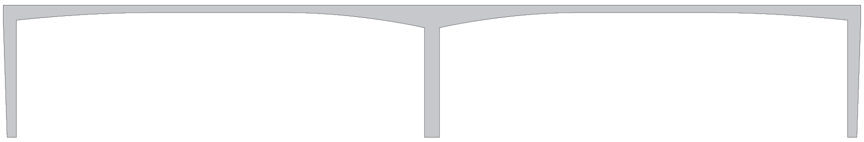
(a) Lowest production cost



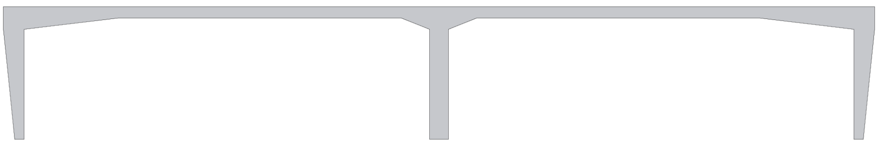
(b) Lowest CO_2-eq emissions



(c) Lowest aesthetic penalty score



(d) Algorithmic choice



(e) Case study

Figure 4.8: Visual comparison of selected bridge design alternatives.

Table 4.3 further presents the geometric input parameters, resulting objective values, and simplified structural verification results for the selected bridge alternatives. Alternatives (a) and (b), representing the lowest production cost and lowest CO_2-equivalent emissions respectively, correspond to the same bridge configuration and are therefore presented within the same table column.

The table illustrates how variations in geometric design parameters influence both the evaluated objective values and the structural performance of the bridge alternatives.

In particular, the alternative with the lowest aesthetic penalty score is associated with substantially larger bridge deck dimensions and concrete volume compared to the alternative with the lowest production cost and CO_2-equivalent emissions, resulting in increased production cost and environmental impact. The thicker bridge deck geometry is largely related to the P1 and P3 proportional relationships, where the chosen target values favor these geometric characteristics. The selected proportional target values presented in Section 3.5.3 may however be adjusted depending on project-specific design intentions and aesthetic objectives.

The algorithmic choice, in contrast, represents a more balanced solution with relatively low production cost and CO_2-eq emissions while still achieving a lower aesthetic penalty score than the selected case study bridge.

Table 4.3: Input and output data for the selected bridge design alternatives.

Alternative:	**(a) & (b)**	**(c)**	**(d)**	**(e)**
Input				
$D_{fl,bot}$ [mm]	500	500	500	500
$D_{fl,top}$ [mm]	700	700	700	1100
$D_{ms,bot}$ [mm]	800	1000	800	1000
$D_{ms,top}$ [mm]	800	1000	800	1000
$D_{bd,fl}$ [mm]	800	1600	800	1200
$D_{bd,span}$ [mm]	400	1000	400	600
$D_{bd,ms}$ [mm]	1200	1600	1200	1200
$L_{haunch,fl}$ [mm]	4500	7500	7500	5000
$L_{haunch,ms}$ [mm]	4500	7500	7500	1500
Haunch type	tapered	parabolic	parabolic	tapered
Output				
Total concrete volume [m^3]	871.6	1531.0	885.8	1150.3
Total reinforcement weight [ton]	95.1	106.6	98.4	95.5
Production cost [MSEK]	7.05	10.67	7.31	8.40
CO_2-eq emissions [ton]	336.7	546.4	343.5	422.0
Aesthetic penalty score [-]	0.529	0.067	0.339	0.448
Weighted sum [-]	0.264	0.490	0.222	0.385
Structural check				
Max deflection [mm]	54.8	12.4	50.6	28.4
SLS deflection utilization [-]	0.99	0.22	0.91	0.51
ULS mid-support utilization [-]	0.88	0.94	0.96	0.45
ULS deck bottom utilization[-]	0.70	0.59	0.66	0.64
ULS deck top utilization [-]	0.57	0.71	0.62	0.61

Alternatives correspond to the subfigures in Figure 4.8: (a) lowest production cost, (b) lowest CO_2-eq emissions, (c) lowest aesthetic penalty score, (d) algorithmic choice, and (e) case study.

Alternatives (a), (b), and (d) exhibit the highest SLS utilization ratios, ranging between 0.91 and 0.99, indicating that the deflection criterion governs these solutions. This is expected due to their relatively thin bridge deck sections at midspan, resulting in reduced flexural stiffness. In contrast, alternative (c) achieves the lowest SLS utilization ratio due to its substantially thicker bridge deck section.

The mid-support utilization ratios are also relatively high for alternatives (a), (b), (c), and (d), ranging between 0.88 and 0.96, indicating that these alternatives approach the unreinforced bending capacity limit at the mid-support section. The ULS bridge deck utilization ratios remain comparatively moderate across all evaluated alternatives, indicating that the required reinforcement areas remain within the allowable limits.

Figures 4.9 and 4.10 further illustrate the normalized objective performance of the selected bridge alternatives. The visualizations enable comparison of how the alternatives perform relative to one another across the three evaluated objectives. The stacked bar chart presents the relative contribution of each objective to the overall weighted evaluation, while the radar chart provides a comparative visualization of the performance distribution across the three objectives.

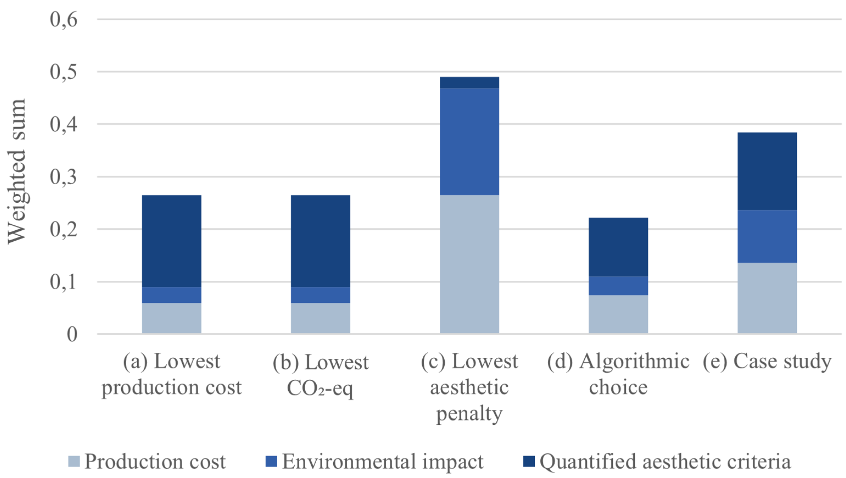


Figure 4.9: Stacked bar chart showing the objective performance of the selected alternatives.

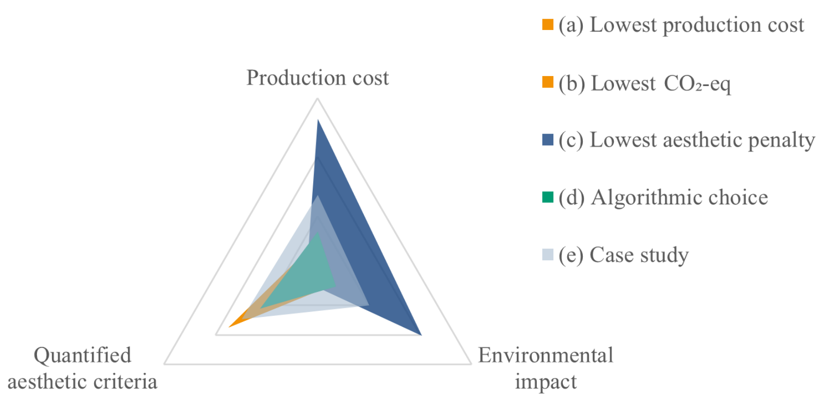


Figure 4.10: Radar chart showing the objective performance of the selected alternatives.

5 Proposed SBD method for integrating both quantitative and qualitative criteria

This chapter presents the proposed SBD method developed within the thesis. The method was developed based on the literature study, professional consultations, as well as the development and assessment of the digital prototype. Since the prototype results are presented in Chapter 4, this chapter focuses on the general method and uses the prototype as an example where relevant.

