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Set-Based Design for Bridge Optimization: Minimizing Cost, Construction Time, and CO₂ Emissions

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Abstract: While bridges are an essential part of the infrastructure, their construction is resource intensive. Reducing construction time and optimizing bridges could reduce their climate impact. The aim of this study was to investigate the potential for reducing material and construction cost (henceforth referred to as cost), as well as construction time and CO₂ emissions for grouping and optimizing bridges using set-based design (SBD). The grouping is based on the free area under the bridges and the benefits of construction time due to the learning curve. In this study, a script is developed that performed finite-element analysis and conducted necessary design checks for all the bridges investigated. The bridges generated from SBD were then compared with bridges from a reference project. The results show that in a project with several bridges, SBD could be used to group bridges and reduce cost and construction time without a negative impact on CO₂ emissions. Reducing cost and construction time without negative impact on CO₂ levels in infrastructure projects is a huge benefit for the society. **DOI: 10.1061/JBENF2.BEENG-7725.** This work is made available under the terms of the Creative Commons Attribution 4.0 International license, <https://creativecommons.org/licenses/by/4.0/>.

Practical Applications: The results of this paper could be applicable for practicing bridge engineers. It shows potential with set-based design, both from an optimizing perspective and how it could be used to group bridges. The groups were based on the free area under the bridges, reducing construction time due to repetitive work. The greatest potential with grouping is to reduce construction time, which is beneficial for the society. When building bridges, it is important to have a holistic view and to be aware that bridges are part of a larger network. Using set-based design could help engineers to find the best trade-off between minimizing material in the bridges and reducing construction time and thereby deliver the overall best-performing solution for the society.

Author keywords: Climate impact; Construction time; Group design of bridges; Infrastructure; Optimization; Productivity; Set-based design; Standardization.

Introduction

It is well known that the construction industry lags behind other industries in terms of efficiency and productivity (Ofori et al. 2022; Sveikauskas et al. 2016; Wodalski et al. 2011). The use of construction materials alone accounts for 15% of global emissions

(UNEP 2022), 30% of waste generation, and 50% of resource extraction (Arnold 2024). One way to improve productivity and reduce construction time is to reduce variability in construction (Barbosa et al. 2017). For example, standardization and off-site construction approaches have been shown to increase productivity and reduce climate impact (Larsson and Simonsson 2012; Sandanayake et al. 2019). Hence, the question arises whether on-site standardization of infrastructure projects yields similar positive effects in reducing cost and climate impact.

A study of the Swedish bridge construction industry has shown that repetition is one way to increase productivity (Lagerkvist et al. 2022b), and a feasibility study has shown that grouping bridges has the potential of reducing cost, CO₂ emission, and time for construction (Lagerkvist et al. 2024). With equally designed elements, the formwork could be reused, which would decrease climate impact (Kim et al. 2013). When more and larger infrastructure projects are being planned in Sweden, such as the North Bothnia Line and the East Link, which comprehend several bridges, a grouping of bridges could be an effective way of reducing the cost and climate impact of such projects.

Structural optimization can reduce the amount of material and, thus, also the amount of embedded CO₂ emissions. Several researchers studied optimization in structural design focusing on cost and/or climate impact, e.g., optimization of slab frame bridge construction to reduce investment cost (Yavari et al. 2016b) and environmental impact (Yavari et al. 2016a), while multiobjective optimization, which includes both cost and environmental impact has also been examined (Chalouhi 2019; Garcia-Segura et al.

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2018; García-Segura and Yepes 2016; Mathern et al. 2020). Yet another approach to optimize structures is to seek optimal shapes, as explored in Briseghella et al. (2013), Kazakis et al. (2017), Li et al. (2022), Sobótka (2020), and Wu and Wu (2017). Parametric design has been used to optimize structures and to explore design space for conceptual design for bridges (Balmer et al. 2024; Hlal et al. 2024).

In contrast to a traditional point-based design approach (PBD), a design method that has been proven valuable for bridges is set-based design (SBD), which in a transparent way may be used to assess reduced cost and climate impact for individual bridge structures (Lagerkvist et al. 2022a; Rempling et al. 2019). In addition to reducing the amount of material, it is important to also reduce the climate impact from the materials themselves as well as the negative impact of the materials manufacturing processes (Ek et al. 2020; McGarry et al. 2022). SBD can include any differentiation between several aspects of climate impacts of the materials in the design, which is an advantage since there is no single optimal solution. Rather, optimal solutions will depend on the relation between materials and their assigned material values.

Reducing construction time is also a means of reducing climate impact, e.g., shorter construction activities, effective use of machinery and construction services, and efficient energy consumption (Simonsson 2011; Institution of Structural Engineers 2022; Yu et al. 2017). In addition, reduced construction time decreases climate impact associated with transport detours, which have been shown to have a major impact (Boros et al. 2024). By grouping bridges or structural elements, repetitive construction activities are generated, which could reduce construction time (Bekdik 2017; Gottlieb and Haugbølle 2010; Panas and Pantouvakis 2018; Thomas et al. 1986). The potential time reduction due to repetitive work has been demonstrated in a bridge that had 755 simply supported prefabricated spans (Rosignoli 2011). Similar results were obtained for modular construction in the United Kingdom (Armitage et al. 2024).

