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Parametric Optimization of Slab Frame Bridges Considering Investment Cost, Environmental Impact and Buildability

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Abstract

This paper presents research performed on set-based multi-criteria optimization for the preliminary design of slab frame bridges. As a result of immense CO_2 emissions emerging from concrete production, there is a need for optimization methods decreasing the volume of concrete without affecting the function of the structure. Previous research suggests a general correlation between CO_2 footprint- and cost reduction, due to minimized material use. However, the aspect of buildability may conflict with lessened material, as optimized designs might simultaneously be less buildable. This research aimed to develop an optimization method with respect to the investment cost and environmental impact while also considering buildability cost aspects. The optimization algorithm shows the possibilities of reducing the environmental impact by up to 13.7% for a slightly increased cost of 2.3%. Thus, by implementing optimization procedures in the early stages of the planning process the holistic cost effects related to green solutions can be presented, favoring the choice of sustainable designs amongst clients during tendering procedures.

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Keywords: Parametric design;Optimization;Set-based design;Multi-criteria analysis;Construction;Sustainability;Buildability;Automation

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1. Introduction

In 2018, the Swedish parliament established environmental laws as a result of the Paris agreement, with the goal of achieving climate neutrality in 2045. An action plan has been developed under the leadership of Skanska, signed by the main contractors within the industry, to ensure necessary changes within the construction field [1]. Today's construction industry is responsible for a vast environmental impact due to its extensive emissions of greenhouse gases [2]. Cement production alone is accountable for approximately 8% of global CO_2 emissions [3]. Consequently, it is of great importance to take measures for mitigating the use of concrete, which can be done by developing optimization methods minimizing the concrete mass.

Today's traditional design procedure is governed by point-based design (PBD) [4], in which decisions need to be made for every step in the design process [5]. This research focused on the methodology of SBD, in which the design procedure maintains a wide design space for as long as possible. Consequently, information can be provided during a project's progress when there is still a possibility to adjust the design without major additional costs, thus maintaining the assigned budget [6].

Implementing SBD can facilitate optimization procedures of concrete structures, contributing to the work towards the climate goals set by the Swedish legislation [7]. Moreover, this research investigates possibilities of generating large data sets for structural optimization, as means of obtaining statistical significance of the optimization distribution, while mitigating the computational complexity of the procedure.

This paper focuses on the implementation of SBD in a multi-criteria parametric optimization of slab frame bridges, with respect to investment cost, environmental impact and buildability. From a corporate perspective, buildability is foremost a matter of cost and worker safety, as complexity entails increased labor and, thereby, expenses [8]. Additionally, the work explores quantifiable measurements of buildability in an automated process.

Nomenclature

SBD	Set-based design
PBD	Point-based design
ULS	Ultimate limit state
SLS	Serviceability limit state

2. Theoretical background

The research sought to explore and implement the principles of SBD in combination with an optimization procedure, both to which the theoretical background is explained in this chapter.

2.1. Set-based and point-based design

The traditional PBD approach is based on a stepwise chronology, characterized by choosing a plausible design for every step in the process, as information is established by the stakeholders involved [5]. When demands for large changes emerge along the project timeline, the need to completely reconsider the current design alternative might arise, commonly resulting in non-optimized solutions and increased costs [9].

SBD, as opposed to PBD, maintains a broad design space throughout the entire process. Hence, a specific design is not decided in every design step. Instead, a set of possible solutions is narrowed down as new information is provided [10]. The progression of SBD is thus, as opposed to PBD, characterized by a decreasing design space as alternatives are being disregarded, illustrated in Fig. 1.(a). By implementing SBD, all design solutions within the sets are continuously accessible, enabling a constant comparison of alternatives and the possibility of tracing back, facilitating negotiation [5]. Moreover, the criterion of environmental impact can be used as basis for the decision making during early-stage design [11, 12], ultimately challenging the traditional approach of tendering procedures which are governed by economical aspects [13].