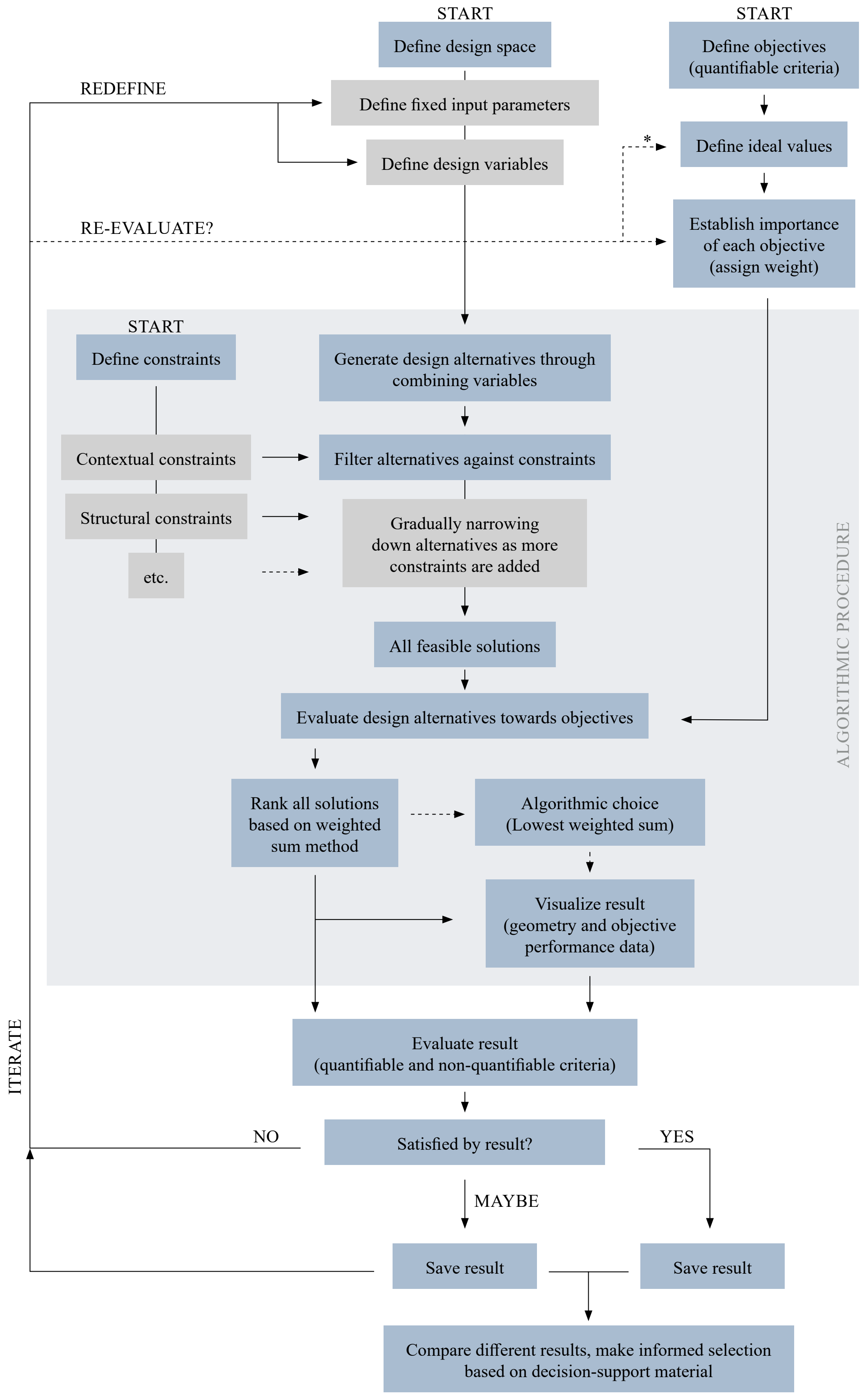
The proposed SBD method is illustrated in Figure 5.1. It describes a general procedure for how both quantitative and qualitative criteria can be considered within a set-based design process. The following subsections explain the main steps of the proposed SBD method and describe how it can be used.

5.1 Representing qualitative criteria in the SBD method

A central part of the proposed SBD method is how qualitative criteria are represented in a process that is partly algorithmic. To be handled directly by the algorithm, a criterion needs to be described in a form that the model can evaluate, for example as a numerical parameter, a predefined design option, or a rule that can be checked systematically. Some qualitative aspects can be translated into this type of representation, while others are more difficult to formalize.

Qualitative criteria do not necessarily need to be treated in the same way as quantitative objectives. Some aspects may be translated into quantified evaluation criteria and included in the objective evaluation. Others may be included as constraints, for example if a solution must satisfy a specific contextual requirement. Additional aspects may remain non-quantified and instead be assessed through visual comparison and professional judgment after the alternatives have been generated.

In this thesis, aesthetic considerations were used as the main example of qualitative criteria. Table 5.1 summarizes aesthetic aspects considered relevant to early-stage bridge design and indicates how they may be represented within the proposed SBD method. The table also shows how the aspects were represented in the digital prototype, where selected aesthetic aspects were translated into quantified evaluation criteria and included in the objective evaluation, while others were fixed as part of the prototype framework or not included. Aspects that are not directly evaluated by the algorithm may still be considered within the proposed method through visual comparison and professional judgment.



* Note that changing the ideal values affects the results and makes them non-comparable with previous runs.

Figure 5.1: Diagram of proposed SBD method for incorporating both quantitative and qualitative values.

Table 5.1: Aesthetic aspects considered in the study and their representation within the proposed SBD method.

Aesthetic aspect	Possible SBD representation	Prototype representation
Variation of superstructure depth	Predefined design option	Multiple haunch alternatives
Abutment placement	Predefined design option	Fixed slab frame configuration close to roadway
Abutment geometry	Predefined design option	Straight slab frame walls applied
Support geometry	Predefined design option	Simplified rectangular supports applied
Proportions	Numerical parameters	Selected proportional relationships implemented
Symmetry	Numerical parameter	Symmetrical layouts applied*
Material	Partly parameterized**	Concrete material
Contextual adaptation	Qualitative assessment or project-specific constraint	Not included
Parapets and railings	Predefined design option	Not included
Detailing and surface treatment	Qualitative assessment or predefined design option	Not included

* All alternatives in the prototype were generated with symmetrical layouts. Symmetry was therefore fixed rather than evaluated as a separate aesthetic criterion.
** Material properties can be represented as design parameters, while the aesthetic perception of material expression is more difficult to formalize.

5.2 Defining the design framework

A key step in the proposed method is to define the design framework. This includes the design space, the objectives, and the constraints that control how alternatives are generated, filtered and evaluated.

Defining the design space means deciding what types of bridge alternatives the model is able to generate. This includes the bridge type, the design variables, and the range of each variable. The design space should be broad enough to allow meaningful exploration, but limited enough to be handled within the computational model.

The objectives define how the alternatives are evaluated. Quantitative objectives, such as production cost and environmental impact, can usually be calculated directly from material quantities and fixed input values. Qualitative criteria, such as aesthetic considerations, first need to be translated into evaluation criteria that can be handled within the computational design process, as described in Section 5.1. Since the objectives may have different units and numerical ranges, they need to be transformed before they can be combined. In the prototype, this was done through normalization and weighted summation, as described in Section 3.5.4. When applying the method, the ideal point value, maximum reference value, and weighting factor for each objective must therefore also be defined before the evaluation is performed.

The constraints define which solutions are feasible. In the prototype, the main constraint was structural feasibility, evaluated through a simplified structural check. In a real project, additional constraints may also be relevant, such as geometric limitations or contextual restrictions. Perhaps there is a river or a building on the site, that gives limitations on the dimensions of the bridge.

5.3 Algorithmic procedure

In the prototype developed in this thesis, the algorithmic part of the SBD method was implemented using Python. However, the proposed method is not limited to one specific software. In principle, the same logic could also be applied using other computational tools, or even manually, although that would be much less efficient. The main benefit of an computational and parametric approach is that it makes it possible to quickly generate and assess many alternatives in a systematic way.

As illustrated in Figure 5.1, the algorithmic procedure consists of four main steps. First, design alternatives are generated from the defined design variables and input data. Second, the alternatives are filtered based on the defined constraints. Third, the remaining feasible alternatives are evaluated with respect to the selected objectives. Finally, the results are prepared for comparison through numerical output and visual representation.

In this way, the algorithmic procedure does not only produce a single solution, but a structured set of feasible alternatives with associated performance data. This supports comparison between alternatives and makes it possible to examine trade-offs within the design space.