Although much of the previous research has shown potential to reduce cost and climate impact for individual bridges, there is a gap in the literature addressing the reduced cost, construction time, and CO₂ emissions by grouping bridges. Therefore, it would be beneficial to find a method whereby several bridges could be grouped and optimized to reduce the total sum of material and construction costs (henceforth referred to as cost), as well as construction time and CO₂ emissions.

This paper presents the potential of a design approach using SBD and group design of a bridge suitable for several locations with different preconditions. The potential is shown by comparing a reference project, consisting of 11 bridges, designed according to

Eurocode and PBD with the results from (1) an SBD approach to an individually designed bridge for each location, and (2) an SBD approach in which the bridges are grouped to create repetition and hence increase productivity. The aim of this study is to investigate how grouping and optimizing several bridges using SBD could reduce cost, construction time, and CO₂ emission.

Reference Project

In this study, a built railway project in the south of Sweden consisting of 12 slab frame bridges is used as a reference case. The project was procured as a design build contract, meaning that the responsibility lies with the contractor (Lædre et al. 2006). The bridges were designed to carry double-track railway traffic. Out of the 12 bridges, 11 were included in this study; the 12th, being much larger, did not have the characteristics to fit into any of the groups. The bridges cross different obstacles, such as pedestrian walkways or roads. The free passage area (width × height), amount of reinforcement, and amount of concrete for the reference bridges are presented in Table 1. The amount of material in the reference bridges is taken from as-built documentation from the project.

The studied reference bridges were built with a radius for the underside of the bridge deck [Fig. 1(d)]; alternative construction would be with a straight underside with or without haunches [Figs. 1(a–c)]. Using a radius rather than haunches was shown to reduce the amount of material (Alhede and Beskow 2020). However, Lagerkvist et al. (2022b) estimated that the shape without haunches [Fig. 1(a)] yielded the highest productivity (in terms of buildability) compared to haunch or radius.

Set-Based Design Method

SBD allows for parallel and delayed decision-making processes (Jeffrey et al. 1995; Sobek et al. 1999). In comparison with traditional PBD, in which one single solution (point) is investigated and developed during the design process, SBD generates numerous alternatives that investigate the entire design space. With SBD, alternatives are gradually filtered during the project, based on limitations and decisions that are made, and the sets converge to a solution (Rempling et al. 2019; Sobek et al. 1999). The applicability and potential of the proposed method were assessed by implementing an automated full-factorial SBD approach for slab frame bridges with different free areas under the bridge. To automate the design process, the finite-element (FE) modeling and all the design checks were scripted using Python (version 3.11.5). The

Table 1. Data for the studied reference bridges

Bridge no. (number in the reference project)	Free area (width × height) (m)	Amount of reinforcement (t)	Amount of concrete (m ³)
1	15.7 × 5.5	75.4	569.6
2	15.7 × 5.5	87.4	566.5
3	12.3 × 5.4	50.6	405.0
4	6.0 × 3.5	15.8	165.6
5	6.0 × 3.3	17.4	146.7
6	6.0 × 3.3	17.7	145.9
7	5.7 × 3.3	22.7	176.1
8	7.9 × 5.2	33.4	212.2
9	7.7 × 5.6	30.2	252.0
10	6.7 × 3.3	26.8	211.1
11	6.0 × 2.8	19.1	173.2
Σ	—	396.6	3,023.9

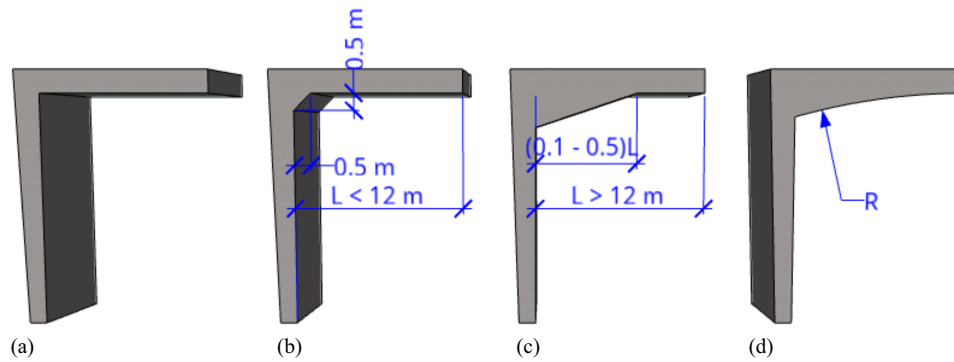


Fig. 1. Different shapes of the cross sections of slab frame bridges.

Table 2. Varied parameters and ranges for the set-based design

Parameter	Configuration 1	Configuration 2
Free bridge width (m)	1 value: 12.75	—
Frame leg height (underside of bridge deck to top of bottom slab) (m)	2 values: 3.6, 5.6	—
Reinforcement diameter (mm)	3 values: 16, 20, 25	—
Stirrups diameter (mm)	1 value: 12	—
Minimum spacing between reinforcement (mm)	90	—
Concrete class	1 value: C35/45	—
Reinforcement	1 value: K500B	—
Concrete cover (mm)	1 value: 35	—
Frame type	2 combinations: open, closed	—
Ground conditions	1 value: “Foundation on hard friction soil,” 60 MPa	—
Bottom slab thickness (m)	5 values: (0.40, 0.80) in steps of 0.1	—
Free opening (m)	5 values: (6.0, 8.0) in steps of 0.5	16 values: (8.5, 16.0) in steps of 0.5
Radius of underside of bridge deck	3 values: (3, 5, 8) $\times L$	3 values: (3, 5, 8) $\times L$
Slab thickness (middle of span) (m)	4 values: (0.35, 0.65) in steps of 0.1	4 values: (0.50, 0.80) in steps of 0.1
Leg thickness (m)	5 values (0.3, 0.7) in steps of 0.1	6 values (0.4, 0.9) in steps of 0.1

script used in this paper was a continuation and development of the work done by Hansson and Tacking (2024).