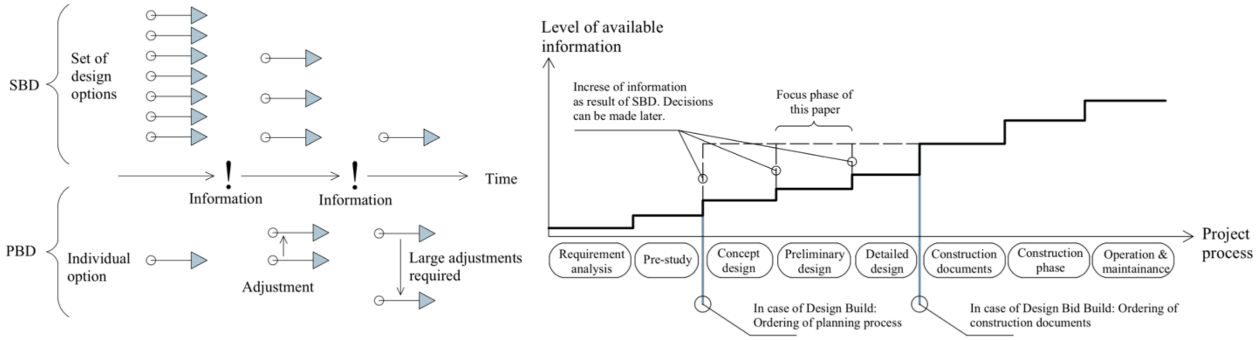


Fig. 1. (a) Principles of SBD and PBD; (b) Level of available information along the project process in relation to SBD

The advantages of further implementing SBD within the construction field are described in relation to the diagram shown in Fig. 1.(b), demonstrating the gradual information gain within a project implementing the more traditional PBD procedure. As new information is gained, decisions are made, resulting in progress. SBD drastically increases the degree of available information in the early design phases, leaving time to ensure that all requirements are met before the final decision is made later [9], facilitating an interdisciplinary cooperation between stakeholders [14]. In the context of this paper, the project stage of interest is the preliminary design phase, as seen in Fig. 1.(b). Consequently, the optimization does not compare different concepts. Rather, design solutions for a defined concept are optimized, in tune with the stepwise design principles implemented today.

Throughout a SBD procedure, alternatives are not fully deleted, making them accessible even if initially disregarded, leaving room for re-evaluation and negotiation. For instance, if the design procedure has soft constraints, alternatives that do not fulfil these requirements might prove to be highly optimized, which can be used as basis for negotiating the requirements. If a PBD approach was instead adopted, it would not be possible to access and compare solutions that did not fulfil the soft requirements, as those designs would have been initially dismissed.

2.2. Optimization

An optimization procedure is, in principle, built upon three building blocks, the *objectives*, the *constraints*, and the *decision variables*, according to Equation 1 [15]. The objective is the aspect that the model will maximize or minimize depending on the problem formulation. When optimizing two contradictory objectives at once, a set of optimal solutions can be identified, a *Pareto front* consisting of one dominating optimal solution in combination with the non-dominating optimal solutions [9] . The constraints are certain conditions that the algorithm must fulfill for the current solution to be considered valid. The decision variables are the variable parameters defined by a domain called the *decision space*.

$$\begin{aligned} &\min\ [f_1(x), f_2(x), f_3(x)] \\ &g_i(x) \leq 1\ , i = 1,2, \ldots, m \\ &h_j(x) \leq 1\ , j = 1,2, \ldots, r \\ &\qquad x \in D \end{aligned} \tag{1}$$

Where:

- $f_1(x)$, $f_2(x)$ and $f_3(x)$ are the objective functions to be minimized,
- $g_i(x)$ and $h_j(x)$ are the constraint functions to be fulfilled by the design alternative, and
- x are all the feasible and unfeasible design alternatives within the decision space D

3. Methods

The method chosen for the research was a parametric multi-criteria optimization based on SBD, implemented as a Python script within the parametric modeling software Grasshopper. The implementation was made for slab frame bridges, constituting the dominantly occurring short-span bridge type in Sweden [16]. The structural analysis was based on a linear elastic 2D frame, enabling the generation of large sets of design data as computational complexity is mitigated.

3.1. Limitations

In order to limit the computational complexity and thereby enable generation of large data sets, a 2D linear elastic frame analysis was conducted, as previously mentioned. The optimization was made for frame legs and bridge deck solely, disregarding foundation slabs and wing walls. Additionally, fatigue was disregarded in the design verification.

3.2. Implementation of SBD

Fig. 2. shows the principle of the SBD implemented, including all decision levels. The initial design space (Design space A) consists of all possible bridge designs, feasible or not. The design space is then narrowed down (Design space B) by establishing the governing input parameters for the bridge structure, being the span length (*L)*, structural height (*H)*, bridge deck width (*W)*, and boundary conditions (*bc)* between frame legs and foundation. The variable design parameters within a bridge construction were set to be the concrete class, cross-sectional heights, and rebar diameters. Bridge designs that do not fulfill the constraints defined according to national requirements on structural performance (ULS and SLS) are then disregarded, resulting in a further narrowing of the design space (Design space C). The subset of passed designs is saved for evaluation according to the objective functions, yielding optimized solutions (Design space D).

