THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

A design approach for cost effective, climate smart and buildable bridges

JOHAN LAGERKVIST

Department of Architecture and Civil Engineering

CHALMERS UNIVERSITY OF TECHNOLOGY

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Department of Architecture and Civil Engineering

Division of Construction Management and Engineering

Chalmers University of Technology

SE-412 96 Gothenburg

Sweden

Telephone + 46 (0)31-772 1000

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Department of Architecture and Civil Engineering
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Abstract

Bridges and transport infrastructure form the backbone of modern societies, enabling mobility, trade, and social connection; their construction constitutes on of society's most significant investments. Therefore, it is essential that design and construction can be performed with high productivity and that bridges and other resource-demanding structures are constructed with the least amount of material.

The research conducted in this thesis is interdisciplinary, and therefore, a wide range of subfields and methods have been explored. The following fields have been approached in this thesis: bridge engineering, climate impact, productivity, optimisation and probabilistic risk analysis. To gain a comprehensive understanding of both the research field and the studied industry, a literature review and a quantitative study were conducted.

First, this thesis focuses on hindrances to productivity in the Swedish bridge-building industry. A quantitative study, using a self-completed questionnaire for data collection was conducted to identify the main obstacles. The results show that the contractor, client and design engineer have diverging long-term productivity incentives. The contractor and design engineer have a profit driven, private-oriented business model that focuses on project-oriented short-term goals, which may hinder long-term productivity.

Second, this thesis focuses on optimising the amount of material by using a set-based design (SBD) method. With this method, it has been shown that cross-sections in the bridges could be optimised, resulting in minimising the amount of material, which then also reduces cost and climate impact. SBD has also been used to compare different bridge types, making it possible to choose the most material-effective alternative. In addition to minimising the amount of material for a single bridge, SBD has been explored to optimise groups of bridges. The results shows that there is a gain cost and construction time due to the repetition effects.

Last, this thesis has studied load models and design loads for soil-steel composite bridges in Sweden. A probabilistic risk analysis was conducted, and the method consisted of three steps: (1) statistical extrapolations of measured loads, (2) finding the number of critical events, and (3) performing Monte Carlo (MC) simulations. The results show that a less conservative implementation is possible and has the potential to reduce the amount of material in the structure, thereby decreasing cost and climate impact.

This thesis has shown and demonstrated the potential to increase the sustainability of common infrastructure projects in Sweden.

Keywords: Bridge construction, Bridge design, Climate impact, Concrete slab frame bridge, Cost reduction, Grouping, Productivity, Set-based design, Soil steel composite bridge,

List of publications included in this thesis

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I **Lagerkvist, J**., Bosch-Sijtsema, P., Lædre O., Karlsson, M., Simonsson, P., & Rempling, R. (2025) Do actors' incentives obstruct sector-wide long-term productivity in the design and production of bridges in Sweden? *Journal of Civil Engineering and Management, 31(1), pp 85-86.* DOI 10.3846/jcem.2024.22720

II **Lagerkvist, J**., Berrocal, C. G., & Rempling, R. (2022). Climate-smarter design of Soil-Steel Composite Bridges using Set-Based Design. *Current Perspectives and New Directions in Mechanics, Modelling and Design of Structural Systems – Zingoni (ed.) (pp. 2001–2006). CRC Press/Balkema, Taylor & Francis Group. ISBN 978-1-003-34844-3*

III **Lagerkvist, J**., Carlsson, F., & Rempling, R., (2025). Comparative analysis of slab frame bridges and soil-steel composite bridges crossing pedestrian walkways: A cost and climate perspective. Published in *Engineering Material, Structures, Systems and Methods for a More Sustainable Future – Zingoni (ed.) (pp. 1596–1601). CRC Press/Balkema, Taylor & Francis Group. ISBN 978-1-041-15001-5. DOI: 10.1201/9781003677895.*

IV **Lagerkvist, J**., Lædre O., Karlsson, M., Carlsson, F., Hansson L., & Rempling, R. Set-based design for bridge optimization: Minimizing cost, construction time and CO_2-emissions. Submitted to *Journal of Bridge Engineering in March 2025 and re-submitted after revisions in September 2025.*

V **Lagerkvist, J**., Berrocal, C. G., Carlsson, F., & Rempling, R. Probabilistic Risk Analysis of Local Verification of Load Model 1 in Eurocode for Soil-Steel Composite Bridges in Sweden. *Bridge Structures, vol 20, no 3-4, pp. 127-140, 7 November 2024. DOI 10.3233/BRS-240228*

CRediT author statement

In paper **I**, the author, Johan Lagerkvist (JL) took full responsibility for: Conceptualization, Methodology, Validation, Visualization, Formal analysis, Writing – original draft preparation, Writing – reviewing and editing.
Co-authors contribution: Petra Bosch-Sijtsema, Ola Lædre, Mats Karlsson and Peter Simonsson: Writing – reviewing and editing. Rasmus Rempling: Writing – reviewing and editing, Supervision, Project administration.

In paper **II**, JL took full responsibility for: Conceptualization, Methodology, Writing – original draft preparation, Writing – reviewing and editing.
Co-authors contribution: Carlos Gil Berrocal: Software, Writing – review and editing. Rasmus Rempling: Writing – reviewing and editing, Supervision, Project administration.

In paper **III**, JL took full responsibility for: Conceptualization, Methodology, Validation, Visualization, Formal analysis, Writing – original draft preparation, Writing – reviewing and editing.
Co-authors contribution: Fredrik Carlsson: Writing – review and editing. Rasmus Rempling: Writing – reviewing and editing, Supervision, Project administration.

In paper I**V**, JL took full responsibility for: Conceptualization, Methodology, Validation, Visualization, Formal analysis, Writing – original draft preparation, Writing – reviewing and editing.
Co-authors contribution: Ola Lædre, Mats Karlsson and Fredrik Carlsson: Writing – review and editing. Rasmus Rempling: Writing – reviewing and editing, Supervision, Project administration.

In paper **V**, JL took full responsibility for: Conceptualization, Methodology, Validation, Visualization, Formal analysis, Writing – original draft preparation, Writing – reviewing and editing.
Co-authors contribution: Carlos Gil Berrocal: Writing – review and editing. Rasmus Rempling: Writing – reviewing and editing, Supervision, Project administration.

All co-authors of the publications above have agreed that they are included in this thesis.

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Preface

This thesis is the result of work carried out from September 2020 until October 2025. The first part was carried out at the Division of Structural Engineering and the final part was carried out at the Division of Construction Management and Engineering, both at Chalmers University of Technology.

This work has been an Industrial PhD project, financed by the Swedish Transport Administration.

I would like to thank my group of supervisors, Associate Professor Rasmus Rempling, Professor Petra Bosch-Sijstema, Professor Ola Lædre, Dr Fredrik Carlsson and Mats Karlsson, for all their support during this work. I would also like to dedicate a special thanks to my former colleague at the Swedish Transport Administration Dr Peter Simonsson for believing in me and giving me the opportunity of this PhD education.

I would like to thank present and former PhD students at the Division of Structural Engineering and at the Division of Construction Management and Engineering for support and interesting discussions. A special thanks to Linda Cusumano for support and inspiration during this education. It has been valuable to be able to share this with someone in a similar life situation. A special thanks also to senior lecturer Carlos Gil Berrocal for cooperation and support during part of my education.

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Finally, I would like to thank my wife and children for all their love and support during this journey. It would not have been possible to finish this education without them by my side. I also got the opportunity to spend more than one year of education at the same time as both my children.

Johan Lagerkvist, Gothenburg 2025

Other related publications

Licentiate thesis:

Lagerkvist, J. (2023). Improving productivity in design and construction of bridges. Department of Architecture and Civil Engineering, Chalmers University of Technology.

Peer-reviewed conference papers:

1 **Lagerkvist, J**., Simonsson, P., Karlsson, M., Rempling, R., Bosch-Sijtsema, P., & Lædre, O. (2021). Climate impact estimation – from feasibility study to handover. Published in *IABSE Congress Ghent 2021, Structural Engineering for Future Societal Needs (pp. 622–628). IABSE.*

2 Antonsson, F., Lindvall, D., **Lagerkvist, J**., & Rempling, R. (2022). Optimal time for contractors to enter infrastructure projects. Published in *Procedia Computer Science, 196, 990–998.*

3 **Lagerkvist, J**., Karlsson, M., Rempling, R., Bosch-Sijtsema, P., Lædre, O., & Simonsson, P. (2022). Important parameters for increased productivity in bridge design and production. Published in *Proceeding of IABSE Congress Nanjing 2022, Bridges and Structures: Connection, Integration and Harmonisation, 80–88.*

4 **Lagerkvist, J**., Lædre, O., Rempling, R., Bosch-Sijtsema, P., Carlsson, F., & Karlsson, M. (2024). Productivity increase in the design and construction of bridges. Published in *Proceeding of IABSE Symposium Manchester 2024, Construction's Role for a World in Emergency, (pp. 1268–1276). IABSE.*

5 **Lagerkvist, J**., Rempling, R., Bosch-Sijtsema, P., Lædre, O., Carlsson, F., & Karlsson, M. (2024). Could a grouped design approach of bridges increase productivity and decrease cost and climate impact? Published in *Proceeding of IABSE Congress San Jose 2024, Beyond Structural Engineering in a Changing World, (pp. 1241–1247). IABSE.*

6 Rempling, R., **Lagerkvist, J**., Karlsson, M., & Ekström, D (2025). Can business-driven and climate-based contracting of bridges make us build climate-smarter? Published in *Procedia Computer Science, 256 (2025), pp. 1764-1771. DOI 10.1016/j.procs.2025.02.316*

7 **Lagerkvist, J**., Hällmark, R., Carlsson, F., & Rempling, R., (2025). Probabilistic Cost-Benefit Analysis for bridge alternatives as decision support. Published in *Proceeding of IABSE Symposium Tokyo 2025, Environmentally Friendly Technologies and Structures: Focusing on Sustainable Approaches, (pp. 1043–1051). IABSE.*

Master's theses conducted at Chalmers University of Technology and supervised by the author:

1 Antonsson, F., Lindvall, D. (2021). Optimal time for contractors to enter infrastructure projects A case study of a Swedish ECI project. Master's thesis in Design and Construction Project Management.

2 Kramer, H., Sjölund, T. (2024). Grouping and optimization of several slab frame bridges. Master's thesis in Structural Engineering and Building Technology.

3 Hansson, L., Tacking, N. (2024). Set-Based Design: A method for improving requirement definition in the bridge procurement process: How Set-Based Design can manage uncertainty in the preliminary design phase and procurement of frame bridges. Master's thesis in Structural Engineering and Building Technology, Design and Construction Project Management.