Selection of Parameter Ranges and Sets

For a selection of parameters and ranges to evaluate, the starting conditions were that all built bridges in the reference project should be covered. For the span, the shortest and the longest spans from the reference project were chosen as the limitations. The free height was chosen so that it could be either a bridge over a pedestrian walkway or a bridge over a road. For the other

parameters, lower and higher values, based on prior research (Hansson and Tacking 2024; von Kraemer and Sjölund 2024), were evaluated and chosen based on the site conditions of the reference bridges. All the parameters and ranges, generating approximately 30,000 possible geometric configurations, are presented in Table 2. The geometric configurations together with the tested reinforcements generated almost 70,000 configurations. A large number of generated configurations were evaluated automatically using a scripted workflow integrating parametric modeling, FE analysis, and rule-based filtering. For each configuration, the script generated the bridge geometry, assigned material properties,

Table 3. Unit prices and time for construction of evaluated materials and work tasks

Parameter	Cost ^a	References
Concrete C35/45	3,366 SEK/m ³	Chalouhi (2019), Yavari et al. (2016b)
Concrete work of frame legs (1.5 h/m ³)	1,403 SEK/m ³	Yavari et al. (2016b)
Concrete work of bridge deck (2 h/m ³)	1,496 SEK/m ³	Yavari et al. (2016b)
Form (material)	311 SEK/m ²	Mathern et al. (2020)
Formwork of frame legs on straight walls (250 SEK + 1.5 h/m ²)	1,870 SEK/m ²	Chalouhi (2019), Yavari et al. (2016b)
Formwork of deck with radius (500 SEK + 2 h/m ²)	2,805 SEK/m ²	Yavari et al. (2016b)
Formwork for foundation slabs	374 SEK/m ²	Chalouhi (2019)
Reinforcement, K500C-T	17 SEK/kg	Chalouhi (2019), Yavari et al. (2016b)
Reinforcement work on frame legs (30 h/t)	28 SEK/kg	Yavari et al. (2016b)
Reinforcement work on bridge deck (35 h/t)	33 SEK/kg	Yavari et al. (2016b)

Note: Prices have been index-adjusted according to SCB (2024) up to the year 2024.

^a1 SEK $\approx$ 0.087 euro (€), September 2024.

Table 4. CO₂ emissions

Parameter	CO ₂ equivalent (A1–A3)	Reference
Reinforcement, low	0.37 kg CO ₂ /kg	EPD (2021)
Reinforcement, high	0.883 kg CO ₂ /kg	Boros (2023)
Concrete, high	321.92 kg CO ₂ /m ³	García-Segura and Yepes (2016)
Concrete, low	248.8 kg CO ₂ /m ³	Boros (2023)
Formwork	2.08 kg CO ₂ /m ²	García-Segura and Yepes (2016)
Production	700 kg CO ₂ /1.355 MSEK	Institution of Structural Engineers (2022)

performed FE analysis, and checked all relevant design criteria according to Eurocode requirements, including ultimate limit state (ULS) and serviceability limit state (SLS).

Cost, Construction Time, and CO₂ Emissions

In this study, the cost items related to concrete and reinforcement volume, formwork, and associated work items were included; hence, the reported costs should be interpreted as comparative production costs rather than total bridge project costs. The chosen unit prices and time for construction of materials and work tasks are presented in Table 3, and the used CO₂ emissions considered are presented in Table 4. In Table 4, there are two different CO₂ emissions for both reinforcement and concrete. All these values are used, which gives four different possible emission combinations for every solution. It is worth mentioning that different costs for different CO₂ emissions were not considered. The reported CO₂ emissions represent embodied emissions from concrete and reinforcement within the modeled bridge components and should be interpreted as comparative indicators rather than full project life cycle emissions.

Grouping

Using a set-based design approach allows performance design parameters to be used directly as design requirements, making it possible to postpone design decisions based on design parameters that traditionally govern point-based design, such as constructability

and foundation type. This provides an advantage, as all feasible design options that satisfy the main performance requirement are included in the final set of solutions. This final set of alternatives is then used for further evaluation, e.g., with respect to the contractor's needs and requirements. For this particular bridge type, the main performance requirement is the structure's ability to meet the free opening and load-carrying requirements. The metric of free opening, i.e., the required free width and free height underneath the bridge, was selected because it represents the main site-specific boundary condition common to all bridge locations and therefore provides a practical basis for grouping bridges that may share similar formwork logic, reinforcement layout principles, and construction sequences. Other variables, such as reinforcement ratio and member thickness, were treated as dependent design outputs within each group. No formal correlation analysis was performed between alternative grouping variables and constructability; this should be addressed in future work. For grouping, the first bridge in a set determines the requirements for the other bridges regarding reinforcement spacing, underside radius, varying part thicknesses, and so on. If the reinforcement amount differs between two bridges within a group, maintaining the same reinforcement spacing is preferable (Lagerkvist et al. 2022b). The concept of grouping aims to use a set of bridges to cover several sites and the preconditions of the reference bridges, resulting in shorter construction times compared to designing and building each bridge separately. To estimate the construction time reduction—due to repetition effects—the learning curve effect proposed by Olofsson et al. (2010) was used [Eq. (1)]. Although