5.4 Evaluation of algorithm outcome

An important part of the proposed SBD method is how the generated alternatives are evaluated and presented. For the method to be useful in practice, the outcome needs to be shown in a way that supports comparison and discussion. This is particularly important when qualitative criteria are included, since not all relevant aspects can be fully captured by the algorithm.

Each design alternative can therefore be described through both its geometric model and its performance data, such as production cost, environmental impact, and quantified aesthetic measures. Presenting these results in a clear and comparable format makes it easier to identify patterns, trade-offs, and promising solutions within the design space.

The evaluation should not be limited to only the Pareto-optimal alternatives. Such an alternative may perform well according to the defined objective functions, but it should not automatically be interpreted as the best solution for the project as a whole. Non-quantifiable aesthetic aspects, contextual conditions, and professional judgment may still influence the final assessment. It is therefore important that a wider set of feasible alternatives can be reviewed by the design team.

Different types of visualizations are useful for different parts of the evaluation. For a large number of alternatives, such as the full feasible design space, scatter plots and parallel coordinates plots can be used to identify general patterns, clusters, and trade-offs between objectives. In the prototype assessment, these types of visualizations are used to compare production cost, CO_2-equivalent emissions, and aesthetic penalty score across the evaluated alternatives, as shown in Sections 4.1–4.3.

For a smaller number of selected alternatives, other visualizations may be more suitable. A stacked bar chart makes it easier to compare the total weighted performance of the alternatives, while a radar chart shows more clearly how each alternative performs with respect to the separate objectives. Visual comparison of the generated bridge geometries is also important, since it allows aspects that are not included in the numerical evaluation to be considered. In the prototype assessment, these forms of output are illustrated through the selected bridge alternatives, their performance data, and their geometric representations in Section 4.4.

The outcome can also be presented through an interactive visualization tool, as described in Section 3.6. Such a tool can allow users to explore the generated alternatives, filter the results, and compare numerical performance together with visual representations. This may be especially useful in a set-based process, since the purpose is not only to present a final selected alternative, but to support exploration and discussion within the feasible design space.

Together, the numerical results, visual representations and interactive tool provide decision-support material rather than a final design decision. The purpose of the evaluation is therefore not primarily to identify one algorithmically preferred alternative, but rather to support transparent comparison and discussion between several feasible solutions.

5.5 Iteration and design space refinement

Iteration is an important part of the proposed SBD method. In early runs, the design space may be defined relatively broadly in order to explore a wide range of alternatives. Based on the outcome, the design space can then be refined by adjusting variable ranges, adding constraints, or increasing the level of detail around promising regions.

A broader design space increases the possibility of identifying unexpected or well-performing alternatives, but it also increases the computational effort. A practical approach may therefore be to start with a coarser design space and then refine it in later iterations. This allows the design team to first identify general trends and then study selected parts of the design space in more detail.

From a workflow perspective, iteration should be controlled and traceable. If design variables, constraints, or weighting factors are adjusted, the updated results can still be compared with earlier runs, provided that the same normalization reference values are used. However, redefining the ideal point values or maximum reference values affects the normalized objective values. Such changes should therefore be made with caution, since the results may no longer be directly comparable with previous runs.

5.6 Collaboration between disciplines and human judgment

The literature study and professional consultations highlights the importance of collaboration between disciplines in early-stage bridge design. While some criteria can be parameterized and evaluated computationally, other aspects, especially those related to architectural quality and contextual adaptation, require professional judgment.

The proposed SBD method should therefore not be understood as a tool for replacing certain professions. Rather, it provides a shared basis for decision support and dialogue between bridge engineers, architects, planners, and clients. By making alternatives and their performance data easier to compare, the method can support interdisciplinary discussion rather than replace it.

The frame of reference also shows the importance of integrating architectural intentions as early as possible in the design process, together with structural and other technical considerations. Different disciplines should therefore be involved both when defining the framework, as described in Section 5.2, and when evaluating the outcome, as described in Section 5.4.

5.7 Scope of the set-based model

An important methodological question is what types of alternatives can reasonably be included in the same set-based model. In theory, set-based design encourages the exploration of many alternatives within one shared framework. In practice, however, the degree of variation that can be handled in one model is limited by how comparable the alternatives are and by how they can be described parametrically.

In bridge design, this issue is especially important because many design variables depend on each other. For example, the dimensions of supports are directly related to the geometry of the bridge deck, and the boundary conditions affect how the structural checks are carried out. A change in one part of the structure will therefore affect other parts of the design. This makes it difficult to combine fundamentally different bridge types within one coherent parametric model.

The question is therefore not only how many alternatives can be generated, but also how different they can be while still being handled within the same algorithmic procedure. One possible implication is that different bridge families or structural concepts may need to be handled in separate but related models, rather than in one universal model.

The scope of the model may also be limited by geometric representation. In the present prototype, this became clear when alternatives with different haunch geometries were included in the same workflow. As discussed in Section 3.6, different geometric types may require different modeling strategies, which increases the complexity of the computation.

There is therefore a trade-off between including a wider range of design alternatives and keeping the model simple, robust, and efficient. In some cases, it may therefore be preferable to run several parallel set-based design models, or parallel parts of the workflow, and then evaluate the results together based on the same objectives within a common decision-support framework. This procedure is illustrated in Figure 5.2.

Even if different bridge families or structural concepts are handled in separate models, parts of the workflow can still be shared. For example, the same functions may be used for parts of the algorithm where possible, such as constraint calculations, objective evaluation, normalization or visualization. This makes it possible to keep the models separate where necessary, while still keeping the computation efficient and easier to maintain.

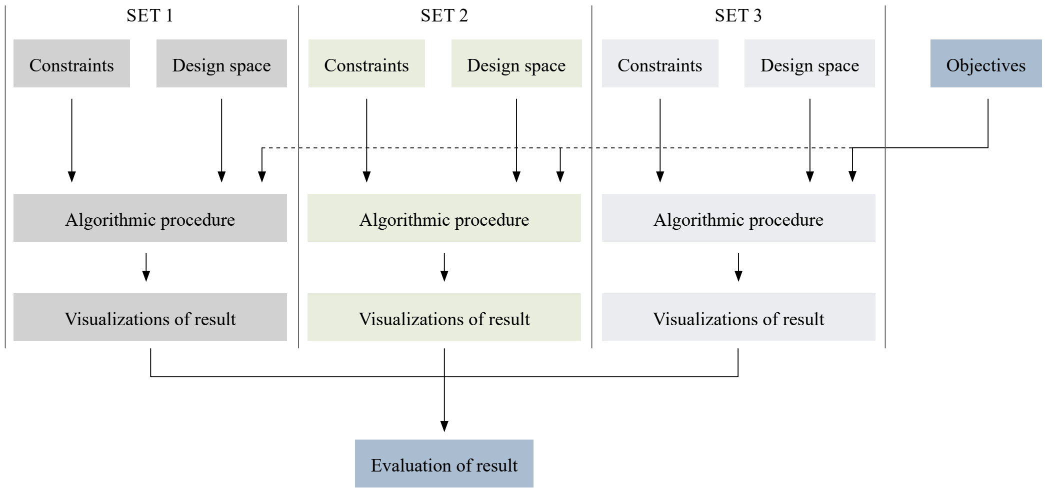


Figure 5.2: Overview of the proposed SBD method for combining separate sets of design alternatives within a common evaluation process.

5.8 Applying the proposed SBD method within the planning and design process at the STA

The proposed method is mainly intended for use in the early-stage bridge design process at the STA, described in Section 2.2, specifically during the land acquisition planning stage. At this stage, important decisions are made regarding bridge type, geometry, and overall design direction, while the design space is still relatively open. As the Macleamy curve in Figure 2.12 illustrates, design changes at this stage are comparatively easy to make, and the associated costs are still low. This makes the stage well suited to a set-based approach, where several alternatives can be generated, compared, and gradually narrowed down.