1 Introduction

This thesis builds on the work conducted in five studies, reported in Papers I – V [1–5]. Further, the thesis develops work published in a licentiate thesis [6] that constituted a mid-step towards the degree of Doctor of Philosophy.

1.1 Background

Building transport infrastructure is not an end in itself; rather, it is a need that allows people and goods to reach their goals. The infrastructure is enabling the development of society, connecting people and communities with the rest of the world. It is important that the development of the infrastructure is done in a sustainable way. As part of the global construction industry, the construction of new infrastructure has a huge climate impact. Globally, the construction industry is responsible for 37% of the total CO_2 emissions [7]. The use of construction materials alone accounts for 15% of global emissions [7], 30% of waste generation and 50% of resource extraction [8].

Minimising the amount of material used in the infrastructure could reduce both cost and CO_2 emissions. Several researchers have shown the potential to reduce cost and/or CO_2 by structural optimisation [2, 9, 18, 19, 10–17]. CO_2 emissions are not the only problem with the amount of material used [8]. Even if it would be possible to produce concrete with no CO_2 emissions, if you want to pour 100 m^2 of concrete, you still need to extract 120 tonnes of gravel, 60 tonnes of sand, 60 tonnes of limestone and 17,000 litres of fresh water [8]. Minimising the amount of material could also positively impact wildlife since research has shown that the extraction of material has a large impact on wildlife [20].

In addition to the construction of infrastructure, transportation has a significant impact on the climate, accounting for 23% of energy-related greenhouse gas emissions [21]. This makes it important to have a holistic perspective on the construction of new infrastructure. It is possible that emissions from traffic during construction exceed those from the infrastructure that is built [22].

With this amount of impact, it is important that the industry uses resources in a responsible way. Another main challenge is the productivity. The productivity increase in the construction industry lags behind other industries [23–25]. It only increased by 1% during the last 20 years, compared to 2.8% for the rest of the economy [26]. If construction could reach the same level of productivity, the total value added could be increased by $1.6 trillion each year. This would meet half the cost of the world's annual infrastructure need, it would also boost global gross domestic product (GDP) by 2% [26].

The lack of productivity is as well present in the bridge construction industry [27–30]. The value-added time during rebar installation has been shown to be as low as 32%, while 29% is pure waste [24]. Striving to increase productivity demonstrates responsibility toward society's common resources. Increased productivity will generate more value for the money spent. The importance of productivity and innovation in the industry has been recognised by the Swedish government. In 2018, they commissioned The Swedish Transport Administration (STA) to measure and present their productivity over a three-year period, and standardisation was identified as one way to improve productivity [31].

It is important for the industry to understand how standardisation of bridges can be used to increase productivity. In addition to decreasing project costs, productivity could also contribute to a decreased climate impact. This is due to shorter usage of construction services and machinery and reduced energy consumption [29, 32, 33]. In addition, reduced construction time could also decrease the indirect cost and climate impact associated with transport detours during construction [22, 34].

Even though research has shown that there exists a potential for productivity increase [35, 36] and a potential to decrease cost and climate impact [15], none of this potential has been largely realised in projects [26]. There are probably several reasons for this. Lack of financial incentives has shown to be important for workers and could be one reason [37–39].

How can infrastructure be built to fulfil its purpose (allowing people and goods to reach their goal) at a lower cost, with lower climate impact and in a shorter construction time? When larger projects, such as the North Bothnia Line [40] and the East Link [41], are to be built in Sweden, it is important to take steps in this direction and thereby contribute to a more sustainable society.

Even though research has shown potential for productivity and for optimisation of different bridges, there is a gap of how these could be realised and combined. Could optimised structures contribute to productivity and would that be beneficial for society?

1.2 Purpose and research questions

The overall purpose of this research is to contribute to knowledge about how to achieve higher productivity and use less resources used when designing and building bridges. To fulfil the purpose, the thesis explores how bridges could be built in a more sustainable way for society and the following two research questions (RQ) were developed:

- **RQ 1:** What are the major hindrances to productivity in the bridge-building industry in Sweden today?
- **RQ 2:** How could smart design reduce cost and climate impact for commonly built bridges in Sweden?

The RQ are broken down into four main objectives, which are:

1. identify major hindrances to productivity in the bridge-building industry in Sweden today (Paper I),
2. identify how smart design could reduce cost and climate impact for commonly built bridges in Sweden (Paper II - paper V),
3. identify how cost, construction time and climate impact could be affected by a grouped design approach for several bridges (Paper IV).
4. identify how risk analysis could be used for governing load cases for soil-steel composite bridges, and thus decrease the amount of material (Paper V),

The overarching relationship between papers and RQ is presented in Figure 1.

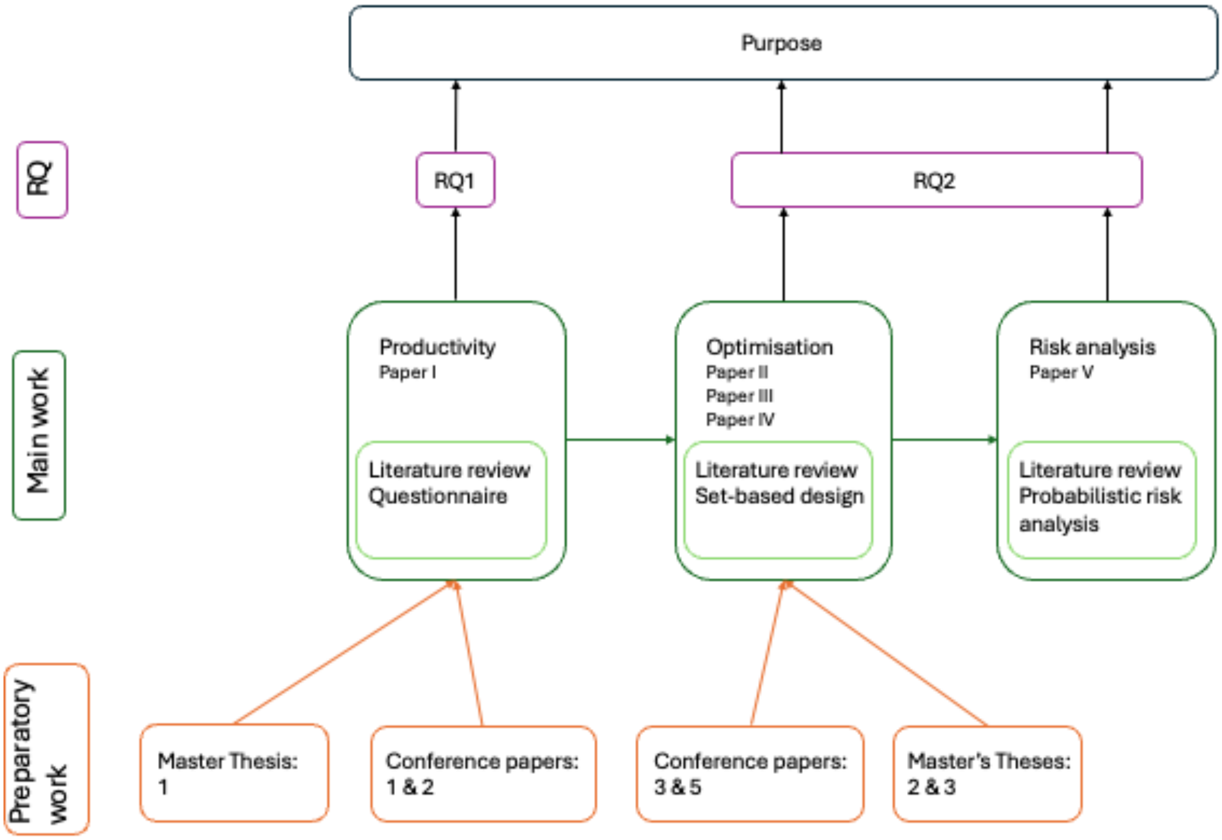

Figure 1. Connection between papers and RQ.

1.3 Limitations

The work in this thesis has been limited to Sweden, which means that bridges built in Sweden have been used for comparisons, the Swedish bridge industry has been surveyed, real traffic loads based on measurements in Sweden have been studied, and design has been done according to Swedish regulatory requirements.

Further limitations have been construction techniques, materials and methods available today.

For concrete bridges, only cast-in situ has been considered, since this is the most common construction method in Sweden today.

For productivity, this thesis follows the definition given in [42]: "Productivity means that the value added to the product increases despite the same amount of resources being used as before, and/or that the needed resources to produce the same value decreases".

In this thesis, potential productivity increases in society due to a new infrastructure are not considered, only productivity in the realisation of the construction project is considered.

When using set-based design, the generated design information can be used in one project and reused in a later project. Potential cost savings during design due to this have not been considered.

Even though much of the literature studied is international, the focus of this thesis is on Sweden. However, since many of the developed countries are struggling with the same problem, I believe that the results from this thesis could be applicable in an international perspective.

1.4 Outline of the thesis

This thesis is a summary of five scientific papers. The first paper was submitted in October 2022, accepted in September 2024 and published (online) in December 2024. The second is a conference paper that was presented in September 2022. The third paper is a conference paper that was presented in September 2025. The fourth was submitted in March 2025, re-submitted after revisions in September 2025, and is currently under review in the Journal of Bridge Engineering. The last paper was submitted in March 2024, accepted in September 2024 and published in November 2024.

The main work in this thesis is divided into three blocks. In terms of papers, the optimisation block is the largest. For the frame of reference, method and results, the thesis is divided into these blocks.

Chapter 2 presents the frame of reference in this thesis. Chapter 3 describes the research method. Chapter 4 presents results. Potential with findings in the work done within this thesis is discussed in Chapter 5. In Chapter 6, conclusions are presented, and finally, future work is presented and discussed in Chapter 7.

2 Frame of reference

2.1 Productivity, Paper I

To contribute to the development of society, it is important that bridge projects are delivered with high productivity. In this thesis, productivity follows the definition given in [42]: "Productivity means that the value added to the product increases despite the same amount of resource being used before, or that the need for resource decreases to produce the same value". Resources could be both materials and time spent on construction.

To be able to increase productivity, it is essential to find out what incentives the three major actors' (client, contractor and engineer) find important, and how these incentives could be obstacles to long-term productivity.

When procuring transport infrastructure projects, it is important to have attractive business models for the different actors. In this thesis, three different project delivery models for contractors have been studied and two different compensation formats for design engineers. The chosen models are the most used in Sweden today.

2.1.1 Project delivery models for contractors

Traditionally, Sweden has often used design-bid-build (DBB) contracts, i.e., the contractor receives complete design documents which they should bid on and construct after. It has also been quite common that bridges have been broken out and procured as a design-build (DB) in the DBB contract. The responsibility for detailed design is a major difference between DB and DBB where the responsibility lies with the contractor in DB and the client in DBB [43].