Table 5. Included loads in the design

Load assumption	Value	Reference
Dead weight	$\gamma_{\text{concrete}} = 25 \text{ kN/m}^3$	EN 1991-1-1
Infills	$\gamma_{\text{soil,dry}} = 20 \text{ kN/m}^3$, $\gamma_{\text{soil,wet}} = 13 \text{ kN/m}^3$	Trafikverket (2022)
Pavement	$\gamma_{\text{pavement}} = 23 \text{ kN/m}^3$	EN 1991-1-1, Trafikverket (2021)
Ballast	$\gamma_{\text{ballast}} = 20 \text{ kN/m}^3$	EN 1991-1-1
Even increase in temperature	Temperature in the air: $T_{\text{min}} = -28^\circ\text{C}$, $T_{\text{max}} = +35^\circ\text{C}$ Temperature in concrete: $T_{\text{e,min}} = -20^\circ\text{C}$, $T_{\text{e,max}} = +37^\circ\text{C}$	EN 1991-1-5, Transportsyrelsen (2018)
Shrinkage	0.00024	EN 1992-1-1
Creep	$\Phi(0) = 2$	EN 1992-1-1
Railway loads	LM71, $\alpha = 1.33$	Eurocode SS-EN-1991-2, Transportsyrelsen (2018)
Dynamic factor	$\Phi_2 = 1.44/[(L_\Phi)^{0.5} - 0.2] + 0.82$, $1.00 \leq \Phi_2 \leq 1.67$ and $L_\Phi = k \times L_m$, where $k = 1.3$ and $L_m = 1/n \times (L_1 + L_2 + \dots + L_n)$	Eurocode SS-EN-1991-2, Transportsyrelsen (2018)
Surcharge	$q_{\text{eq}} = \alpha \times Q_{\text{vLM71}}/3 = 1.33 \times 4 \times 250/6.4 \times 3.0 = 69.3 \text{ kPa}$ $q_{\text{eq}} = K_0 \times q_{\text{eq}}$	Eurocode SS-EN-1991-2
Earth pressure	$P_{\text{earth}} = K_0 \times z \times \gamma$, $K_0 = 0.39$	Trafikverket (2022)
Increased earth pressure against frame leg	$\Delta p = c \times \gamma \times z \times \delta/2$, $c = 600$ when favorable and 300 when unfavorable, $z = h/2$, $\delta = \text{horizontal displacement of the top of the structure against the earth}$	Trafikverket (2022)
Traction force	$1.0 \times 1.33 \times 33 \times L$	Eurocode SS-EN-1991-2, Transportsyrelsen (2018)
Braking force	$1.0 \times 1.33 \times 20 \times L$	Eurocode SS-EN-1991-2, Transportsyrelsen (2018)
Nosing force	$Q_{\text{sk}} = \alpha \times 100 \text{ kN} = 133 \text{ kN}$	Eurocode SS-EN-1991-2
Support yielding	Vertical on both supports, 0.01 m Horizontal, 0.05 m	Trafikverket (2020), Eurocode SS-EN-1991-2

Table 6. Cost, construction time, and CO₂ emissions for reference bridges

Group	Bridge no.	Cost (MSEK)	CO ₂ emission (t)				Construction time (days)
			High–high	High–low	Low–high	Low–low	
1	1	8.77	253.9	215.2	212.2	173.6	84
	2	9.48	263.7	218.8	222.2	177.4	92
	3	6.38	178.4	152.4	148.8	122.8	61
2	4	3.14	78.9	67.2	66.0	54.3	31
	5	2.59	64.4	55.5	53.7	44.8	25
	6	2.61	64.4	55.3	53.8	44.7	26
	7	2.80	69.3	61.2	57.2	49.1	27
3	8	4.03	100.3	83.2	84.8	67.7	40
	9	4.17	110.4	94.9	92.0	76.5	41
	10	3.50	93.6	79.9	78.2	64.5	34
	11	3.11	74.9	65.1	62.2	52.4	31
Σ	—	50.58	1,352.2	1,148.7	1,131.1	927.8	492

Note: The values given in Table 4 were used to calculate CO₂ emissions of the reference bridges. High–high, high–low, and so forth refer to high and low values of concrete and the reinforcement given in Table 4. The number of bridges in each group was finally chosen so that the most significant reduction of construction time was achieved with a reasonable number of bridges that a construction team could construct as a constraint.

simplified, the learning number is used as a practical proxy for repetition effects in construction, allowing a consistent comparison between grouped and nongrouped bridge solutions

$$T_n = T_1 \left[1 - (1 - l) \frac{\ln(n)}{\ln(2)} \right] \quad (1)$$

where T_n = time to perform a task the n th time; T_1 = time to perform a task the first time; and l is the learning number. To address uncertainty in the assumed learning effect, an expanded sensitivity analysis was performed for learning numbers of 80%, 85%, 90%, and 95% (Table 9). The baseline value of 90% was retained because it is consistent with Swedish bridge-production measurements, done at Ölandsbron in Sweden, reported by Olofsson et al. (2010) for repetitive on-site activities, but the broader interval was used to test the robustness of the conclusions. Across this range, the grouped SBD alternative remained advantageous with respect to construction time, while cost varied moderately and CO₂ emissions were only marginally affected. These results indicate that the main conclusion of the study—that grouping primarily improves productivity and project duration—is robust to the assumed learning factor. The number of bridges in each group was based on the reasonable number of bridges for one team to construct according to the Swedish bridge industry (Lagerkvist et al. 2022b) while achieving the highest possible reduction of construction time.