The proposed SBD method requires the design team to define the design space, objectives, and constraints at an early stage. This can be related to the early formulation of project conditions, architectural intentions, and landscape-related considerations described in Section 2.2. In this phase, the design team would need to define which types of bridge alternatives should be explored, which quantitative objectives should be included, and which qualitative criteria or aesthetic intentions should guide the evaluation. This is also relevant in relation to the STA's handling of aesthetic ambitions, where qualitative goals are encouraged to be translated into requirements that can be assessed in a transparent way, even if they are not fully quantified. Within the proposed method, such requirements could be included as constraints, quantified evaluation objectives, or qualitative aspects to be assessed through visual comparison and professional judgment. Instead of selecting a small number of preliminary alternatives too early, the method could allow a broader set of alternatives to be kept and evaluated in parallel for a longer part of the process. More constraints can be added throughout the process, the objectives and evaluation criteria could be refined, progressively narrowing down the feasible design space.

During stakeholder consultation and interdisciplinary review, the method could provide a shared basis for decision support. Feasible alternatives within the design space could be presented together with their performance data and visual representations. This would make it possible to compare alternatives not only with respect to quantitative objectives such as production cost and environmental impact, but also in relation to qualitative aspects such as architectural considerations. At this stage, the design space could still be relatively coarse, since the purpose would be to support comparison and discussion rather than to define a final design.

During and after the consultation and review stages, the design space could be refined through iteration. Variable ranges could be narrowed, constraints could be adjusted, and promising parts of the design space could be studied in more detail. Based on the combined numerical evaluation, visual assessment, and professional judgment, a smaller set of alternatives or a preliminary design could then be selected for further development.

The proposed method should not be understood as replacing the existing planning process at the STA. Rather, it could complement current practice by providing a structured way to generate, compare, and discuss design alternatives throughout the early-stage design process.

6 Discussion

This chapter discusses the study from a broader perspective. It reflects on the possibilities of including qualitative considerations within a set-based design process, how such considerations may influence the design space, the limitations of the proposed approach, and possible directions for further development.

6.1 Qualitative assessment within a SBD process

The study shows that qualitative considerations can be included in a set-based design process without reducing them to a final numerical answer. In the prototype, selected aesthetic principles were translated into quantified evaluation criteria, which made it possible to consider aesthetic aspects together with production cost and environmental impact. This created a more structured basis for comparing alternatives than if the aesthetic assessment had been carried out separately.

A central outcome of the work is that the quantified criteria can make selected aesthetic aspects more visible in the design process. Instead of only presenting production cost and environmental impact, each alternative can also be described in relation to selected geometric proportions and aesthetic principles. This supports a broader comparison of alternatives and makes it easier to identify trade-offs between different types of values.

The method also shows how qualitative assessment can be combined with visual comparison and professional judgment. The numerical evaluation can be used to structure the design space and identify alternatives of interest, while the visualizations allow the design team to interpret the alternatives in relation to the project context. The use of interactive visualizations can further support this process by allowing the design team to explore alternatives, compare performance data, and relate numerical results to visual representations. In this way, the method supports human judgment rather than replacing it.

This is important in early-stage bridge design, where many decisions are still open and several alternatives may be reasonable. By keeping a wider set of feasible alternatives available, the proposed method can support discussion between disciplines and make the reasoning behind design decisions more transparent.

6.2 Influence of qualitative considerations on the design space

The study shows that qualitative considerations can influence the design space without necessarily being used as strict constraints. In the prototype, aesthetic considerations were included as quantified evaluation criteria. This meant that the feasible design alternatives were not only compared with respect to production cost and environmental impact, but also in relation to selected aesthetic principles.

The inclusion of aesthetic criteria added another evaluation dimension to the design space. Production cost and environmental impact were closely related in the prototype, since both were largely influenced by the amount of concrete. The aesthetic penalty score introduced a different type of evaluation, where alternatives with low cost or low environmental impact did not always perform best. This made it possible to identify trade-offs that would not have been visible if the evaluation had only included quantitative objectives.

The influence on the design space was therefore mainly related to evaluation and interpretation, rather than only filtering. The structural checks defined which alternatives were feasible, while the objective evaluation made it possible to rank, compare, and select alternatives for further review. Since all feasible alternatives were retained after the objective evaluation, the whole design space could still be reviewed visually and interpreted beyond the numerical ranking.

In a broader application of the method, qualitative considerations could influence the design space in different ways. Some aspects may be formulated as constraints, for example if a bridge must not obstruct a specific view. Others may be included as quantified criteria, or assessed through visual comparison and discussion. This flexibility is important, since qualitative values in bridge design are often context-dependent and may affect the design process in different ways depending on the project.

6.3 Limitations of the proposed approach

A central outcome of the proposed approach is also one of its main limitations, that aesthetic quality is partly represented through numerical criteria. This creates a risk of giving the aesthetic penalty score more authority than it should have. A low penalty score means that an alternative is close to the selected ideal values, but it does not necessarily mean that the alternative is the most aesthetically suitable solution for a specific project.

The result is also dependent on how the ideal values, acceptable ranges, and weighting factors are defined. If these values are changed, the ranking of alternatives may also change. A proportion that is generally recommended in literature may therefore still lead to a bridge geometry that is not preferred in a specific context. The criteria should therefore be possible to adjust depending on the project, the site, and the design intentions.

The prototype should be understood as an example of how selected aesthetic principles can be translated into evaluation criteria, rather than as an attempt to cover all aspects of bridge aesthetics. The included criteria were chosen because they could be related to geometric parameters in the early design stage. Other aspects, such as material expression, detailing, lighting, and landscape integration, were not investigated as criteria in the implementation of this thesis. Such aspects may therefore either be developed further as evaluation criteria or considered through visual assessment and professional judgment.

The proposed method should therefore be understood as a structured decision-support method rather than an automatic design generator. Its purpose is not to identify the best-looking bridge, but to support the design team in comparing feasible alternatives and discussing trade-offs in a more transparent way.

6.4 Possible further development

The proposed SBD method could be further examined by applying it to other bridge types, geometries, and site-specific conditions. The prototype in this thesis was limited to a two-span concrete slab frame bridge, but the general method could be adapted to other structural systems. Further work could also investigate how much variation can be handled within one set-based model, and when separate but related models are more suitable.

The structural checks could also be developed further. In this thesis, simplified checks were used to demonstrate the method. In a real project implementation, more detailed structural analysis would be required, including more realistic load cases, reinforcement design, foundation effects, and additional limit states. This could be done by connecting the parametric workflow to established bridge analysis software or by extending the finite element model used in the prototype.

The environmental impact assessment could also be made more detailed. The prototype mainly considered material quantities, while a future implementation could include reinforcement, transport, construction activities, maintenance, and other life-cycle stages. It could also be relevant to study how bridge geometry affects exposure conditions. For example, the distance between the road and structural elements may influence exposure to splash water and de-icing salts. This could affect durability requirements, concrete composition, and thereby the environmental impact. Such relationships were not included in the prototype, but could be relevant in future development.

Additional evaluation criteria could also be included. Buildability is one example, since it has been included in previous set-based bridge design studies but was not further developed in this thesis. Other possible criteria are traffic safety, perceived safety, contextual adaptation, maintenance, and landscape integration. Some of these aspects could be formulated as constraints or quantified objectives, while others would need to be assessed through visual comparison and professional judgment.

The digital tool could also be developed using more advanced multi-objective solution methods. In this thesis, the weighted sum method was used because it is simple and transparent. Future work could explore methods such as the *ε-constraint* method or the *normal boundary intersection* method, especially for discrete and constrained design spaces. Sensitivity analyses of weighting factors, ideal point values, and maximum reference values could also be used to study how these assumptions affect the ranking of alternatives.

The method could also be tested in a more user-oriented design process. Designers, architects, planners, clients, or other stakeholders could compare and select between generated alternatives using both numerical results and visual representations. This would make it possible to study how the method supports discussion and how professional judgment is used when several feasible alternatives are available.

A possible long-term development is to use AI or ML to support parts of the evaluation process, for example by identifying patterns in repeated user evaluations or supporting exploration of large design spaces. Such methods should be seen as additional decision-support tools within the proposed workflow.