Another difference between DB and DBB is the contracts between the actors. In DB, the client has one single contract to perform design and construction [44, 45]. For a DBB, the client has two separate contracts, one for design and one for construction. Projects delivered with DB are often procured with a fixed price model, while DBB projects are often procured with a unit price model. Research has shown that a fixed price model tends to give higher productivity [26]. With a fixed price model, when cost is the only criterion for the choice of a contractor, the contractor receives a strong incentive to be productive [46].

An advantage with DB is that the contractor can use their knowledge and experience when drawings are developed for the project. The advantage of constructing drawings based on a specific contractors preferences has been demonstrated by a case study where the contractor redesigned DBB drawings to a more productive solution [47]. DB contracts could thereby be seen as a way to increase productivity since the contractor can contribute with their experiences from earlier projects delivered; this was also concluded in [48]. That DB perform better than DBB with regard to building time and/or cost was concluded by [49–52]. However, contradictory results regarding cost performance for DB and DBB could be found in the literature [53–55], meaning that the performance could depend on the situation and not only the project delivery model.

Early contractor involvement (ECI) is a project delivery model that has gained popularity in the last years. In Sweden, ECI has mostly been used in large and complex projects. In this delivery model, the contractor is involved earlier in the process compared to DB and DBB. In Sweden, it has often been in the stage before they traditionally get into a DB contract, i.e., they are involved in the stage of designing the traditional DB documents. During this stage, the contractor and the client should agree on a target price for construction during the next stage. By involving the contractor earlier, buildability and cost estimation will improve [56]. Early involvement of the contractor is an important factor for increased productivity, according to [29]. ECI has also led to reduced time for construction and better conditions for constructing projects in urbanised areas [57]. For ECI delivery, there is often a possibility to have financial incentives, which is an important motivator for contractors to increase productivity [39].

2.1.2 Forms of compensation for design engineers

Different compensation forms for design engineers and their ability to affect productivity is a research area that is not very well explored. However, research has shown that engineers tend to produce better quality and more innovative designs if they have financial incentives [58]. Fixed price has also been shown to increase productivity for design engineers. The reason for this could be that design engineers have a potential to increase their profit. Even though productivity would increase, it does not mean that the client will receive the best solution [59].

2.2 Optimisation

The structural design process today is exclusively performed as point-based design (PBD), in which the development of the design is based on one single solution in a step-by-step process [15]. This is an ineffective process that cannot tell whether the solution is good or bad; it only tells that there is a solution. The ineffectiveness of PDB motivated the development of alternative design approaches [15].

Toyota was one of the first companies that started using a concept that allowed parallel and delayed decision-making processes, called set-based design (SBD) [60]. This concept involves sets of alternatives instead of one single solution. During the design process, these alternatives are then filtered based on new knowledge, limitations and other decisions made in the project. This method enables delaying decisions so that the decisions can be made later in the process when more knowledge is available. This makes it possible to make better decisions and to get a better solution compared to what would have been the case if using PBD. The potential cost and climate savings that could be achieved by implementing SBD compared to PBD have been demonstrated for different types of bridges [15].

There are other optimisation methods that could be used. Bayesian optimisation has shown good potential to reduce construction time when finding optimal solutions [19], and it has also been shown to outperform an NSGA-II and random search algorithm by a large margin [16].

2.2.1 Set-based design on soil-steel composite bridges, Paper II

Soil-steel composite bridges (SSCB) are one of the most commonly built bridge types in Sweden [61]. It is a simple structure, consisting of a flexible culvert made of corrugated steel plates exhibiting composite action with the surrounding soil (backfill material). The structural capacity depends on the thickness of the steel plates, the type of backfill material and the cover height (h_c) of the backfill. For a traditional PBD of an SSCB, these three parameters are chosen by the designer, and how they are chosen depends on the experience of the design engineer. With SBD, all solutions within the given ranges for all the described parameters are tested. This makes it possible to achieve a better solution than the solution from PBD.

2.2.2 Set-based design to compare bridge types, Paper III

SBD has been used to reduce cost and CO_2 for different bridge types [2, 15]. SSCB and concrete slab frame bridges (CSFB) are commonly used bridges in Sweden. The two bridge types have been compared and the results have been contradictory [62, 63]. What is of importance when comparing the two bridge types is that the comparison is done in a similar way and that the boundary conditions are equal. If the boundary condition is given in terms of a free opening, the two bridge types could be compared for the same free opening. If both bridge types are designed using SBD, a fair comparison could be made.

2.2.3 Set-based design to group bridges, Paper IV

Minimising cost and climate impact is important when building infrastructure. When large infrastructure projects that consist of several bridges are built, it is also important to reduce construction time. Reduced construction time is important from a societal perspective. If the infrastructure could be built in a shorter time, it could be used earlier, which would govern the society and contribute to sustainable development. The workers who have finished the construction could start with another project, which contributes even more to the society.

Reduced construction time has been shown to reduce the climate impact of the project [29, 33]. The Swedish bridge industry sees potential productivity through the standardisation of bridges or parts of bridges [64].

2.3 Risk analysis, Paper V

Bridges should be designed for several loads and load combinations and with sufficient safety. The load models are developed such that they could be used for all bridges. For the design of bridges, there are different safety factors that should be used. In Sweden, the safe factors depend on the span length of the bridge, where longer spans give a higher safety class. In the safety class, the probability of failure is included, which is the probability that has been accepted by the society.

Bridges in Sweden should be designed according to TRVINFRA and Eurocode. When designing SSCB, which is one of the most commonly built bridge types in Sweden [61], load model 1 (LM1) [65] in Eurocode is often governing the design. LM1 should be implemented in two different scenarios, the first is the normal case where two vehicles are driving in parallel traffic lanes and the vehicles are driving centric in their respectively lane, and the lane width is 3.0 m. In the second scenario, the two vehicles should be driving closer to each other so that the distance between the centre of the wheels is decreasing to 0.5 m, see Figure 2.

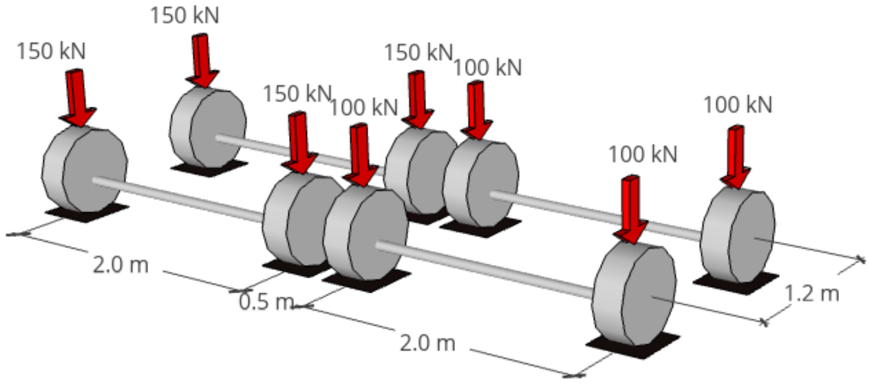

Figure 2. Illustration of local verification of LM1. Reproduced from paper V [5].

From Figure 2 it can be observed that the load model should represent two heavy vehicles. The first vehicle (to the left in the Figure) has a 300 kN axle load, and the second vehicle has a 200 kN axle load. Critical for the design of SSCB is most often the crown (the top of the steel pipe) and the critical load position is when one pair of axles is positioned above the crown. Bridges should be designed for the worst case, which for SSCB means that the local verification application should be placed with one axle from each of the two vehicles right above the crown.

3 Method

The research conducted in this thesis is interdisciplinary, and therefore, a wide range of subfields and methods have been explored. The following fields have been approached in this thesis: bridge engineering, climate impact, productivity, probabilistic risk analysis and optimisation.

3.1 Research approach

The research approach has been adapted to the interdisciplinary nature of this thesis. To obtain a broad and general knowledge of the field of research and the industry, a literature review was conducted. Actively participating in specialised conferences has provided relevant feedback from the scientific community on the work.

In the first stage, a more theoretical and explorative approach was adopted. This gave a knowledge basis about productivity and resulted in Paper I and a licentiate thesis [6]. Simultaneously, the first steps within set-based design were explored, which resulted in Paper II. The licentiate thesis was presented and discussed at a licentiate seminar that was held in May 2023.

In the second part of the doctoral studies, the work with set-based design continued. Concrete slab frame bridges for both roads and railways were studied. For roads, a comparison with soil-steel composite bridges (SSCB) and concrete slab frame bridges crossing pedestrian walkways was investigated using a set-based design approach (Paper III). For railways, results regarding standardisation and productivity from the first stage were implemented (Paper IV). Implementation of these results was mentioned as future work in the licentiate thesis. In the second part, a specific critical design load case for SSCB was investigated based on real traffic measurements using Monte Carlo simulations and Probabilistic risk analysis (Paper V).

The methodology followed in this thesis is based on three blocks, as visualised in Figure 1. Each block contributes to the aim of this thesis, and they could contribute by themselves and/or in combination with one or two of the other blocks.

In the following sub-chapters, the methods used in each block in this thesis are briefly presented. For a more detailed description of the methods, see each Paper.

3.2 Productivity, Paper I

Paper I deal with productivity hindrances. To obtain a general and broad knowledge in both the field of research and the studied industry, a literature review and a quantitative study were performed. The quantitative study used a self-completed questionnaire for data collection. Collecting data through a questionnaire is a way to receive many responses in a time-efficient way [66].

The questionnaire used in Paper I was developed by the authors of that Paper. It was developed during two workshops and the questions were based on the literature review. A pilot test of the questionnaire was performed and six representatives from the industry were chosen for the pilot test. After the pilot test, minor revisions were made, and the questionnaire was finally distributed in September 2021. The final version of the questionnaire included 24 questions, and the respondents were asked to what extent different statements influence productivity in the design and construction of bridges. The respondents ranked the different statements on a 7-point Likert scale. For every question, the respondent was able to add an additional alternative and give comments.

The questionnaire was distributed to 470 recipients working in the Swedish bridge industry. The questionnaire was available for the respondents during 19 workdays and a total of 151 complete responses were collected.

3.3 Optimisation

For the optimisation that has been performed in the work in this thesis, a set-based design (SBD) approach has been used. With this method, both the different cross-sections have been optimised as well as the size of the studied bridges. SBD allow a parallel and delayed decision-making process [60, 67]. In comparison to a traditional point-based design (PBD), where one single solution (point) is investigated and developed during the design process (see Figure 3 a), SBD generates numerous alternatives that investigate a specific given design space. With SBD, alternatives are gradually filtered during the project and the sets converge to a solution (see Figure 3 b) [15, 67].