Structural Design

In this section, regulatory requirements used for loads and finite-element analysis in this study are presented.

All new bridges procured by the Swedish Transport Administration should be designed according to the regulatory requirements stated in the national governing policies (Trafikverket 2020), and according to Eurocodes EN 1990, EN 1991-1-1, EN 1991-1-5, SS-EN-1991-2, EN 1991-1-4, EN 1991-1-1, Eurocode 2, EN 1992-1-1, Eurocode 7, and Eurocode 1 (CEN 2002a, b, 2003a, b, 2005a, b, c, d, 2006), in which design checks in ULS, SLS, and fatigue (fat) should be fulfilled. National implementations of Eurocode are given in Transportsyrelsen (2018). The parts of Eurocode that are of interest for this study are *Eurocode: Basis of Structural Design*, *Eurocode 1: Actions on structures*, *Eurocode 2: Design of concrete structures*, and *Eurocode 7: Geotechnical design*.

Designing bridges requires many different loads, and for this study, only the most governing loads have been considered, which are presented in Table 5.

For the FE analysis, the bridges were modeled and analyzed using BRIGADE/Plus (version 2024.4). All the bridges and their components were modeled with shell elements. For boundary conditions, the bottom of the legs was connected to the ground with springs. The elastic stiffness of the ground was conservatively set to 60 MPa. The linear finite-element analysis was performed for the load cases given in Table 5. The finite-element analysis results in the sectional forces for all sections, e.g., M_{Ed} , which, in the next stage, are used to filter out solutions that fulfill the applied EC requirements. This is made for all solutions in the initial set. To be able to reduce computational time, a convergence study was performed on a bridge with the largest span, concluding the largest acceptable element size for all the bridges. The element size was chosen based on a compromise between bending moment distribution in ULS and computational time; it was deemed acceptable if the deviation was less than 5% from the result of a model with half the element size. This was based on the work done by Hansson and Tacking (2024) and resulted in an element size of 0.2 m.

It is important to state that the numerical results are primarily intended for relative comparison between alternatives and should not be interpreted as final design values.

Results

In this study, a project with 11 reference bridges has been used to demonstrate how cost, construction time, and CO₂ emissions could be reduced if SBD was used. For comparison, two cases were studied in which the optimization by SBD was deployed on (1) a single-design approach of each bridge, and (2) a group-design approach of bridges according to the “Grouping” section. The two approaches were assessed against each other and compared with the reference bridges regarding material volume, construction time, cost, and CO₂ emissions. Results for the reference bridges and the two different SBD approaches are presented subsequently.

Reference Project

Table 6 summarizes the performance of the reference bridges with regard to cost, construction time, and CO₂ emissions, based on the