3.3. Multi-criteria optimization

The chosen multi-criteria optimization was based on three criteria, with the goal of minimizing environmental impact as well as the costs related to initial investment and buildability aspects. The optimization criteria were weighed together into an equivalent cost, being the final objective function in the algorithm. In addition to the equivalent cost, individual functions of respective criteria are calculated. Separating the results by criteria creates a possibility to find solutions optimized for specific criteria, which can be used for sensitivity analyses.

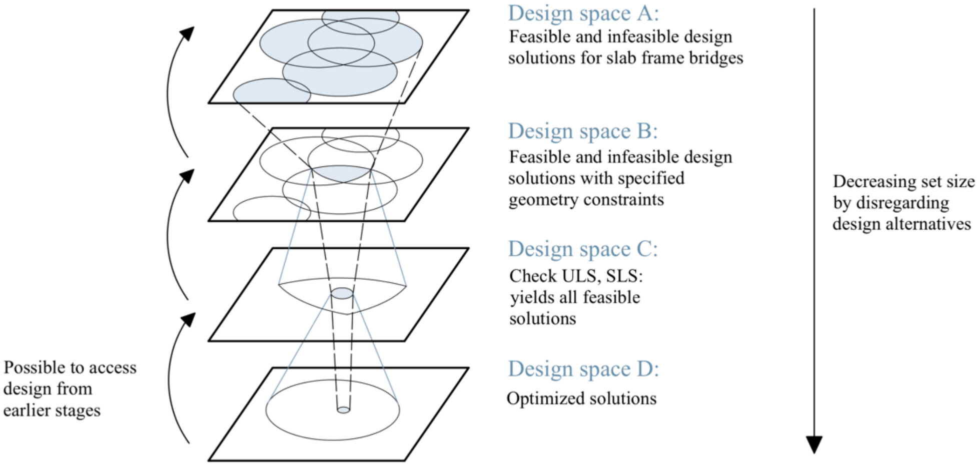


Fig. 2. Illustration of SBD, as implemented in the algorithm

The criterion of environmental impact was defined in terms of CO_2 emissions, translated into an environmental cost using the Ecovalue monetary system. Costs related to material (concrete, reinforcement and formwork) and fundamental labor are included in the definition of the investment cost criterion. Buildability aspects considered were factors related to geometrical complexity, material properties and the reinforcement, assumed to result in a prolonged production process, yielding additional costs. The buildability cost factors were defined according to:

- Varying thickness of structural members is assumed to increase the labor costs related to reinforcement work and formwork, in comparison to straight members,
- The slenderness of structural members is assumed to affect the labor costs related to reinforcement work, since slender members require additional attention in order to ensure good quality,
- The highest concrete class (C50/60) is assumed to increase the labor costs due to further need of concrete vibration in order to ensure good quality,
- The reinforcement diameter is assumed to affect the labor cost, since smaller diameters result in more ineffective reinforcing work ultimately increasing the time consumption for reinforcement work, and
- The need for shear reinforcement is assumed to increase the labor cost related to reinforcement work.

Generally, there is a close correlation between cost mitigation and minimized carbon footprint [7, 17]. However, the challenge is to concurrently consider the conflicting criterion of buildability. Within construction, the mathematically optimal solution is not necessarily the best alternative, considering abstract criteria such as buildability. Being able to evaluate and compare multiple solutions, as SBD enables, is a considerable asset.

3.4. Comparison with reference projects

As a basis for developing the algorithm and analyzing the results, data from an existing slab frame bridge was utilized. By inputting the information of an existing bridge in the code and extracting its results, a calibrated comparison could be made between the generated optimal design alternatives and the reference project. Thereby, a fair analysis of the optimization could efficiently be performed. Moreover, the material parameters and geometry from the reference project was used as a basis when defining domains in which design parameters varied. Thus, the design space could be limited to feasible or nearly feasible input, minimizing the data. Ensuring a substantial fraction of feasible design alternatives is essential in achieving a data set with statistical significance.