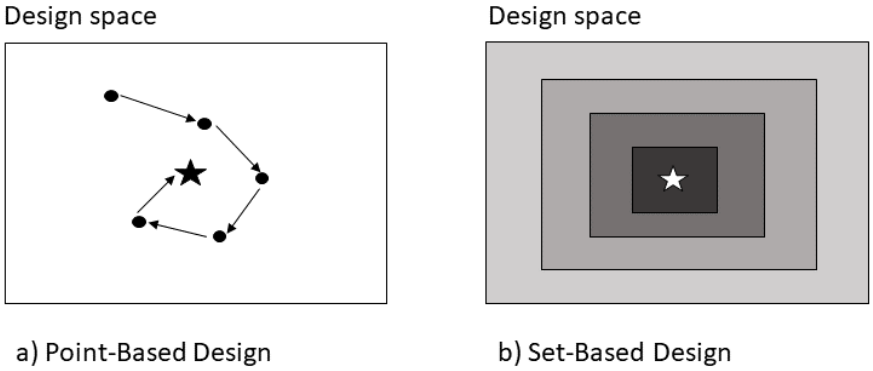

Figure 3. Visualisation of point-based design a) (modified from [60]) and set-based design b) (modified from [68]).

3.3.1 Paper II

In Paper II, SBD was used on soil-steel composite bridges (SSCB). Five different SSCB crossings of a pedestrian walkway were studied. The bridges should fulfil a given free area within the steel pipe, given by a rectangle as shown in Figure 4.

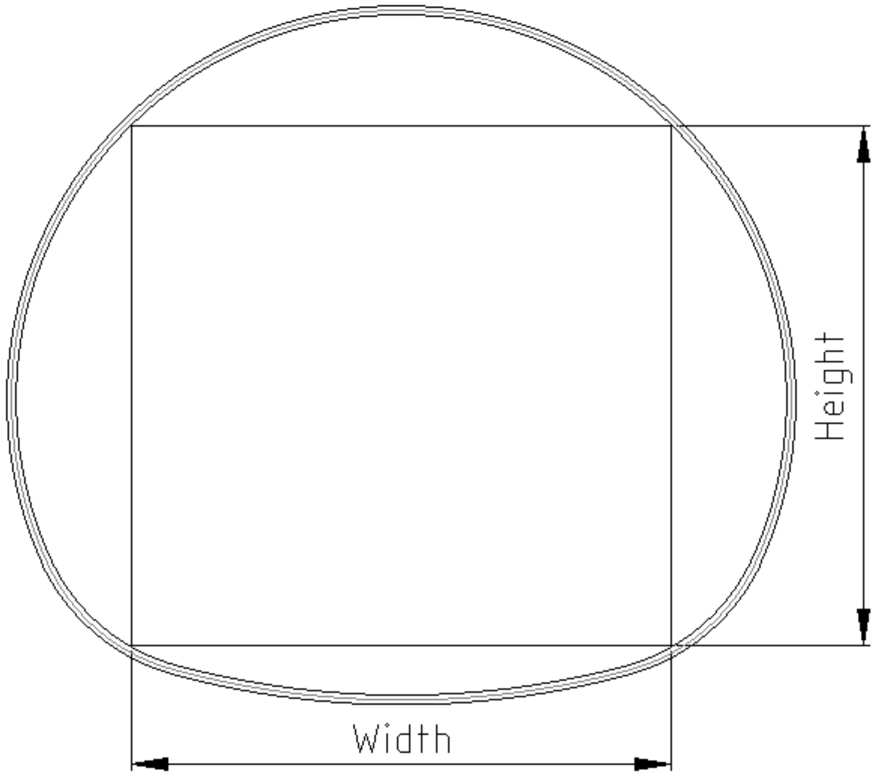

Figure 4. Visualisation of free area in a steel pipe. Reproduced from Paper II [2].

To generate the design space in Paper II, six different closed profiles of SSCB were used (see Paper II [2]) and every profile consists of different sizes. Other parameters that were considered for the design space were plate thickness, type of backfill material and the cover height (h_c) of the backfill material. All the studied parameters and ranges are presented in Table 1. This generated a design space with almost 300,000 alternatives.

Table 1. Parameters and ranges to produce alternatives for SSCB in Paper II.

Parameter	Value	Step	Unit	Number of alternatives
Bridge width	6.0	-	[m]	1
Profiles (sizes)	6	-	[-]	6 (233)
Cover height (hc)	0.5 - 4.0	0.05	[m]	71
Plate thickness	3 - 8	0.5	[mm]	11
Backfill material	Sub-base, Base-course	-	[-]	2

3.3.2 Paper III

In Paper III, SBD was used to design concrete slab frame bridges (CSFB) that fulfil three of the same free openings as for SSCB in Paper II. The bridges in Paper II were all founded on packed soil above clay. CSFB are more sensitive to settlements than SSCB and it is probable that all the CSFB would need a pile foundation. Therefore, in Paper III, the comparisons were done for three cases with different ground conditions in each case. Free opening and assumed ground conditions for CSFB used in Paper III are presented in Table 2.

Table 2. Free opening and assumed ground conditions for CSFB. Reproduced from Paper III [3].

Case nr	Free opening WxH [m]	Assumed ground condition for CSFB
1	2.0x2.4	Rock
2	3.0x2.9	Friction soil
3	4.5x3.0	Clay (piled to rock)

By varying the cross-sectional parameters, slab and frame legs, for the CSFB, a total of 6084 alternatives were generated for the three cases (2028 for each case), see Table 3.

Table 3. Parameters and ranges to produce alternatives for CSFB in Paper III.

Parameter	Value	Step	Unit	Number of alternatives
Bridge width	6.0	-	[m]	1
Sizes	3	-	[-]	3
Slab thickness	0.25 - 0.5	0.01	[m]	26
Frame leg thickness	0.25 - 0.5	0.01	[m]	26
Ground condition	Rock, friction soil, clay	-	[-]	3

The number of alternatives for CSFB is low compared to SSCB. The design of CSFB was done using a finite element (FE) software, BRIGADE/plus. Using a FE software is more time-consuming compared to performing the design by "hand calculations", which was the case for SSCB. To be able to implement the different designs, the modelling and analysis were automated by Python scripting. The Python script was first developed by [69] and modified to be implemented in Paper III. A flow chart of the script is shown in Figure 5.

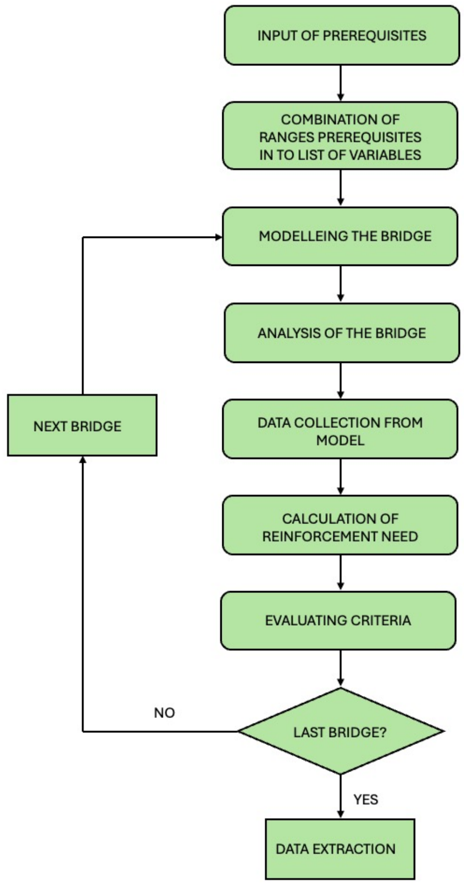

Figure 5. Flow-chart of Python script. Reproduced from Paper III [3].

3.3.3 Paper IV

To generate the design space in Paper IV, similar cross-section parameters as in Paper III were studied, but with much larger ranges. To be able to do this, a Python script was used and this script was first developed by [70] and then modified for Paper IV. The script follows a similar flow chart as shown in Figure 5. In Paper IV, several possible free areas were considered and three different reinforcement diameters, which generated almost 70,000 configurations. All bridges had a free bridge width of 12.75 m, and they were designed with C35/45 concrete, a concrete cover of 35 mm and the reinforcement was K500B. The bridges were founded on packed soil above hard friction soil. All the other parameters that were varied to generate the SBD configurations are presented in Table 4.

Table 4. Parameters to generate the SBD configurations in Paper IV.

Parameter	Value	Step	Unit	Number of alternatives
Frame leg height	3.6, 5.6	-	[m]	2
Reinforcement diameter	16, 20, 25	-	[mm]	3
Frame type	Open, Closed	-	-	2
Bottom slab thickness	0.4 – 0.8	0.1	[m]	5
Radius of underside of bridge deck	[3, 5, 8]*L		[m]	3
Free opening (conf. 1)	6.0 – 8.0	0.5	[m]	5
Free opening (conf. 2)	8.5 – 16.0	0.5	[m]	16
Slab thickness (middle of span, conf. 1)	0.35 – 0.65	0.1	[m]	4
Slab thickness (middle of span, conf. 2)	0.50 – 0.80	0.1	[m]	4
Leg thickness (conf. 1)	0.30 – 0.70	0.1	[m]	5
Leg thickness (conf. 2)	0.40 – 0-90	0.1	[m]	6

In Paper IV, SBD was used to group and optimise bridges. In addition to optimising every bridge individually, grouping takes repetition effects into account, which then increase productivity in terms of reduced construction time. The effect from repetition is considered by implementing the learning curve described in [71] as:

$$T_n = T_1 \left[1 - (1 - I) \frac{\ln(n)}{\ln\,(2)} \right] \tag{1}$$

Where T_n is the time to perform a task the n^{th} time, T_1 is the time to perform a task the first time, and l is the learning number. The leaning number was set to 90%, based on measurements done at the bridge between the mainland and Öland in Sweden.

The groups were based on the free area under the bridge. For the grouping, the first bridge in each group sets the requirements for the other bridges in that group, in terms of reinforcement spacing, radius of underside of the bridge, thickness of parts etc. If the amount of reinforcement differs between bridges in one group, keeping the same distance between reinforcement bars is preferable [64].