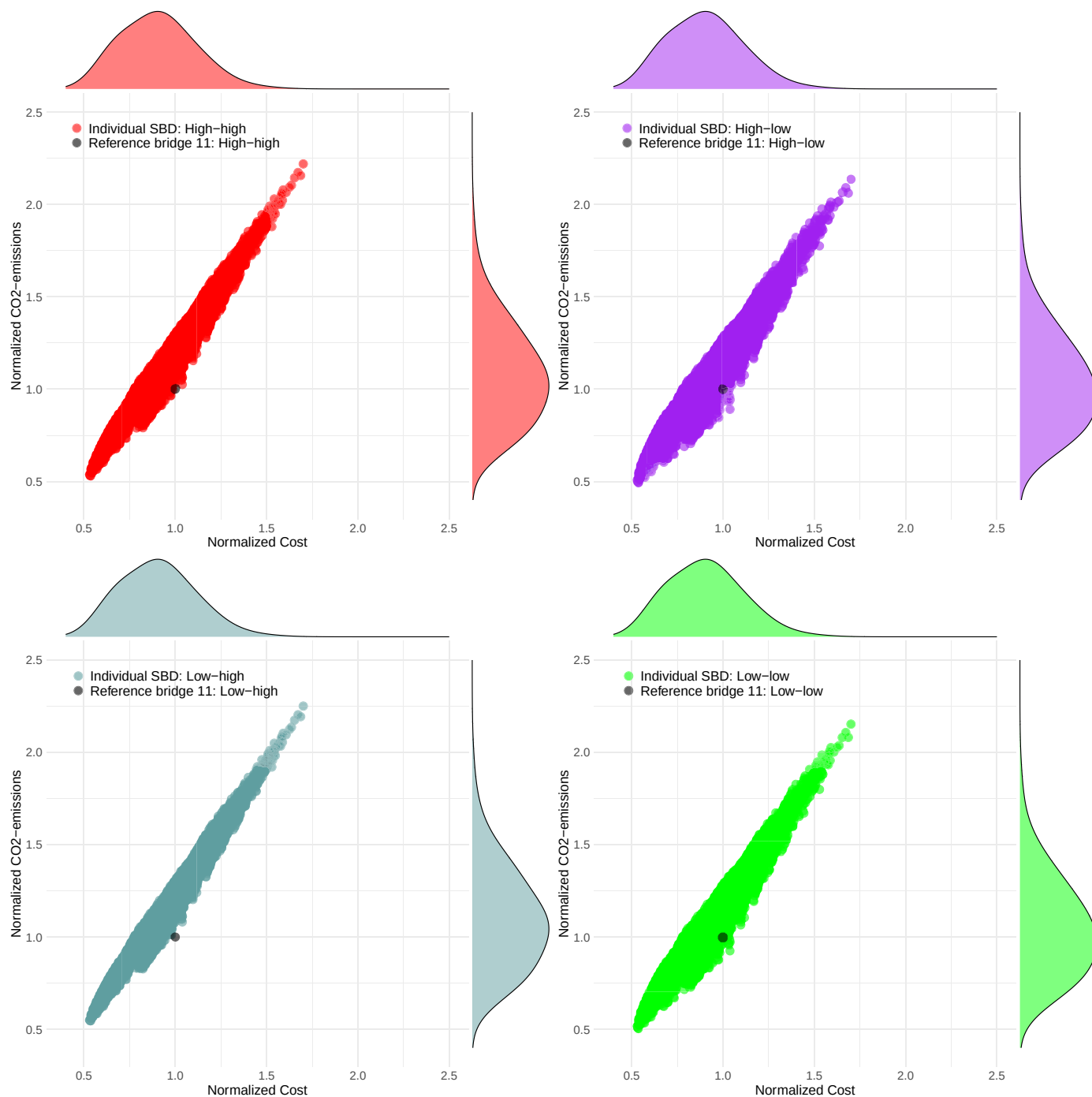


Fig. 2. Normalized cost and CO₂ emissions for SBD solutions, normalized against Reference bridge 11.

data from Tables 3 and 4. The total cost was approximately 50.6 MSEK, the total construction time was 492 days, and CO₂ emissions ranged between 927 and 1,352 t, depending on the material assumptions. The bridges were categorized into three groups based on free area, providing the baseline for subsequent SBD optimization.

Set-Based Design Optimization of Individual Bridges

The SBD approach generated a wide range of feasible solutions for each bridge rather than a single-design alternative. Studying the cost and CO₂ emissions of all 11 reference bridges resulted in several design solutions that could have been chosen for each bridge.

Fig. 2 illustrates normalized cost and CO₂ emissions relative to Reference bridge 11 (here only one reinforcement diameter is shown for the SBD). The density curves indicate that the reference solutions were located in regions with numerous possible SBD alternatives, confirming previous findings on the flexibility of this method (Rempling et al. 2019).

From the results presented in Fig. 2, it can be observed that SBD generates solutions with both higher and lower cost and CO₂ emissions. Table 7 presents the results from individual SBD for all bridges in this study, and it could be observed that the choice of material impacts not only the structural design but also CO₂ emissions, which confirms the findings from previous research (McGarry et al. 2022). In Table 7, the cost and CO₂ emissions

Table 7. Cost, construction time, and CO₂ emissions for individually designed bridges using SBD

Bridge no.	Cost (MSEK)	CO ₂ emission (t)				Construction time (days)
		High–high	High–low	Low–high	Low–low	
1	7.50	200.0	149.1	175.7	124.7	75
2	7.50	200.0	149.1	175.7	124.7	75
3	5.46	141.1	105.2	124.0	88.0	53
4	1.65	39.7	32.1	34.0	26.4	17
5	1.93	49.0	39.3	42.0	32.4	19
6	1.93	49.0	39.3	42.0	32.4	19
7	1.93	49.0	39.3	42.0	32.4	19
8	3.37	86.4	67.4	74.8	55.8	33
9	3.37	86.4	67.4	74.8	55.8	33
10	2.25	54.7	42.0	47.7	35.0	22
11	1.65	39.7	32.1	34.0	26.4	17
—	38.54	995.0	762.3	866.7	634	382

are minimized individually, and they may not necessarily be related.

Compared to the reference bridges, it would be possible to reduce costs by almost 24%. The maximum cost reduction would reduce CO₂ emissions (for high–high CO₂) by 26%. The maximum reduction of CO₂ emissions would be for the high–low case and that could be reduced by up to 33%. For the high–low CO₂ alternative, the cost reduction could be 22%. The construction time could be reduced by a total of 110 days (106 days for alternative with lowest CO₂). The maximum reduction of time would be in Group 3, which could be reduced by 41 days. Group 1 had the longest construction time and is therefore the governing group for

time reduction, and here it was possible with a time reduction of 34 days.

Both cost and CO₂ reductions were primarily linked to material savings, underscoring the importance of material selection in conjunction with structural optimization. However, it should be noted that more detailed design checks, such as fatigue and dynamic load effects, could moderate these reductions.