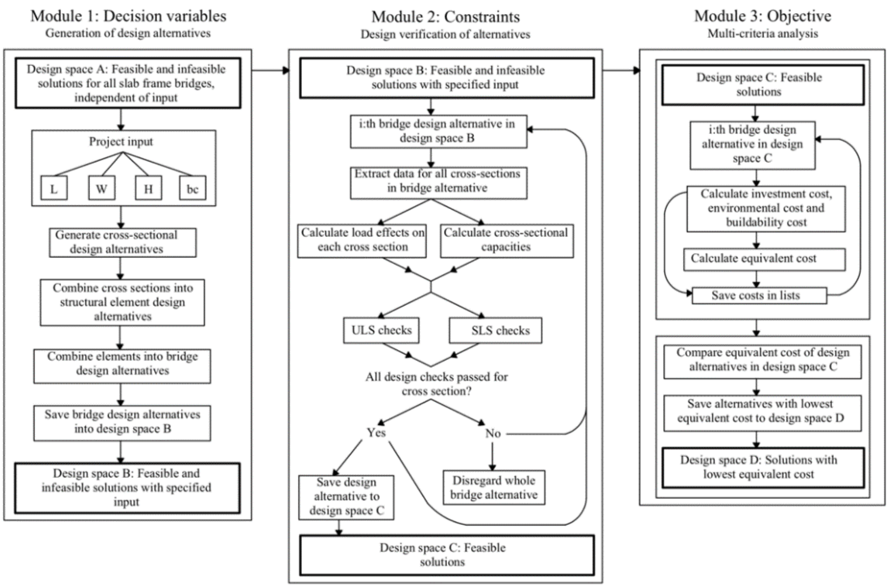


Fig. 3. Schematic flow chart of the algorithm layout

3.5. Algorithm layout

The principal layout of the algorithm was based on three main modules – generation of design alternatives, design verifications (ULS and SLS) and a multi criteria analysis. A schematic flow chart of the algorithm and its main routines is shown in Fig. 3. Design spaces A through D refer to those described in Section 3.2.

4. Results

The initial set (design space B) was decided based on the reference project in order to evaluate the outcome of the optimization procedure created. The concrete class (C32/40, C35/45 and C50/60), reinforcement diameter (∅16, ∅20 and ∅25), reinforcement layout and cross-sectional heights of structural members were all varied within the initial set. Furthermore, varying thickness of structural members was permitted in order to geometrically optimize the bridge design. The initial set of 104 976 bridge designs (Design space B) was narrowed down to the two most optimized designs (Design space D), according to Table 1, within a 5-minute running time of the algorithm.

Table 1. Number of bridge design alternatives in each design space.

Design space	Number of bridge designs in set
B: Initial design set with fixed L, H, W and bc	104 976
C: Set of designs that passed ULS and SLS constraints	9371
D: Set of optimized designs	2

The optimization procedure was performed to identify two optimal designs, one with the lowest overall costs (Design 1) and one with minimized environmental impact (Design 2). According to Fig. 4.(a), Design 1 shows a 4.4% reduction of the environmental impact, with a 5.7% simultaneous decrease in total costs (investment + buildability). Design 2 exhibits a greater decrease in environmental impact, a 13.7% reduction, but for a slightly increased cost of 2.3%. The principal design difference between the two solutions is further illustrated in Fig. 4.(b).

The probability density functions corresponding to the optimization criteria representing all the feasible solutions (Design space C) are plotted in Fig. 5.(a). Furthermore, the two bridge designs with the lowest equivalent cost (Design space D), together with the reference project, are illustrated in Fig. 5.(b), showing their relative cost for the different criteria.

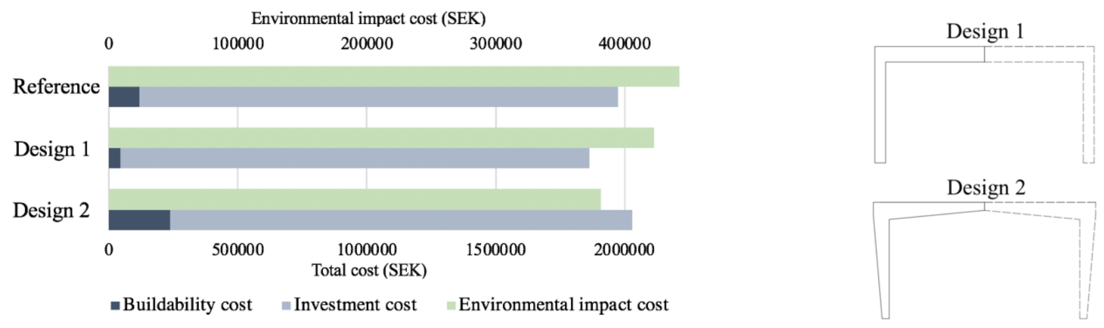
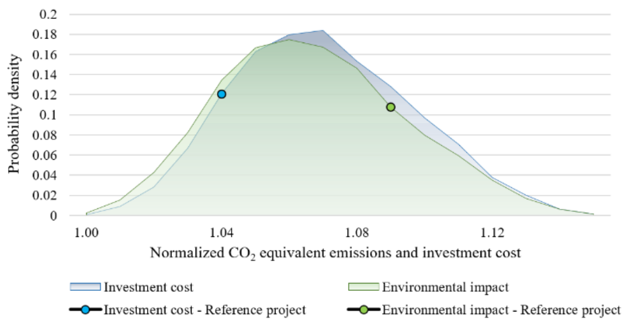