3.4 Risk analysis, Paper V

In Paper V, real vehicles and driving pattern in the traffic lane has been used to simulate the worst possible situation that could be expected to happen during the lifetime of a SSCB. A probabilistic risk analysis was performed, and the method consisted of three steps: (1) statistical extrapolations of measured loads, (2) find the number of critical events and (3) perform Monte Carlo (MC) simulations. For the statistical extrapolation, Rice formula were used, which has been widely used by others in the past [72–75]. Rice formula, introduced in 1945 by Rice [76], can be used to find a parametric fit to a normally distributed stationary stochastic process. Traffic loads can generally be assumed to follow a Gaussian distribution and Rice formula can thus be used to extrapolate traffic loads [73]. After the statistical extrapolation, the number of critical events was found. The event of interest in Paper V is when two heavy vehicles are placed next to each other. This situation can arise either if two heavy vehicles meet each other, or if one heavy vehicle overtakes another heavy vehicle. The number of times that this event can occur, depends on different factors, such as the speed of the vehicles and the influence length of the bridge. Considering that all the mentioned steps are dependent on the yearly day traffic (YDT) of heavy vehicles, a sensitivity analysis was performed where four different YDT were investigated. After the number of critical situations were found, the MC simulation could be performed. The MC simulation followed four steps:

1. Number of critical situations, n_{cr}, each year is randomly drawn from a Poisson distribution.
2. For each critical situation, axle loads for lane 1 and lane 2 are randomly drawn from extrapolated loads.
3. Vehicles position in lane 1 and lane 2 is randomly drawn from a normal distribution.
4. Point 1-3 is repeated 1000 times to represent 1000-year event.

Axle loads and position of vehicles from MC were then used to calculate load effects which then were compared with load effects from Load Model 1 as described in Eurocode.

4 Results

4.1 Productivity, Paper I

An increase in productivity is necessary to reduce economic costs in bridge projects. Previous research indicates that construction productivity has decreased since the 1960s. A quantitative study was performed to find out how the incentives of the three major actors (client, contractor, and design engineer) could be obstacles to long-term productivity in the Swedish bridge-building industry. The study was performed as a self-completed questionnaire and received 151 responses. One question was regarding the potential for productivity with the project delivery models described in Chapter 2.1.1, and these results are shown in Figure 6. The respondents were also asked about the potential for productivity with the described forms of compensation for design engineers, and these results are shown in Figure 7.

Other important results show that the contractors' employees find profit in a single project more important than the company's profit over time. Thus, the project´s incentives obstruct innovation and standardisation, which could benefit future projects and thereby increase long-term productivity and the company's profit over time. In contrast to contractors, design engineers and clients value company profit more than profit in a single project, and they value the quality of delivered products as the most important factor for increased long-term productivity.

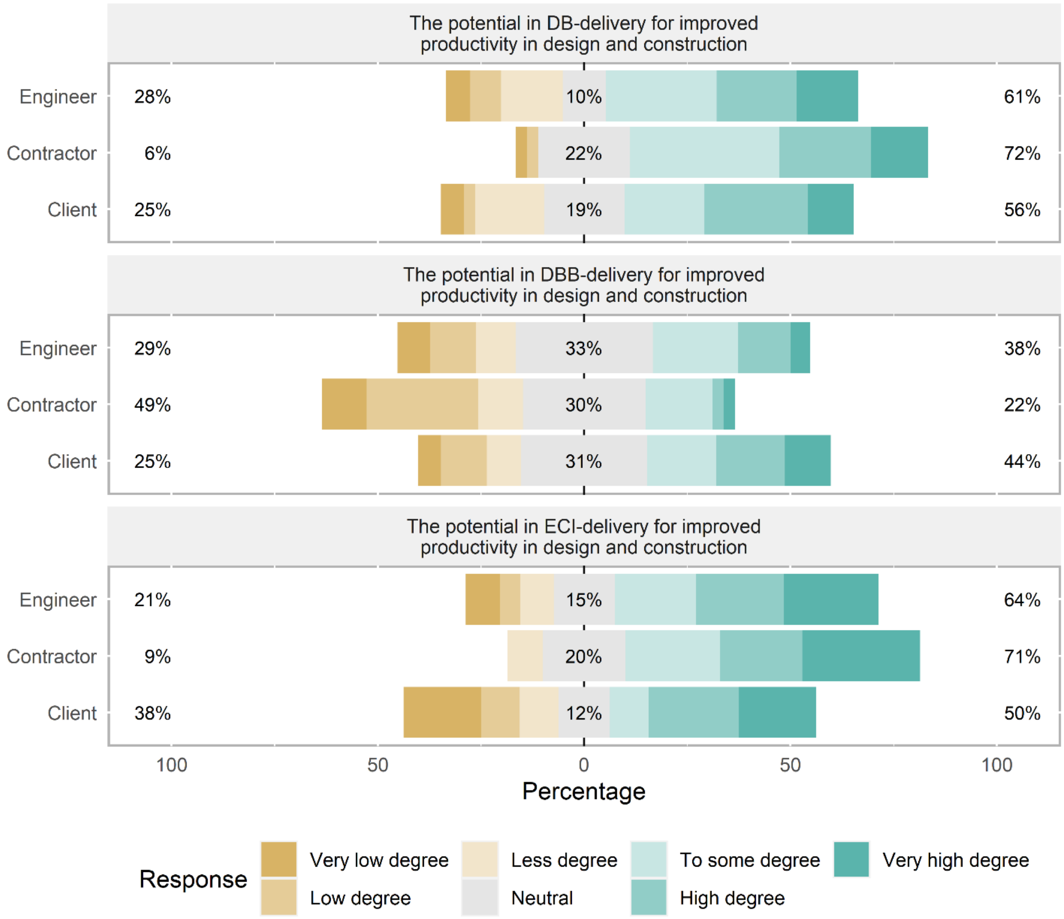

Figure 6. Potential for productivity for different project delivery models. Reproduced from Paper I [1].

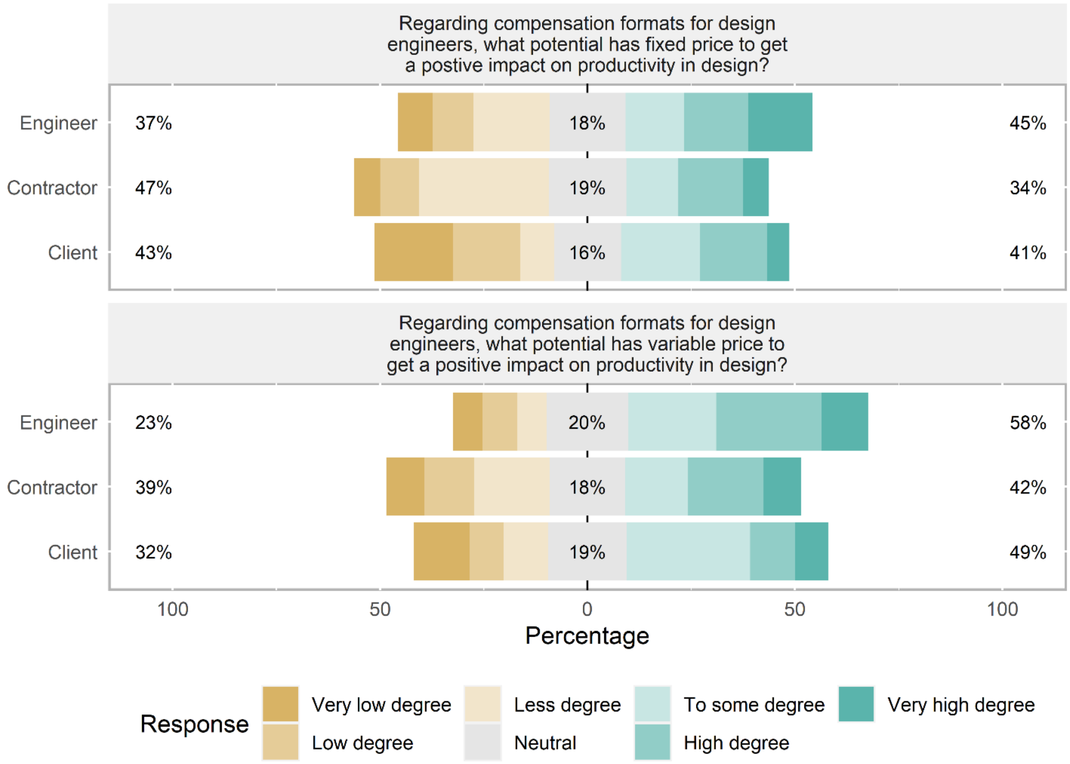

Figure 7. Potential for productivity for different compensation forms for design engineers. Reproduced from Paper I [1].

The actors in the bridge-building industry have different incentives and motivations for productivity. Design engineers and contractors are private companies that need to make a profit. The client, on the other hand does not have the same demand for profit, but they aim to build as much infrastructure as possible for every unit of investment. The client has goals to reduce the climate impact for the construction of infrastructure [77], and this has also been mentioned as one of the most important goals the STA has [78]. Standardisation has shown potential to improve productivity, quality, work environment, give higher profit margins and to reduce climate impact. However, standardisation is related to an initial cost before that investment starts to generate value. Therefore, in Paper I, we asked the actors how they would rank different aspects to strive for productivity. These results are presented in Table 5.

Table 5. Ranked aspects for productivity, where1 is most important and 6 is the least important. Reproduced from Paper I [1].

Aspect	Design engineer	Contractor	Client
Reduced climate impact	5	6	4
Quality of delivered products	1	3	1
Production time	6	4	5
Company profit over time	2	5	3
Profit in a single project	3	2	6
Work environment	4	1	2

From Table 5, it can be observed that all actors consider the quality of delivered products as the top three. Contractor and client value the work environment as number one and number two, respectively.

Design engineers and clients value profit over time, higher than profit in a single project. It can also be observed that climate impact is only considered as number four among the clients, which is a bit contradictory to earlier findings [78].

All the aspects in Table 5 could be expected from standardisation, which makes me wonder why this is not more used than it actually is, and are there other ways to reach any or several of the aspects?

4.2 Optimisation

4.2.1 Paper II

The Swedish Transport Administration (STA) strives to reduce the climate impact in their projects. soil-steel composite bridges (SSCB) are one of the most commonly built bridge types in Sweden. The design of SSCB is traditionally done as a point-based design where one single design is tested. When implementing set-based design (SBD), as described in Chapter 3.3.1, multiple solutions for every single bridge are investigated simultaneously. This gives the possibility to find a more optimal design that fulfils the given design criteria. Figure 8 shows how cost and CO_2 could be reduced compared to a built bridge by optimising in different steps and including more and more parameters. In Figure 8 (a), optimisation is done regarding cover height (h_c) and plate thickness (t). In Figure 8 (b) the backfill material is added to the optimisation. In Figure 8 (c) the size of the pipe is also added to the optimisation, and finally, in Figure 8 (d) the shape of the pipe is also added to the optimisation. In the Figure, cost and CO_2 are normalised against the built bridge it is compared against. The results show that there is significant potential to reduce both climate and material costs by up to 20%. Considering the large number of SSCB that are built, this is an efficient way to reduce the climate impact when building these bridges in the future.