Set-Based Design and Grouping

When bridges were grouped according to free area and a learning curve was applied (the “Grouping” section), further gains were

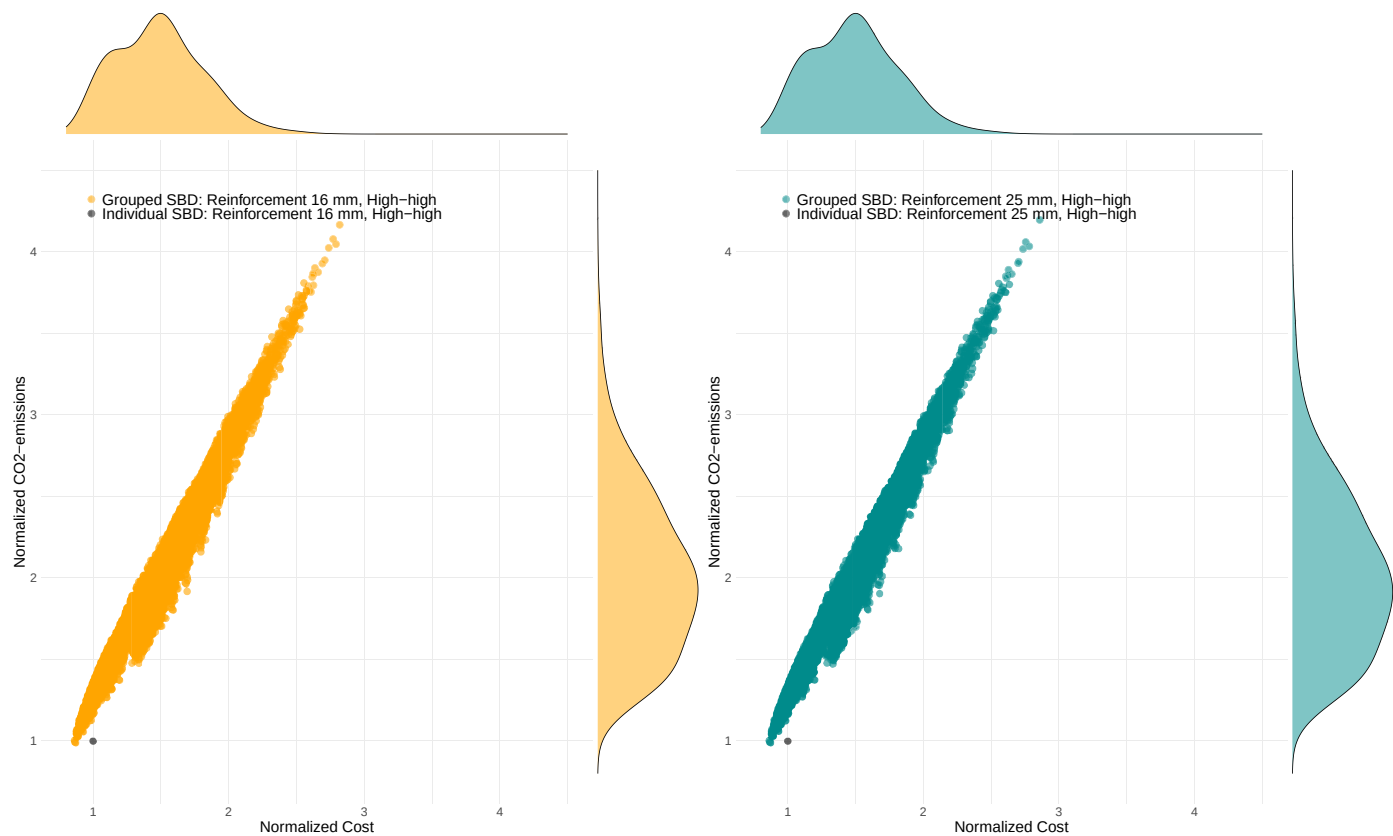


Fig. 3. Normalized cost and CO₂ emissions for grouped solutions, normalized against individual SBD for Bridge 11, with 16 and 25 mm reinforcement bars, are presented with the high–high CO₂ emission combination of concrete and reinforcement.

Table 8. Cost, construction time, and CO₂ emissions for grouped bridges when using SBD and a learning number of 90%

Group	Bridge no.	Cost (MSEK)	CO ₂ emissions (t)				Construction time (days)
			High–high	High–low	Low–high	Low–low	
1	1	7.50	200.0	149.1	175.7	124.7	75
	2	7.03	199.3	148.4	175.0	124.0	67
	3	4.92	140.4	104.5	123.3	87.3	45
2	4	1.65	39.7	32.1	34.0	26.4	17
	5	1.80	48.6	39.0	41.6	32.0	17
	6	1.73	48.6	38.9	41.6	32.0	16
	7	1.68	48.5	38.9	41.5	31.9	15
3	8	3.37	86.4	67.4	74.8	55.8	33
	9	3.15	85.8	66.9	74.2	55.3	30
	10	2.00	54.8	41.8	47.2	34.5	19
	11	1.42	39.3	31.7	33.5	26.0	13
Σ	—	36.25	991.4	758.7	862.4	629.9	347

Table 9. Estimated cost, construction time, and CO₂ emissions for altered learning number

Learning number (%)	Cost (MSEK)	CO ₂ emissions (t)				Construction time (days)
		High–high	High–low	Low–high	Low–low	
80	33.95	989.8	757.2	861.2	628.7	311
85	35.10	990.4	757.8	861.8	629.3	328
90	36.25	991.4	758.7	862.4	629.9	347
95	37.39	991.6	759.1	863.0	630.5	363

realized. Fig. 3 illustrates the comparison for Bridge 11, and Table 8 presents the results of SBD and grouping. While cost benefits over individual SBD were small and few solutions improved significantly, the time reduction was substantial. These results confirm that grouping mainly drives productivity, whereas CO₂ reductions remain dominated by material optimization. The results were derived by analyzing one single SBD-optimized bridge with an applied learning curve.