Fig. 4. (a) Optimization results of the solution with the lowest total costs ; (Design 1) and the solution with minimized environmental impact (Design 2), in relation to the reference project

(b) The principal difference in geometrical complexity between Design 1 and Design 2



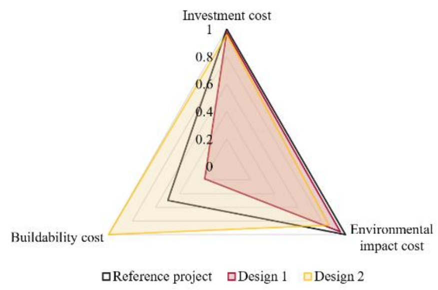


Fig. 5. (a) Normalized environmental impact and investment costs for all ; feasible bridge designs (Design space C) in relation to the reference project

(b) Spider plots showing the relation between optimal solutions and the reference project, based on the three criteria

A sensitivity analysis performed on the result showed that the governing parameters for a more optimized design were slimmer construction members with increased reinforcement amounts (minimized investment costs and environmental impact), with larger rebar diameters (lower buildability costs). Additionally, the optimal solutions have added shear reinforcement (increased buildability cost but enables decreased investment costs) but avoid the highest concrete class (lower buildability cost). The implementation of buildability aspects results in a constant balancing between lower costs due to minimized material amounts and increased costs due to worse buildability circumstances.

5. Discussion

The design solutions proceeding with the more traditional PBD approach commonly appear in proximity to the center of the normalized probability density functions, as illustrated in Fig. 5.(a). The optimized design solutions represented by a lower probability are generally overlooked, being an incentive for implementing optimization procedures in order to effectively identify optimal solutions during the preliminary design phase. As the result indicates, materially optimal solutions typically bring increased buildability costs, making optimization a fine balance between minimizing investment costs (in terms of decreasing material usage) and mitigating additional buildability-related costs. Moreover, the equivalent cost depends on an internal weighting of the three criteria, making the outcome of the optimization flexible for optimizing towards a specific criterion, based on what is prioritized by the client.

Furthermore, the result highly depends upon the chosen initial set of bridge designs. A larger initial set with broad parameter ranges entails a higher probability of finding outliers showing an exceptionally optimized solution. A field of development within the research of this paper would be to run the algorithm for all potential span lengths and dimensions of a slab frame bridge, creating a database containing all possible designs for the specific bridge type [18]. Once the database has been created, the generation of design alternatives never has to be repeated within the optimization algorithm, further mitigating the computational complexity of the method. In the context of this paper, a subset of such a database has been developed, as the input geometries and boundary conditions constitute one bridge project (Design space B) among all possible slab frame bridges (Design space A).

Further development would then be to analyze the variable parameters of the most optimized bridge designs in order to find governing parameters and their respective impact on each criterion (buildability, environmental impact and investment cost). By extension, a *tree regression model* could be created by implementing machine learning, based on the conclusions drawn on governing parameters of the best design alternatives. Once such a tree regression model has been created it can automatically identify highly optimized designs independently from the original optimization algorithm. Thus, the result presented in this paper constitutes the potential learning input for a machine learning procedure. A prerequisite for using the optimization solutions' distribution as a basis for a reliable tree regression model is to have statistical significance, hence the importance of obtaining large data sets. The primary measure taken for mitigating the complexity and thereby maximizing the data sets was, in this work, the use of linear elastic 2D analysis without connection to extensive finite element analyses.

6. Conclusion

The purpose of this research was to investigate the possibility of performing a set-based parametric, multi-criteria optimization of slab frame bridges in early-stage design, with respect to investment cost and environmental impact, whilst considering buildability. Moreover, the method examined the implementation of a linear-elastic 2D frame analysis as means of mitigating computational complexity and thereby enable generation of large data sets.

The result highlights the importance of including buildability aspects when identifying optimal solutions and shows a potential of achieving a 13.7% decrease in environmental impact for a slight increase in costs [19].

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