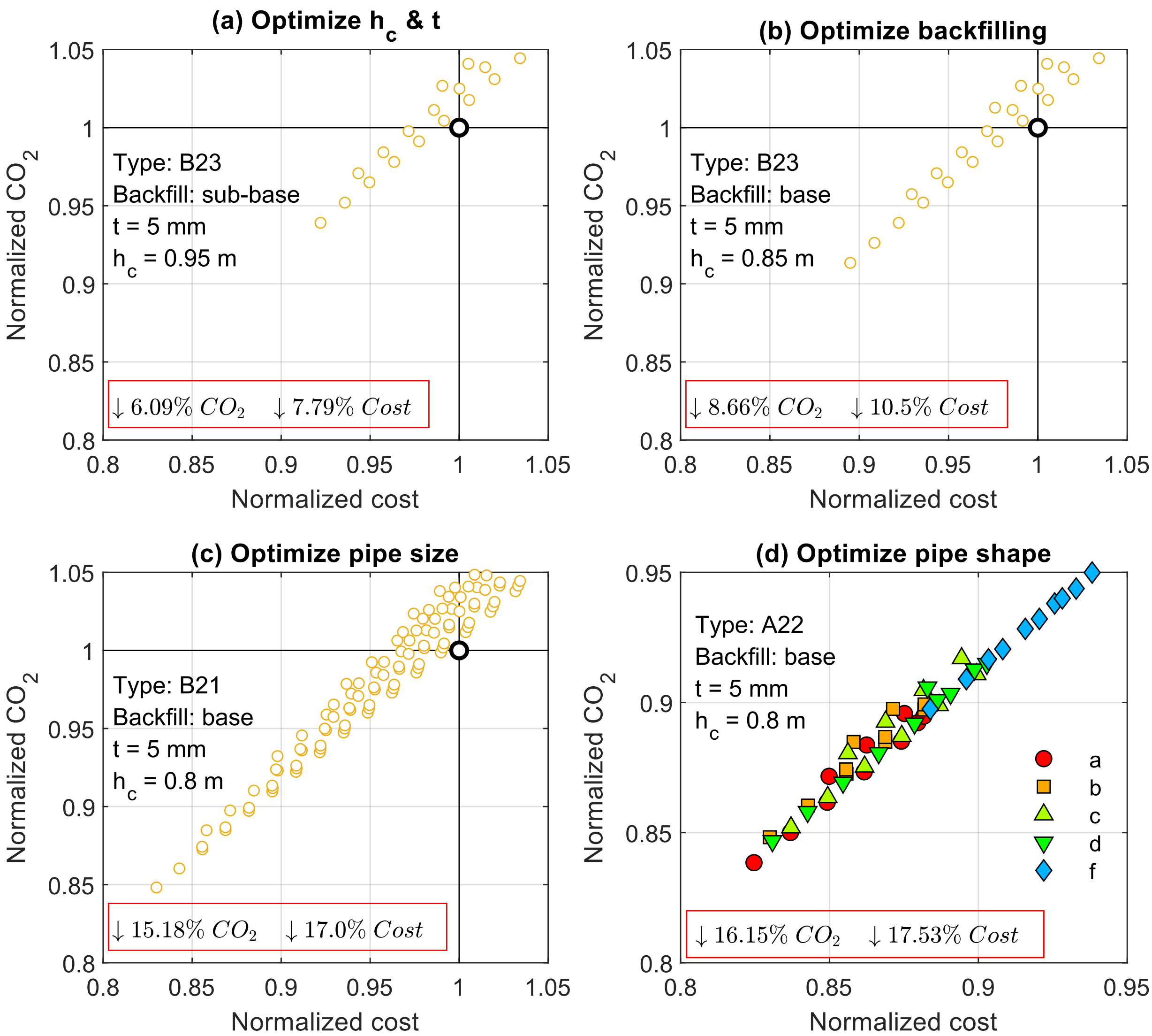

Figure 8. Optimising a SSCB in different steps. Reproduced from Paper II [2].

Here it has been shown how SBD could be used for SSCB and that it is possible to find solutions with lower cost and lower CO_2-emissions than what was built when using traditional PBD. But how could SBD be used to compare two commonly used bridge types in Sweden?

4.2.2 Paper III

Bridges serve as critical infrastructure for transporting traffic over various obstacles, including pedestrian walkways. When building bridges over pedestrian walkways, there is often a demand in terms of a free opening for the people crossing under the bridge. For this kind of bridge, concrete slab frame bridges (CSFB) and soil-steel composite bridges (SSCB) have been commonly used solutions in Sweden. When choosing between different solutions it is important to choose the best-performing solution. As long as both solutions fulfil all the structural requirements, the difference would be in cost and climate impact. In this study, three different case studies in terms of different demands for free opening for the pedestrian walkway have been investigated. Set-based design has been used to find optimal solutions for the two different bridge solutions. The result from this study indicates that there is no significant evidence of which solution is preferable between the two alternative bridge solutions.

When comparing SSCB and CSFB, normalising cost and CO_2-emissions against SSCB gives a good overview of the cost and climate performance between the two bridge types for the three different cases, as shown in Figure 9. In the Figure, it can be observed that SSCB performs better than CSFB for all the studied cases regarding CO_2-emissions. Regarding cost, SSCB performs better than CSFB in two of the three cases.

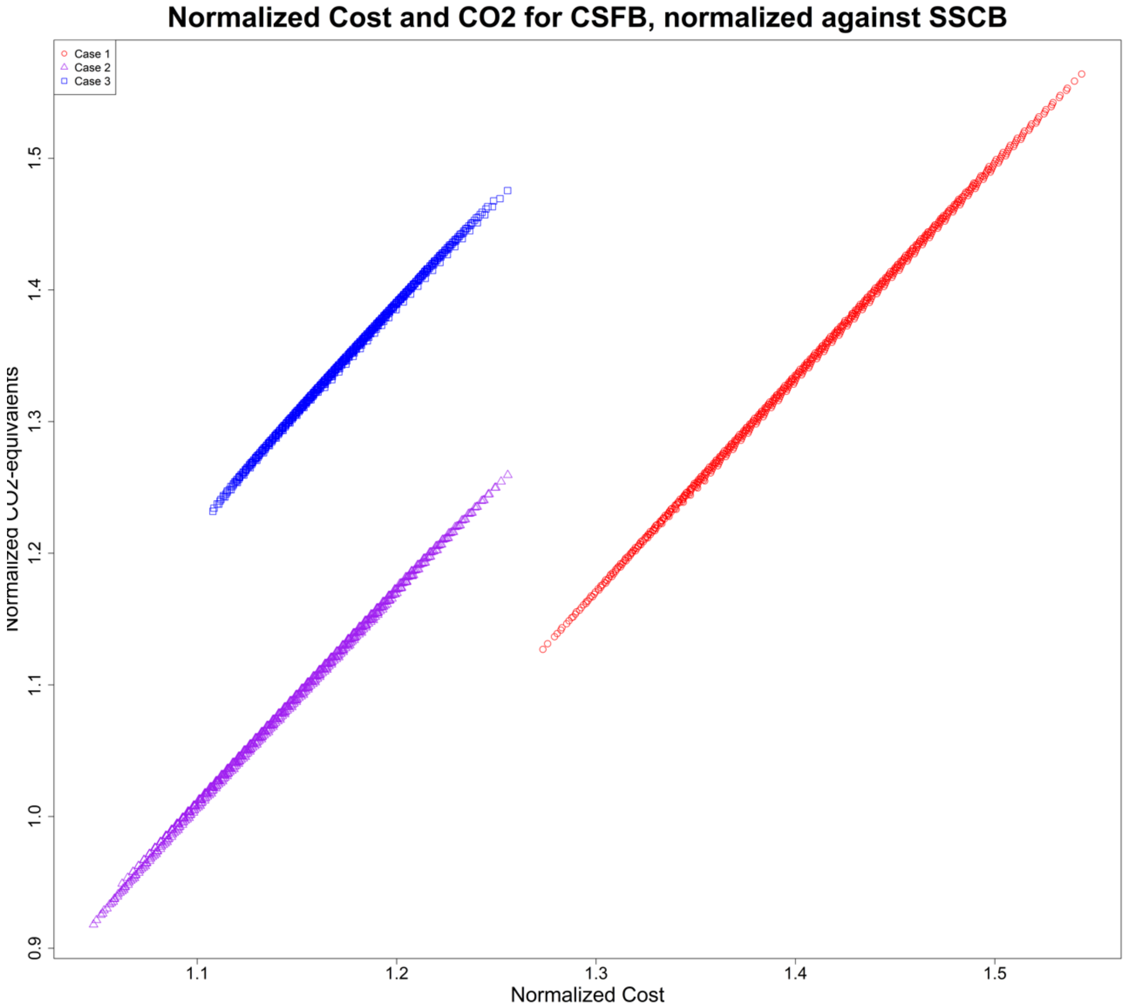

Figure 9. Normalised cost and CO_2-emissions for CSFB. Reproduced from Paper III [3].

It has been demonstrated that SBD could be used to compare two commonly used bridge types. The comparison has been for individual bridges at three different locations. How could SBD be used to take productivity into account, and could that contribute in a positive way to a project with several bridges?

4.2.3 Paper IV

While bridges are an essential part of the infrastructure, their construction is resource-intensive. Reducing construction time and optimising bridges could reduce their climate impact. However, a common standard for such an optimisation is lacking. The aim of this study was to investigate the potential for reducing material and construction cost (henceforth only cost), as well as construction time and CO_2-emissions when grouping and optimising bridges using set-based design (SBD). The grouping is based on the free area under the bridges, reducing construction time due to repetitive work. In this study, a script was developed that performed finite element analysis and necessary design checks for all the bridges that were investigated. The bridges generated from SBD could then be compared with bridges from a reference project. The results show that in a project with several bridges, SBD could be used to group bridges, which then takes repetition effects (as described by equation 1 in Chapter 3.3.3) into account and reduce cost and construction time without negative impact on CO_2-emissions. Figure 10 shows the effect on cost and CO_2 when productivity from repetition is considered. The bridge in the figure is number three of four in its group. From the Figure, it can be observed that the repetition has some effect on the cost, while the effect on CO_2-emissions is negligible. However, the number of solutions that reduce cost compared to an individual optimised solution is few, which means that it could be hard to find these solutions. Reducing cost and construction time without a negative impact on CO_2 levels in infrastructure projects is a huge benefit for society.

When studying critical time for constructing bridges in a project, the possible time savings could be 16 days if the bridges were grouped and optimised compared to individual optimisation. This means that if the bridges are on the critical timeline in that project, the project could be open for traffic 16 days earlier. To be able to use the infrastructure earlier could decrease indirect climate impact from detours for road traffic that pass the construction site and to shift from road to railway for a railway project. Detours in a road project have been shown to have a large impact on the climate [22].