The results show that when considering a construction team's learning curve on a group of bridges, the maximum cost reduction is 28% compared to the nonoptimized reference bridges of that group; compared to the SBD-optimized individual bridges, the reduction is 6%. For maximum cost reduction, CO₂ emissions (for high–high CO₂) would be reduced by almost 27%. The maximum reduction of CO₂ emissions would be for the high–low case and that could be reduced by up to 34% compared to the reference bridges. For the high–low CO₂ alternative, the cost reduction could be 27% compared to the reference bridges and 6% compared to individual SBD.

The construction time could be reduced by a total of 145 days (142 days for the alternative with lowest CO₂ emissions). The maximum time reduction for one group would be in Group 3, which could be reduced by 51 days. Group 1 has the longest construction time and also governs the grouped approach. Here, the possible time reduction was 50 days, which would be the governing time reduction in terms of completing the project earlier. Compared with the individual SBD, grouping could decrease the governing construction time by 16 days.

As can be seen in Table 8, grouping mainly governs cost and construction time. The time reduction in a group increases as the number of bridges in that group increases. Group 1, which was the only group that had three bridges, had a time reduction of 21%, whereas Groups 2 and 3 had a time reduction of 35% and 40%, respectively. It is worth mentioning that the time for concrete

to reach its 28-day strength is not included, which would affect the reduction in percentage if that had been considered, but the number of reduced days would still be the same.

In contrast to the reduction of time and construction time, the reduction of CO₂ emissions is not considerable compared to the individual SBD approach. However, finalizing a project ahead of time can have indirect climate benefits. For example, shifting traffic from roads to railway for a railway project or to open a new road earlier could be possible, potentially decreasing the climate impact of traffic. It could also mitigate the indirect CO₂ emissions from traffic detours due to the construction site.

Comparison with the reference bridges is the same here as for the individual SBD so that the reduction could be less if a complete structural design had been performed. The comparison between grouped and individual alternatives would still be the same, resulting in the potential to reduce cost and construction time.

From Fig. 3, it can be observed that grouping can generate solutions with lower costs. However, the number of solutions that reduce costs compared to individual SBD is few. This can also be observed in the density plots in which the individual SBD solution is close to the edge of the best-performing grouped solutions.

Time reduction from grouping is dependent on the estimated learning number. In this study, the authors estimated and used a learning number of 90%. As mentioned in the “Grouping” section, a sensitivity study was performed in which the learning number varied by $\pm 5\%$; Table 9 presents the summarized results. The sensitivity analysis shows that construction time is sensitive to altered learning numbers. Since cost depends on construction time and the amount of material, it is somewhat affected by different learning numbers, while the estimated value of CO₂ emissions is less sensitive to the learning numbers. To reduce CO₂ emissions, it is more important to have a material-optimized structural design of the bridges and to choose concrete and reinforcement with low CO₂ emissions.

Conclusion

This study has shown that a group-designed bridge, i.e., designing one bridge for several sites and preconditions in infrastructure projects, has positive effects of leveraging repetitive work, thereby reducing cost and construction time. In addition, an SBD approach to individual and group-designed bridges has a positive effect of reducing the amount of material and, thereby, CO₂ emissions.

Results show that using an SBD approach to group-design and optimize bridges could reduce costs by 28% and CO₂ emissions by 34% compared to traditionally designed bridges in a reference project. Compared to individual-designed and optimized bridges, grouped bridges would reduce costs by 6% while CO₂ emissions would remain the same. In the studied case, group-designed bridges could be built 145 days faster than reference bridges, while the total time saved for a previous project completion was estimated to be 50 days. Group-designed bridges would reduce the governing construction time by 16 days compared to individual optimized bridges. This means that a project with several bridges could implement a group design of bridges to reduce cost and construction time without increasing the total CO₂ emissions from the bridges.

The number of bridges in one group impacts the total savings. This means that saving increases as the number of bridges in a group increases as long as they are built by the same team and that the team keeps climbing the learning curve. These results are based on a comparison with 11 reference bridges of one project, which limits the generalizability of the results. Further work is therefore warranted to verify the results using several reference projects. In addition, the results depend on the selected parameters and the parameter ranges (Table 2) for the set-based design, especially on the free pass-through area constituted by the free width and the frame leg height. The results suggest that free area is a relevant first-order grouping metric because the possibility of group design was strongly influenced by the pass-through area constituted by the free width and frame leg height. However, future work should evaluate multiparameter grouping strategies, for example, including foundation conditions, structural system, and reinforcement demand, to determine whether they provide a better predictor of constructability and cost than free area alone.

In this study, only slab frame bridges for railways have been studied, and the bridges are designed to meet Swedish regulatory requirements and the available site conditions. In a detailed design, requirements would alter the results moderately, such as the ground conditions of the sites. However, the shown potential reduction of an SBD individual-designed bridge compared to a group-designed bridge would be consistent. The learning number and the maximum number of bridges that could be built by one team have been shown to impact the results, especially the construction time.

Since boundary conditions are already set in the land acquisition plan, the implementation of an SBD group-design approach needs to be considered at this stage. In order to achieve the benefits shown in this study, the client needs to be proactive and drive the change.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Author Contributions

Johan Lagerkvist: Conceptualization, Formal analysis, Methodology, Validation, Writing—original draft, Writing—review and editing; Ola Lædre: Writing—review and editing; Mats Karlsson: Writing—review and editing; Fredrik Carlsson: Writing—review and editing; Lucas Hansson: Software, Writing—review and editing; Rasmus Rempling: Project administration, Writing—review and editing.

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