7 Conclusion

The purpose of this thesis was to investigate how aesthetic considerations can be incorporated as qualitative criteria within a set-based design process for early-stage concrete bridge design. Based on the literature study, professional consultations, and the development and assessment of the digital prototype, the following conclusions are drawn:

- Key aesthetic attributes relevant to early-stage concrete bridge design were identified from literature, guidelines, and professional practice. These included proportions, symmetry, variation of structural depth along the span, support configuration, and the relationship between the bridge and its surroundings.
- A structured SBD method was proposed for incorporating selected aesthetic attributes as qualitative criteria alongside quantitative objectives. The method combines design space definition, constraints, objective evaluation, visualization, iteration, and professional judgment to support comparison of feasible bridge alternatives. The method was also discussed in relation to the early-stage bridge planning process at the STA.
- A digital prototype was developed to exemplify the proposed SBD method for a two-span concrete slab frame bridge. The prototype demonstrated that the method could be implemented in a computational process to generate, filter, evaluate, and visualize design alternatives with respect to production cost, CO_2-equivalent emissions, and quantified aesthetic criteria.
- The inclusion of aesthetic criteria influenced the design space mainly by adding an additional evaluation dimension. In the prototype, the aesthetic criteria did not remove alternatives from the feasible design space, but affected how alternatives were ranked, compared, and interpreted. Visualizations of the evaluated alternatives supported this interpretation by making trade-offs between production cost, environmental impact, and selected aesthetic principles more visible.

Overall, the thesis shows that selected aesthetic considerations can be included in a set-based design workflow together with quantitative objectives. The proposed method should be understood as decision support rather than as an automatic design generator. It can support early-stage bridge design by making alternatives, trade-offs, and design reasoning more transparent, while still leaving the final assessment to the design team.

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A Model input parameters

This appendix summarizes the fixed input parameters used in the finite element analysis, objective function calculations, and structural verifications.

A.1 Material properties

The material properties used in the structural model are presented in Table A.1.

Table A.1: Material properties used in the structural analysis.

Description	Parameter	Value	Reference
Concrete (C35/45)			
Elastic modulus	E_c	34 000 MPa	SS-EN 1992-1-1:2005
Mean tensile strength	f_{ctm}	3.2 MPa	SS-EN 1992-1-1:2005
Density	ρ_c	25 kN/m^3	SS-EN 1992-1-1:2005
Reinforcement steel (K500C-T)			
Elastic modulus	E_s	200 000 MPa	SS-EN 1992-1-1:2005
Characteristic yield strength	f_{yk}	500 MPa	SS-EN 1992-1-1:2005
Design yield strength	f_{yd}	434 MPa	SS-EN 1992-1-1:2005
Density	ρ_s	7850 kg/m^3	(Pro Tool Solutions, 2025)

A.2 Production cost parameters

The production cost properties used for the optimization are presented in Table A.2.

Table A.2: Fixed input parameters used for production cost calculations.

Description	Parameter	Value	Reference
Concrete material cost (C35/45)	ρ_{mc}	3366 SEK/m^3	(Chalouhi, 2019; Yavari et al., 2016)
Labour cost rate concrete	ρ_w	1450 SEK/h	taken as a mean value of framelegs and bridge deck (Yavari et al., 2016)
Labour time per cubic meter of concrete	t_{betong}	1 h/m^3	(Yavari et al., 2016)
Reinforcement steel cost, K500C-T	ρ_{mr}	30000 SEK/ton	The value was selected as a simplified representative estimate based on reinforcement material and installation costs reported by Chalouhi (2019) and Yavari et al. (2016)

A.3 Environmental impact parameters

The environmental impact properties used for the optimization are presented in Table A.3.

Table A.3: Fixed input parameters used for environmental impact calculations.

Description	Parameter	Value	Reference
CO_2-equivalent emissions for concrete (C35/45)	eq_c	305 kg CO_2-eq/m^3	(Heidelberg Materials, n.d.)
CO_2-equivalent emissions for reinforcement steel	eq_r	745 kg CO_2-eq/ton	(7-Steel Service Sweden, n.d.)

A.4 Normalization parameters

The normalization bounds for production cost and environmental impact were determined based on the range of solutions obtained from the design space exploration. The upper bounds were selected slightly above the highest observed values, while the lower bounds were selected slightly below the lowest observed values.

Table A.4: Normalization parameters used in the objective functions.

Description	Parameter	Value
Minimum production cost used for normalization	C_{min}	6 000 000 SEK
Maximum production cost used for normalization	C_{max}	12 000 000 SEK
Minimum environmental impact used for normalization	E_{min}	300 000 kg CO_2-eq
Maximum environmental impact used for normalization	E_{max}	700 000 kg CO_2-eq

A.5 Finite element model parameters

The number of elements used for the Finite Element Model are presented in Table A.5.

Table A.5: Finite element discretization parameters used in the structural model.

Description	Parameter	Value
Number of deck elements per span	n_{deck}	20
Number of elements in each frame leg	n_{leg}	3
Number of elements in the middle support	n_{mid}	3

A.6 ULS parameters

The parameters used for the ULS check are presented in Table A.6.

Table A.6: ULS design parameters used in the simplified structural checks.

Description	Parameter	Value	Reference
Long-term effect factor for concrete	α_{cc}	0.85	SS-EN 1992-1-1:2005
Partial safety factor for concrete	γ_c	1.5	SS-EN 1992-1-1:2005
Practical upper reinforcement limit for bottom reinforcement	$A_{s,\text{practical,max,bottom}}$	5000 mm^2/m	Decided based on calculated reinforcement for the case study
Practical upper reinforcement limit for top reinforcement	$A_{s,\text{practical,max,top}}$	7000 mm^2/m	Decided based on calculated reinforcement for the case study

B Structural constraints

This appendix represents the equations and formulations for the structural check of the bridge used in this study. The fixed input parameters are provided in Appendix A.

B.1 Finite element model

The finite element model used in this study was implemented in Python. The implementation was based on the finite element formulations presented in the CALFEM manual (Lund University, 2019), including the frame element stiffness matrices, coordinate transformations, and assembly procedures. The equations and matrices presented in this appendix therefore follow the CALFEM formulation, while the computational implementation was developed specifically for this study.

Table B.1: Symbols used in the finite element formulation.

Symbol	Description
u_x	Translational displacement in the global x-direction [mm]
u_y	Translational displacement in the global y-direction [mm]
θ	Nodal rotation [rad]
$\mathbf{K}$	Global stiffness matrix
$\mathbf{a}$	Global displacement vector
$\mathbf{F}$	Global load vector
$\bar{\mathbf{K}}^e$	Local element stiffness matrix
$\mathbf{K}^e$	Element stiffness matrix in the global coordinate system
$\mathbf{T}$	Transformation matrix between local and global coordinates
E	Young's modulus of concrete [MPa]
A	Cross-sectional area [mm^2]
b_{strip}	Unit strip width 1000 mm
$h(x)$	Local structural depth at position x [mm]
I	Second moment of area [mm^4]
L_e	Element length [mm]
c	Directional cosine in the global x-direction [-]
s	Directional cosine in the global y-direction [-]
$x_1,\ y_1$	Coordinates of the first element node [mm]
$x_2,\ y_2$	Coordinates of the second element node [mm]
x	Longitudinal coordinate along the bridge deck [mm]
y	Vertical coordinate along the frame leg or middle support [mm]
L_{span}	Bridge span length [mm]
$L_{h,fl}$	Haunch length at the frame leg [mm]
$L_{h,ms}$	Haunch length at the middle support [mm]
H_{fl}	Total height of the frame leg [mm]
H_{ms}	Total height of the middle support [mm]
$h_{fl}(y)$	Local structural depth of the frame leg [mm]
$h_{ms}(y)$	Local structural depth of the middle support [mm]

The bridge was represented by a two-dimensional frame model consisting of beam-column elements connected at discrete nodes, as illustrated in Figure B.1. The elements represented the bridge deck, frame legs, and middle support. The model was used to evaluate the structural response of the bridge frame under traffic loading and to determine displacements and internal forces for the generated bridge alternatives.

Fixed boundary conditions were applied at the bottom nodes of the frame legs and middle support, restraining translational and rotational degrees of freedom.