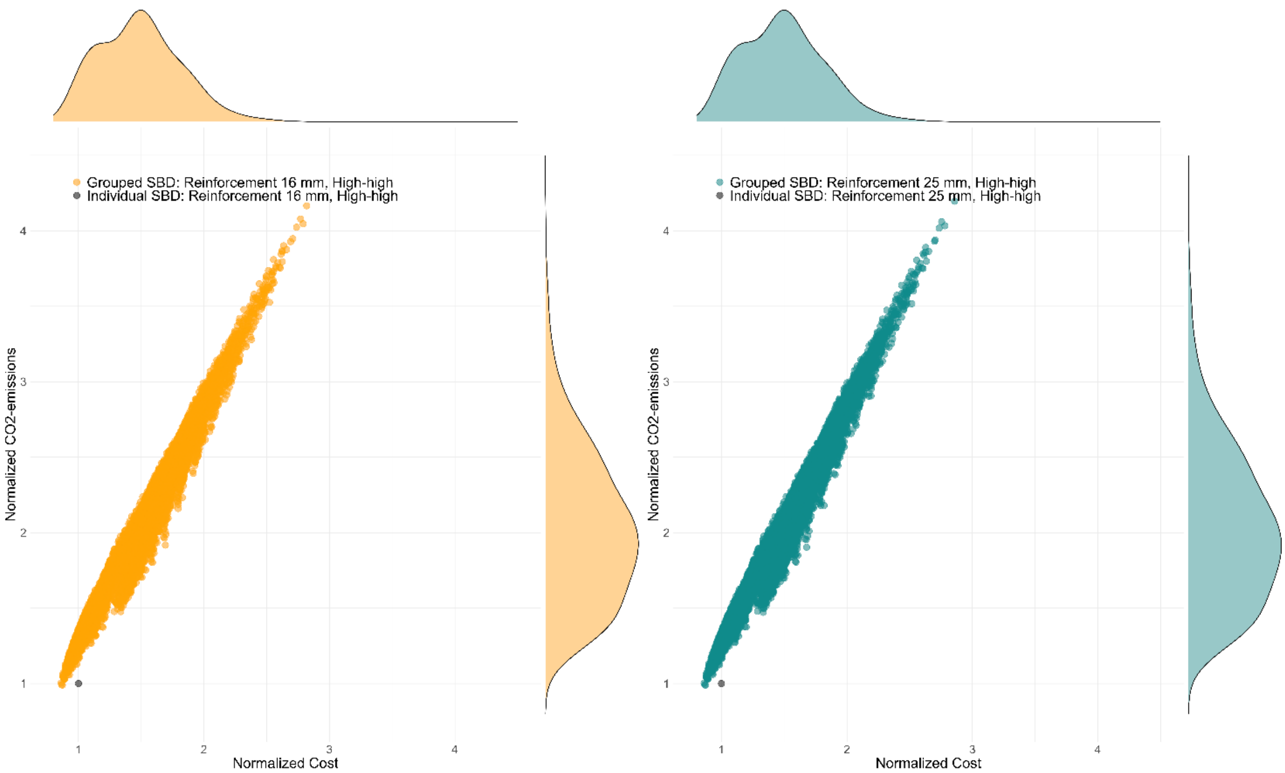

Figure 10. Normalised cost and CO_2-emissions for a grouped bridge, normalised against the same bridge for individual SBD. Reproduced from Paper IV [4].

By a grouped design approach, it could be possible to decrease cost and construction time without compromising with CO_2-emissions. However, when the amount of material has been minimised, could there be other ways to further reduce cost and CO_2-emissions?

4.3 Risk analysis, Paper V

Bridges must be designed to ensure safety for all users. At the same time, the design should be performed at an appropriate risk level. In Sweden, soil-steel composite bridges (SSCB) are the most common bridge type. For SSCB, local verification of Load Model 1 in Eurocode is most often governing the design. The objective of this study was to investigate whether local verification of LM1 load case could be modified without decreasing the agreed risk level in Eurocode. Weight in motion measurements from real traffic were extrapolated with the Rice formula. Monte Carlo simulations were used to simulate the 1000-year return period event to obtain the acceptable risk level as prescribed in Eurocode. The results showed that load effects from MC simulations are less than the load effects from LM1. Figure 11 shows the load ratios between MC simulations and LM1 for different distances between LM1 and for different cover heights. The Figure shows the ratios for different amounts of yearly day traffic for heavy vehicles. SSCB are mostly built on roads where the number of heavy vehicles is in the lower range of the four studied amounts, and here it could be observed that the load effects from MC simulations are always lower than the load effects from LM1. This indicates that a less conservative implementation of LM1 could be used for SSCB in Sweden.

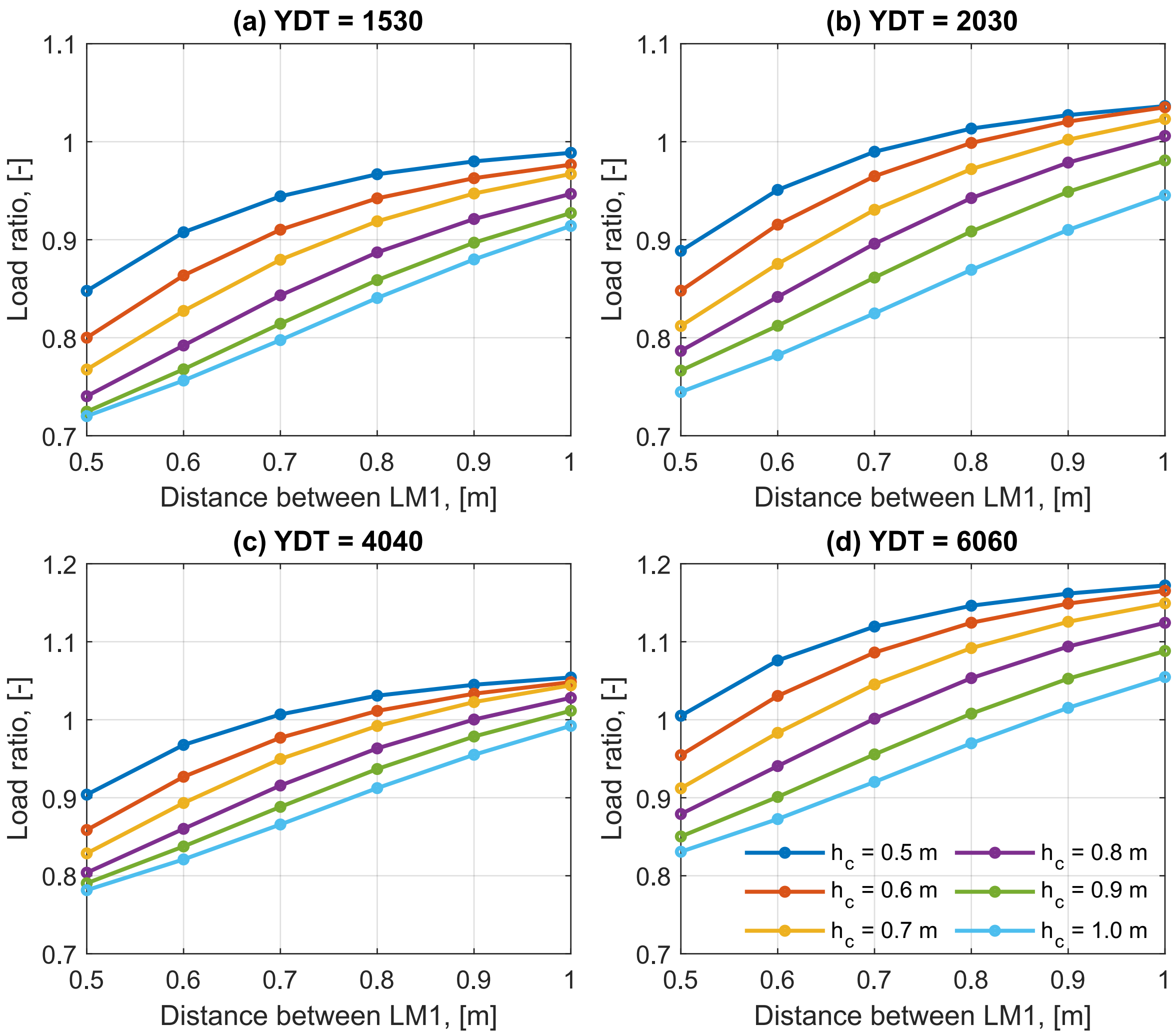

Figure 11. Load ratio from MC simulations and different distances between LM1. Reproduced from Paper V [5].

If SBD from paper II and less conservative implementation as proposed in paper V could be implemented, it could be possible to save up to 14% in cost and CO_2-emissions. Figure 12 shows potential savings for six common profiles for SSCB over a pedestrian walkway. The profiles in Figure 12 are the same as those presented in Paper II [2].