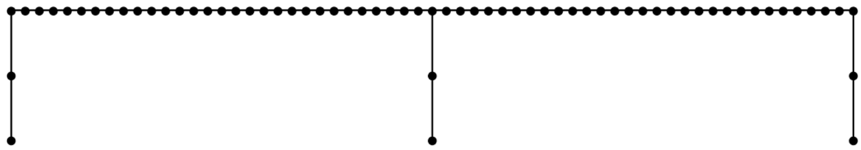

Figure B.1: Frame nodes

The structural system was discretized into multiple frame elements with three degrees of freedom per node:

$$[u_x,\ u_y,\ \theta]$$

The finite element equilibrium equation was formulated as

$$\mathbf{Ka} = \mathbf{F} \tag{B.1}$$

Each element was modelled using a two-dimensional Euler-Bernoulli frame element formulation including axial and bending behaviour. The local element stiffness matrix was defined as

$$\bar{\mathbf{K}}^e = \begin{bmatrix} EA/L_e & 0 & 0 & -EA/L_e & 0 & 0 \\ 0 & 12EI/L_e^3 & 6EI/L_e^2 & 0 & -12EI/L_e^3 & 6EI/L_e^2 \\ 0 & 6EI/L_e^2 & 4EI/L_e & 0 & -6EI/L_e^2 & 2EI/L_e \\ -EA/L_e & 0 & 0 & EA/L_e & 0 & 0 \\ 0 & -12EI/L_e^3 & -6EI/L_e^2 & 0 & 12EI/L_e^3 & -6EI/L_e^2 \\ 0 & 6EI/L_e^2 & 2EI/L_e & 0 & -6EI/L_e^2 & 4EI/L_e \end{bmatrix} \tag{B.2}$$

The local stiffness matrix was transformed into the global coordinate system according to

$$\mathbf{K}^e = \mathbf{T}^T \bar{\mathbf{K}}^e \mathbf{T} \tag{B.3}$$

where $\mathbf{T}$ is the transformation matrix relating local and global coordinates:

$$\mathbf{T} = \begin{bmatrix} c & s & 0 & 0 & 0 & 0 \\ -s & c & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & c & s & 0 \\ 0 & 0 & 0 & -s & c & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{B.4}$$

where

$$c = \frac{x_2 - x_1}{L_e} \tag{B.5}$$

and

$$s = \frac{y_2 - y_1}{L_e} \tag{B.6}$$

represent the directional cosines of the element orientation in the global coordinate system.

The bridge deck, frame legs, and middle support were modeled using variable cross-sectional heights along their lengths. The cross-sectional area was calculated assuming a rectangular cross-section:

$$A = b_{strip}\, h(x) \tag{B.7}$$

The second moment of area was calculated as

$$I = \frac{b_{strip}\, h(x)^3}{12} \tag{B.8}$$

The bridge deck was assigned a variable structural depth $h(x)$ along the span in order to represent different haunch geometries; constant depth bridge deck, tapered hauch and parabolic haunch. The structural depth was defined as a piecewise function depending on the longitudinal coordinate x along the bridge deck. The expressions used for each haunch geometry are presented in Table B.2.

Table B.2: Calculation of bridge deck height $h(x)$ along the span for different haunch types.

Haunch type / zone	Expression for $h(x)$
Constant depth bridge deck	
Along the whole span	$h(x) = h_7$
Tapered haunch	
$0 \leq x \leq L_{h,fl}$	$h(x) = h_5 + \frac{(h_7 - h_5)x}{L_{h,fl}}$
$L_{h,fl} < x \leq L_{span} - L_{h,ms}$	$h(x) = h_7$
$L_{span} - L_{h,ms} < x \leq L_{span}$	$h(x) = h_7 + \frac{(h_9 - h_7)\,(x - (L_{span} - L_{h,ms}))}{L_{h,ms}}$
Parabolic haunch	
$0 \leq x \leq L_{h,fl}$	$h(x) = h_6 + (h_5 - h_6)\left(1 - \frac{x}{L_{h,fl}}\right)^2$
$L_{h,fl} < x \leq L_{span} - L_{h,ms}$	$h(x) = h_7$
$L_{span} - L_{h,ms} < x \leq L_{span}$	$h(x) = h_9 + (h_7 - h_9)\left(1 - \frac{L_{span} - x}{L_{h,ms}}\right)^2$

The structural depth of the frame legs and middle support was assumed to vary linearly along the vertical direction. The expressions used to calculate the local structural depth are summarized in Table B.3.

Table B.3: Calculation of structural depth for vertical frame elements.

Structural element	Expression for $h(y)$
Frame legs	$h_{fl}(y) = h_{fl,bot} + \dfrac{(h_{fl,top} - h_{fl,bot})y}{H_{fl}}$
Middle support	$h_{ms}(y) = h_{ms,bot} + \dfrac{(h_{ms,top} - h_{ms,bot})y}{H_{ms}}$

B.2 Loading

The loads considered consist of Load Model 1 (LM1) traffic loading, the self-weight of the bridge deck, and two concentrated axle loads representing the tandem system. Traffic loading was applied according to Load Model 1 (LM1) defined in SS-EN 1991-2:2003, Section 4.3.2 (European Committee for Standardization, 2003), together with the Swedish national annex specified in TSFS 2018:57 (Transportstyrelsen, 2018). LM1 consists of a tandem system (TS) and a uniformly distributed load (UDL), as illustrated in Figure B.2.

In this study, only lane 1 was considered. The characteristic values used in the calculations are presented in Table B.4, while the applied adjustment factors are presented in Table B.5.

The distributed load was converted into equivalent nodal loads for each bridge deck element, while the axle loads were transformed into equivalent nodal forces and moments and applied to the adjacent element nodes.

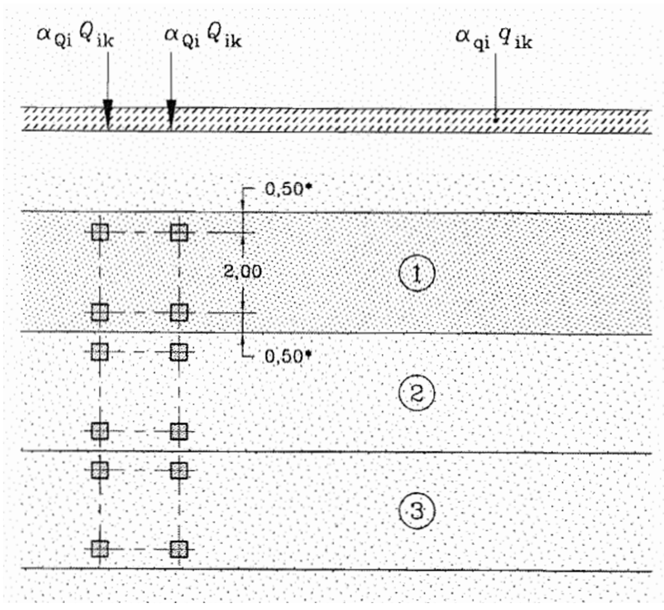

Figure B.2: Principle of application of Load Model 1 (LM1), adapted from SS-EN 1991-2:2003, Section 4.3.2.

Table B.4: Characteristic values for LM1 (SS-EN 1991-2:2003, Table 4.2).

	TS	**UDL**
Location	**Axle loads Q_{ik} [kN/axle]**	**q_{ik} [kN/m^2]**
Lane num. 1	300	9.0
Lane num. 2	200	2.5
Lane num. 3	100	2.5

Table B.5: Adjustment factors for LM1 used in the present study according to TSFS 2018:57, 4.3.3(4).

	TS	**UDL**
Location	**Adjustment factor α_{Qi}**	**Adjustment factor α_{qi}**
Lane num. 1	0.9	0.8
Lane num. 2	0.9	1.0
Lane num. 3	0.0	1.0

A traffic lane width of $w_{lane} = 3000$ mm and an axle spacing of $d_{axel} = 1200$ mm were adopted according to SS-EN 1991-2:2003, Section 4.3.2. A reference strip width of $w_{strip} = 1000$ mm was used in the finite element model.

The applied load expressions used in the numerical deflection calculations are presented in Table B.6. The LM1 load expressions were derived from SS-EN 1991-2:2003 and TSFS 2018:57, while the self-weight expressions were formulated specifically for the finite element model developed in this study.

Table B.6: Load expressions applied in the SLS deflection verification.

Load	Expression
Uniformly distributed loads	
LM1 traffic load	$q_{UDL} = \alpha_{q1} q_{1k} w_{strip}$
Dead weight bridge deck	$q_{dead}(x) = \rho_c h(x) b_{strip}$
Total distributed load	$q_{tot}(x) = q_{UDL} + q_{dead}(x)$
Point loads	
Tandem axle load	$P_{axel} = \dfrac{\alpha_{Q1} Q_{1k}}{w_{lane}/w_{strip}}$
Position of first axle	$d_1 = \dfrac{L_{span}}{2} - \dfrac{d_{axel}}{2}$
Position of second axle	$d_2 = \dfrac{L_{span}}{2} + \dfrac{d_{axel}}{2}$

B.3 SLS check of bridge deck

The serviceability limit state verification was based on the vertical displacements obtained from the finite element analysis.

The displacement vector was obtained by solving

$$\mathbf{a} = \mathbf{K}^{-1}\mathbf{F} \tag{B.9}$$

for the unconstrained degrees of freedom.

The maximum vertical bridge deck deflection was extracted from the global displacement vector and compared against the allowable deflection limit

$$\delta_{max} \leq \frac{L_{span}}{400} \tag{B.10}$$

where L_{span} denotes the bridge span length.

In addition to the displacement response, internal section forces and bending moments were evaluated along each frame element using the Euler–Bernoulli beam formulation employed in the finite element model. The resulting bending moment distribution was subsequently used in the ULS verifications of the bridge deck and middle support.

B.4 Simplified ULS check of the bridge deck

A simplified ULS verification of the bridge deck was performed based on reinforced concrete design principles according to SS-EN 1992-1-1:2005 (European Committee for Standardization, 2005). Simplified expressions were adopted to allow computationally efficient evaluation of a large number of bridge alternatives within the optimization framework. Positive bending moments were assumed to cause tension in the bottom reinforcement, while negative bending moments were assumed to cause tension in the top reinforcement.

Table B.7: Symbols used in the simplified ULS check of the bridge deck.

Symbol	Description
$A_{s,req}$	Required reinforcement area [mm^2/m]
$A_{s,bottom}$	Required bottom reinforcement area for positive bending moments [mm^2/m]
$A_{s,top}$	Required top reinforcement area for negative bending moments [mm^2/m]
$A_{s,min,crack}$	Minimum reinforcement area based on cracking criterion [mm^2/m]
$A_{s,min,\rho}$	Minimum reinforcement area based on minimum reinforcement ratio [mm^2/m]
$A_{s,min}$	Governing minimum reinforcement area [mm^2/m]
$A_{s,bottom,used}$	Required bottom reinforcement including minimum reinforcement [mm^2/m]
$A_{s,top,used}$	Required top reinforcement including minimum reinforcement [mm^2/m]
$A_{s,max}$	Maximum allowable reinforcement area [mm^2/m]
$A_{s,practical,max}$	Practical upper reinforcement limit [mm^2/m]
M_{Ed}	Design bending moment [Nmm]
$M_{Ed,+}$	Positive design bending moment [Nmm]
$M_{Ed,-}$	Negative design bending moment [Nmm]
f_{yd}	Design yield strength of reinforcement steel [MPa]
f_{ctm}	Mean tensile strength of concrete [MPa]
z	Internal lever arm [mm]
$h(x)$	Cross-sectional height [mm]
h_{min}	Minimum cross-sectional height [mm]
b_{strip}	Unit strip width [mm]
ρ_{min}	Minimum reinforcement ratio [-]
ρ_{max}	Maximum reinforcement ratio [-]

The required reinforcement was compared against the governing maximum reinforcement area, taken as the lesser of the EC2 maximum reinforcement ratio limit ($\rho_{max} = 0.04$) and a practical upper reinforcement limit. The practical limit was calibrated based on the reinforcement demand obtained for the case study bridge and was introduced to exclude design alternatives requiring substantially higher reinforcement quantities than the reference design. The bridge deck was considered acceptable if both the top and bottom reinforcement requirements were below this limit.

$$A_{s,req} = \frac{M_{Ed}}{f_{yd} z} \tag{B.11}$$

For simplification, the internal leverarm was assumed

$$z = 0.9h \tag{B.12}$$

$$A_{s,bottom} = \frac{M_{Ed,+}}{f_{yd} z} \tag{B.13}$$

$$A_{s,top} = \frac{M_{Ed,-}}{f_{yd} z} \tag{B.14}$$

$$M_{Ed,+} = \max(M_{Ed}, 0) \tag{B.15}$$

$$M_{Ed,-} = \max(-M_{Ed}, 0) \tag{B.16}$$

The minimum reinforcement requirements were determined according to KB 7.1.10.1[1].

$$A_{s,min,crack} = \left(\frac{4f_{ctm}}{3}\right) 100 \tag{B.17}$$

$$\rho_{min} = \begin{cases} 0.0008, & b_{strip} > 5h_{min} \\ 0.0005, & b_{strip} \leq 5h_{min} \end{cases} \tag{B.18}$$

$$A_{s,min,\rho} = \rho_{min} b_{strip} h_{min} \tag{B.19}$$

$$A_{s,min} = \max(A_{s,min,crack}, A_{s,min,\rho}) \tag{B.20}$$

$$A_{s,bottom,used} = \max(A_{s,bottom}, A_{s,min}) \tag{B.21}$$

$$A_{s,top,used} = \max(A_{s,top}, A_{s,min}) \tag{B.22}$$

$$A_{s,max} = \min\left(\rho_{max}\, h(x), A_{s,practical,max}\right) \tag{B.23}$$

$$A_{s,bottom,used} \leq A_{s,max} \tag{B.24}$$

$$A_{s,top,used} \leq A_{s,max} \tag{B.25}$$

[1]The formulation was adopted following consultation with a bridge engineering specialist at the Swedish Transport Administration (STA).

B.5 Simplified ULS check of the middle support

A simplified bending verification was performed for the middle support based on elementary beam theory. The middle support was assumed to be unreinforced. The design bending moment, $M_{Ed,B}$, acting on the middle support was approximated by the bridge deck bending moment at the section adjacent to the middle support, and the support was considered satisfactory if the utilization ratio satisfied $\eta_B \leq 1.0$.

Table B.8: Symbols used in the simplified ULS check of the middle support.

Symbol	Description
$M_{Ed,B}$	Design bending moment at the middle support obtained from the maximum absolute bridge deck moment near middle support [Nmm]
M_{deck}	Bridge deck bending moment [Nmm]
W	Elastic section modulus of the middle support cross-section [mm^3]
b_{strip}	Unit strip width [mm]
D_{ms}	Governing middle support thickness [mm]
$D_{ms,bot}$	Middle support thickness at the bottom [mm]
$D_{ms,top}$	Middle support thickness at the top [mm]
f_{cd}	Design compressive strength of concrete [N/mm^2]
α_{cc}	Coefficient accounting for long-term effects on concrete compressive strength [-]
f_{ck}	Characteristic compressive cylinder strength of concrete [N/mm^2]
γ_c	Partial safety factor for concrete [-]
$M_{Rd,B}$	Simplified bending moment resistance of the middle support [Nmm]
η_B	Utilization ratio of the middle support [-]

$$W = \frac{b_{strip} D_{ms}^2}{6} \tag{B.26}$$

$$D_{ms} = \min(D_{ms,bot}, D_{ms,top}) \tag{B.27}$$

$$f_{cd} = \frac{\alpha_{cc} f_{ck}}{\gamma_c} \tag{B.28}$$

$$M_{Rd,B} = f_{cd} W \tag{B.29}$$

$$\eta_B = \frac{M_{Ed,B}}{M_{Rd,B}} \tag{B.30}$$

$$\eta_B \leq 1.0$$

C Objective functions

This appendix presents the equations and formulations used in the optimization framework. The generated bridge alternatives were evaluated with respect to production cost, environmental impact, and aesthetics. The appendix further describes the normalization procedures, Pareto-based evaluation, and the weighted objective function used for the final selection of the algorithmic solution.

C.1 Production cost estimation

The production cost was estimated based on concrete volume, reinforcement quantity, labour cost and additional fabrication cost associated with complex haunch geometries. The fixed input parameters are provided in Appendix A.

Table C.1: Symbols used in the production cost formulation.

Symbol	Description
$C(x)$	Total production cost [SEK]
C_m	Material cost [SEK]
C_w	Labour cost [SEK]
C_{haunch}	Additional fabrication cost for parabolic haunches [SEK]
Q_c	Concrete volume [m^3]
Q_r	Reinforcement quantity [kg]
T_w	Estimated labour time for concrete production [h]
V_{haunch}	Total volume of parabolic haunches [m^3]
ρ_{mc}	Concrete material cost [SEK/m^3]
ρ_{mr}	Reinforcement steel cost [SEK/ton]
ρ_w	Labour cost rate [SEK/h]
t_{betong}	Labour time per concrete volume [h/m^3]
α_{haunch}	Parabolic haunch additional cost factor [-]

The total production cost was calculated as

$$C(x) = C_m + C_w + C_{haunch} \tag{C.1}$$

The total material cost was calculated as

$$C_m = \rho_{mc} Q_c + \frac{\rho_{mr}}{1000} Q_r \tag{C.2}$$

The labour cost was estimated as

$$C_w = \rho_w T_w \tag{C.3}$$

where the labour time was approximated by

$$T_w = t_{betong} Q_c \tag{C.4}$$

For bridges with parabolic haunches, an additional fabrication cost was included to account for the increased formwork complexity compared to triangular haunches. The additional cost was calculated as a percentage of the standard concrete material cost applied to the haunch volume:

$$C_{haunch} = \alpha_{haunch} \rho_{mc} V_{haunch} \tag{C.5}$$

A value of $\alpha_{haunch} = 0.20$ was assumed, corresponding to a 20% surcharge on the concrete material cost of the haunch volume to account for the additional cost of curved formwork.

C.2 Environmental impact

The environmental impact was estimated based on the embodied carbon emissions from concrete and reinforcement steel production.

Table C.2: Symbols used in the environmental impact formulation.

Symbol	Description
$E(x)$	Total environmental impact [kg CO_2-eq]
eq_c	Carbon emission factor for concrete production [kg CO_2-eq/m^3]
Q_c	Concrete volume [m^3]
eq_r	Carbon emission factor for reinforcement steel [kg CO_2-eq/ton]
Q_r	Reinforcement quantity [kg]

The total environmental impact was calculated as

$$E(x) = eq_c Q_c + \frac{eq_r}{1000} Q_r \tag{C.6}$$

C.3 Normalized production cost and environmental impact

The symbols used in the normalization formulations are summarized in Table C.3.

Table C.3: Symbols used in the normalization formulations.

Symbol	Description
C_{norm}	Normalized production cost [-]
$C(x)$	Calculated production cost for the evaluated bridge configuration [SEK]
C_{min}	Lower bound of the production cost range used for normalization [SEK]
C_{max}	Upper bound of the production cost range used for normalization [SEK]
E_{norm}	Normalized environmental impact [-]
$E(x)$	Calculated environmental impact for the evaluated bridge configuration [kg CO_2-eq]
E_{min}	Lower bound of the environmental impact range used for normalization [kg CO_2-eq]
E_{max}	Upper bound of the environmental impact range used for normalization [kg CO_2-eq]

The production cost was normalized in order to enable comparison between different bridge configurations within the optimization framework.

$$C_{norm} = \frac{C(x) - C_{min}}{C_{max} - C_{min}} \tag{C.7}$$

The environmental impact was normalized in order to enable comparison between different bridge configurations within the optimization framework.

$$E_{norm} = \frac{E(x) - E_{min}}{E_{max} - E_{min}} \tag{C.8}$$

The numerical values of the normalization parameters are provided in Appendix B.

C.4 Aesthetic penalty score

The aesthetic performance of each bridge configuration was evaluated using a deviation-based score. The score was calculated from selected geometric proportions, where each proportion was compared to an ideal value and bounded by minimum and maximum acceptable values.

$$A(x) = \sum w_i t_i \tag{C.9}$$

where the symbols used in the aesthetic evaluation are summarized in Table C.4.

Table C.4: Symbols used in the aesthetic penalty score formulation.

Symbol	Description
$A(x)$	Aesthetic penalty score (fa) [-]
w_i	Weighting factor for proportion i [-]
t_i	Transformed deviation score for proportion i [-]
P_1	Span-to-depth ratio of the bridge deck [-]
P_3	Pier width-to-deck depth ratio [-]
$P_{5,l}$	Haunch depth ratio at the frame leg [-]
$P_{5,r}$	Haunch depth ratio at the middle support [-]
$P_{6,l}$	Haunch length ratio at the frame leg [-]
$P_{6,r}$	Haunch length ratio at the middle support [-]
$D_{support}$	Average middle support width used in the aesthetic proportion [mm]
t_{haunch}	Aesthetic score contribution from haunch type [-]
$P_{i,ideal}$	Ideal value of proportion i [-]
$P_{i,min}$	Minimum acceptable value of proportion i [-]
$P_{i,max}$	Maximum acceptable value of proportion i [-]

The aesthetic proportions were calculated as

$$P_1 = \frac{L_{span}}{D_{bd}} \tag{C.10}$$

$$P_3 = \frac{D_{support}}{D_{bd}} \tag{C.11}$$

$$P_{5,l} = \frac{D_{haunch,fl}}{D_{bd}} \tag{C.12}$$

$$P_{5,r} = \frac{D_{haunch,ms}}{D_{bd}} \tag{C.13}$$

$$P_{6,l} = \frac{L_{h,fl}}{L_{span}} \tag{C.14}$$

$$P_{6,r} = \frac{L_{h,ms}}{L_{span}} \tag{C.15}$$

The average middle support width was calculated as

$$D_{supporrt} = \frac{D_{ms,bot} + D_{ms,top}}{2} \tag{C.16}$$

The transformed deviation score was calculated as

$$t_i = \begin{cases} \min\left(1, \dfrac{|P_i - P_{i,ideal}|}{P_{i,ideal} - P_{i,min}}\right), & P_i \leq P_{i,ideal} \\ \min\left(1, \dfrac{|P_i - P_{i,ideal}|}{P_{i,max} - P_{i,ideal}}\right), & P_i > P_{i,ideal} \end{cases} \tag{C.17}$$

The aesthetic contribution from the haunch type was defined as

$$t_{haunch} = \begin{cases} 0.0, & \text{parabolic haunch} \\ 0.5, & \text{tapered haunch} \\ 1.0, & \text{constant depth bridge deck} \end{cases} \tag{C.18}$$

For bridge configurations with constant depth geometry, the aesthetic score was calculated as

$$A(x) = w_{1,s}t_1 + w_{3,s}t_3 + w_{h,s}t_{haunch} \tag{C.19}$$

For tapered and parabolic haunch geometries, the aesthetic score was calculated as

$$A(x) = w_1t_1 + w_3t_3 + w_{5,l}t_{5,l} + w_{5,r}t_{5,r} + w_{6,l}t_{6,l} + w_{6,r}t_{6,r} + w_ht_{haunch} \tag{C.20}$$

Equal weighting was assigned to all proportional relationships included in each bridge configuration. Consequently, the weighting factors for the constant-depth bridge deck were set to $w_{1,s} = w_{3,s} = w_{h,s} = 1/3$, while the weighting factors for tapered and parabolic haunch geometries were set to $w_1 = w_3 = w_{5,l} = w_{5,r} = w_{6,l} = w_{6,r} = w_h = 1/7$.

C.5 Evaluation of design alternatives

Each feasible design alternative was evaluated with respect to production cost, environmental impact, and aesthetics. The calculated criteria were normalized so that lower values represented better performance:

$$F_c = C_{norm} \tag{C.21}$$

$$F_e = E_{norm} \tag{C.22}$$

$$F_a = A(x) \tag{C.23}$$

where F_c, F_e, and F_a represent the normalized production cost, normalized environmental impact, and aesthetic deviation score, respectively.

Pareto front

A Pareto front was used to identify non-dominated design alternatives. A design alternative was considered dominated if another alternative performed at least as well in all objectives and strictly better in at least one objective.

For two design alternatives r_1 and r_2, r_2 dominates r_1 if

$$F_{c,2} \leq F_{c,1} \tag{C.24}$$

$$F_{e,2} \leq F_{e,1} \tag{C.25}$$

$$F_{a,2} \leq F_{a,1} \tag{C.26}$$

and at least one of the inequalities is strict. The Pareto-optimal solutions are therefore the alternatives that are not dominated by any other solution.

Selection of algorithmic solution

A final algorithmic solution was selected using a weighted objective function:

$$F_{tot} = w_c F_c + w_e F_e + w_a F_a \tag{C.27}$$

where w_c, w_e, and w_a are the weighting factors for production cost, environmental impact, and aesthetics, respectively.

In this study, the weighting factors were chosen equally as

$$w_c = w_e = w_a = \frac{1}{3} \tag{C.28}$$

The algorithmic solution was defined as the design alternative with the lowest value of F_{tot}.

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