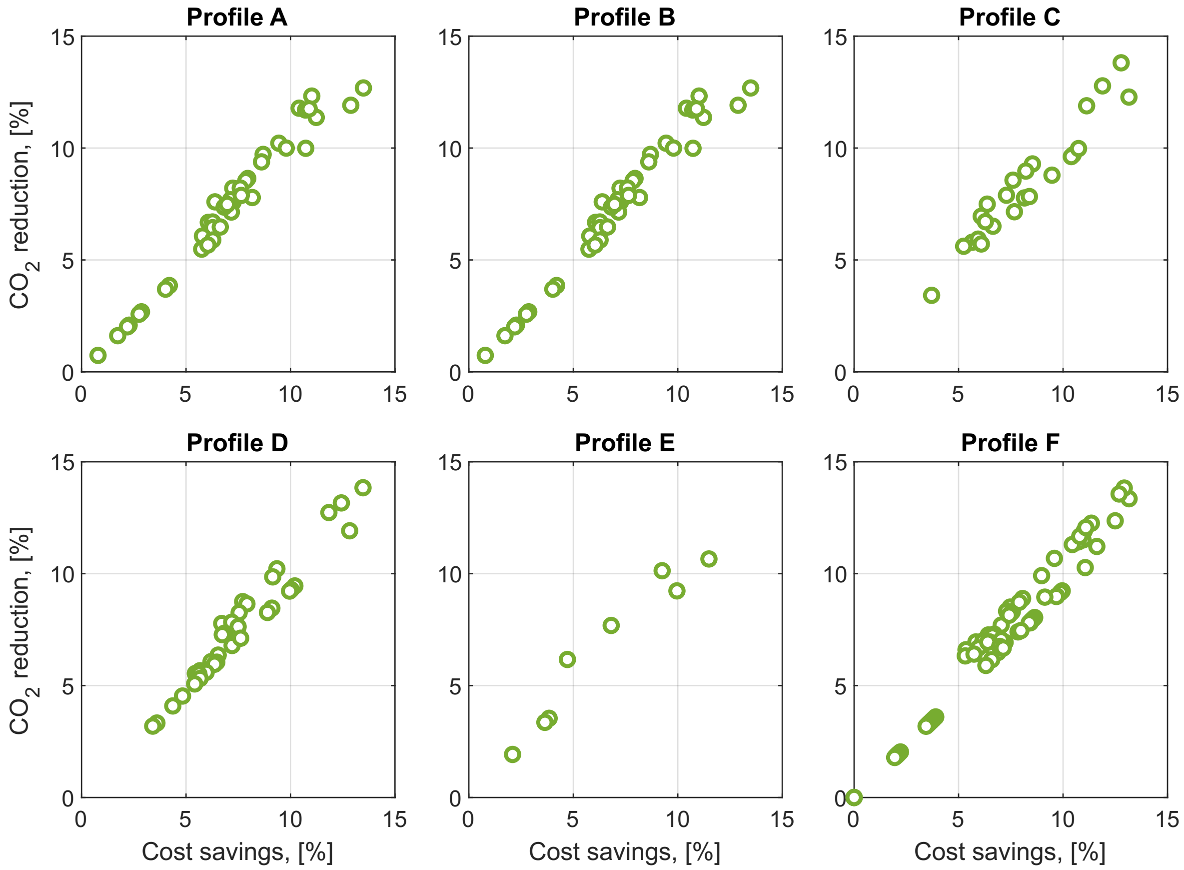

Figure 12. Potential savings in cost and CO_2-emissions if six different SSCB profiles were designed without local verification of LM1. Reproduced from paper V [5].

5 Discussion

The overall purpose of this research was to contribute to knowledge about how to realise higher productivity and use less resources when designing and building bridges. This is so that bridges could be built in a more sustainable way for the society. In a larger perspective, the ambition is that the results from this thesis could contribute to changes in the bridge-building industry in Sweden.

To fulfil the purpose, the following two research questions were developed:

- RQ1: What are the major hindrances to productivity in the bridge-building industry in Sweden today?
- RQ2: How could smart design reduce cost and climate impact for commonly built bridges in Sweden?

As has been demonstrated in this thesis, there are several ways to decrease cost and CO_2-emissions and thereby increase the benefits for society when building new bridges. Shorter construction time has the potential to reduce cost without compromising with CO_2-emissions. At the same time, if the infrastructure could be finished in a shorter time, it could be used earlier and thereby serve its purpose.

5.1 Research question 1

According to the Swedish bridge industry, standardisation has potential for productivity [64]. However, as shown in Paper I, contractors are more interested in making a profit in an ongoing project than in increasing the long-term profit of the company. This might be due to the organisational structure among the contractors, and how they are evaluated within their organisation hinders productivity [1]. Therefore, I believe that the client needs to push for standardisation when procuring new projects to make this happen. This is, off course, under the assumption that the client believes that this will govern the society in the long run. It is important that standardisation is considered at an early stage of a project. The reason for this is both to ensure that enough space is considered in the phase of land acquisition plan, and that the standardisation is considered when performing cost and climate evaluations for different alternatives. It would also be important to standardise in the best way for every single project. A number of parts that are reasonable for one team to build is important to consider, and between 5-10 parts have been shown to be reasonable [64], which was considered in Paper IV. If standardisation should be considered, this could put another level of complexity on the procurements since there is more to consider. It could also be important for the client to have discussions with the industry before larger projects are procured to get the right input when working with the land acquisition plan.

All three actors consider the quality of delivered products as the top three among the ranked aspects. This means that all actors would like to deliver a project of high quality. From a productivity point of view, it would be important to have the same view of what constitutes the right quality, so that everyone involved in the project knows what to expect, and disagreements regarding this do not negatively affect productivity.

Both the contractor and the client rank the work environment high. I believe that the work environment is paramount, and people working at constructions sites should always be able to get home safely after a day's work. Productivity should never come at the expense of a good work environment. When measuring productivity in a single project, I do not think that the work environment has any effect on productivity, but when comparing productivity over time, I believe that this can affect productivity if the work environment improves over time.

5.2 Research question 2

Another way to increase the benefit for society is to reduce the amount of material that is used in the bridges that are being built. If bridges could be built with less material and still allow for the same loads, this could reduce cost and climate impact. Set-based design (SBD) has shown potential to reduce cost and climate impact for several types of bridges. Paper II has shown that the cost and climate impact of soil steel composite bridges (SSCB) could be reduced if SBD were implemented in the design of these bridges. SBD allows for a transparent design process where all steps and choices can be traced back. It allows all possible solutions within the given design space to be part of the evaluations. When new requirements are set as the project progresses, solutions that do not meet these requirements could be filtered out, only allowing solutions that meet all the requirements to remain during the next evaluation. With SBD, several solutions that will not be built are evaluated and this is something that could be questioned. This means that time is spent on designing unused alternatives and that time could have been used in a better way. There are other optimisation methods that evaluate fewer alternatives that can give similar results. However, with SBD the data set of alternatives is stored and could then be used in future projects. This means that for a project where the solution already exists in the available dataset created in an earlier project, the best solution can be found quickly. If some of the cost and climate parameters for the materials are changing, only these need to be changed and not the entire structural design. This allows for comparisons between alternatives depending on different cost and climate data.

When evaluating solutions for a specific bridge type, Paper II studied SSCB and showed potential to reduce cost and CO_2-emissions using SBD. In Paper III, this is extended to also include concrete slab frame bridges (CSFB), which then allow comparison between the two bridge types within given conditions and for specific requirements. This allows a project to have more alternatives during the project and could then find the solution that best fulfils the specific project requirements. This allows the project to delay decisions with more available alternatives and then to make better decisions based on more and better data. If any requirement is changing, another solution could then be found among the alternatives that has been studied.

In Paper IV, SBD was used to group bridges, which considers productivity from repetition and standardisation. This study is based on the theory that repetition governs productivity and that people working is learning from repetition. If that is not the case, the results would be different. To be able to realise productivity from repetition, it assumes that there is enough space at the construction site and that the construction site is structured in a way that provides conditions for this to be realised [29]. When using SBD in this way, it is possible for the contractor to adjust the groups in a way that is beneficial from their production point of view. It also gives the contractor the possibility to find how to group bridges in a way that will govern the project. In addition to reducing material, SBD, together with grouping has shown potential to reduce the construction time. Making use of the infrastructure earlier is of great importance for society and could reduce climate impact due to shorter time for detours for cars or to be able to shift traffic from road to railway. The amount of climate savings depends on each situation, but studies have shown that reducing the disturbance of traffic can have a larger impact on the emissions than what is built [22], and this is also in line with the relation of climate impact from the traffic and from the construction and maintenance of the infrastructure [79, 80]. In addition to cost and climate savings from finalising the infrastructure earlier, the users also gain benefits from this. Most of the time, new infrastructure reduces the time for the users to travel from A to B. The reduced time could then be used in a better way than transportation.

Using SBD (or other methods) to reduce the amount of material in a structure will finally converge and reach an end. This means that something more than structural optimisation needs to be studied to further reduce the amount of material. In Paper V, a design case that most often governs the design of SSCB was studied. Weight in motion measurements were used, and together with Montecarlo simulations, less conservative load cases could be analysed and compared with the critical design case. In Paper V, the result showed that a less conservative load implementation could be used, and this has the potential to reduce cost and climate impact up to 14% for the construction of a new SSCB in Sweden. I think that this shows that it is difficult to develop load models and load cases that should be used for all structures on all occasions. I believe that research has a responsibility to contribute in a positive way to help the industry reduce cost and climate impact and be more beneficial for society. The method used in this paper could be used for other bridges if there are other critical design cases that could be shown to be conservative.

The research that this thesis is based on has shown potential to decrease cost and CO_2-emissions from the design and construction of bridges in different ways. To be able to build infrastructure that fulfils the same purpose at a lower cost and with less CO_2-emissions is beneficial for the society today and for future generations. In addition to reducing cost and CO_2-emissions, it has also been shown that grouping and standardisation have the potential to reduce construction time. To be able to realise the results from this research, I believe that the client has a huge responsibility due to its positions and their procurements. They need to be proactive and make attractive procurements with incentives for the actors working in the industry. If they see potential, they need to be brave and test new ideas in real projects and force it to happen and take the risks. Otherwise it is highly possible that everything remains as it has always been.

6 Conclusions

I believe that the results from this thesis could be extended to other bridge types, other parts of the infrastructure, other parts of the construction industry and to other countries. With the right procurements, it would be possible to implement the results from this research and to realise it in real projects. The recommendations regarding distances between LM1 from paper V have been implemented in the regulatory requirements stated by the Swedish Transport Administration.

The overall purpose of this research was to contribute to knowledge about how to realise higher productivity and use less resources when designing and building bridges. The most important findings in this thesis are:

- Standardisation has potential for productivity. However, the finding that contractors are more interested in making short-term profit in an ongoing project than long-term profit hinders productivity. To overcome this hindrance, it is important to find incentives for the contractors in each project so they can see the benefits of standardisation.
- Set-based design could be used to decrease both cost and CO_2-emissions for commonly built bridges in Sweden. In addition to reducing cost and CO_2-emissions, it could also be used to group bridges, which then could be used to reduce construction time and further reduce costs. Deliver bridges that meet the same requirements at a lower cost, with reduced CO_2-emissions and shorter construction time, which govern overall productivity.
- Developing load models that are accurate for all types of bridges and for various conditions is challenging. Research could contribute to modified load models that are not too conservative. This has the potential to reduce the amount of material in the structures which contributes to a more sustainable society.
- All the actors working in the industry can contribute to a more sustainable bridge industry, and it is important to find incentives for all the actors to strive against this. Contractors and design engineers strive for profit, which means that finding the right procurements is important to realise a more sustainable bridge industry.

All the findings described above contribute to a more sustainable society. They could be implemented individually or combined. All findings are both theoretical and, maybe mostly, practical contributions.

7 Future work

For the future, it would be important to study cost-benefit analysis for different bridge alternatives. In Paper III, SSCB was shown to perform better than CSFB regarding cost in two of three cases and in all cases regarding CO_2-emissions. The difference in construction time between the two bridge types makes it important to investigate further how this affects the societal costs and benefits for the different alternatives.

To have a more holistic view, and not only consider the bridges, it would be important to implement SBD in a larger perspective where there are several alternatives, such as different corridors for a road or a railway. To be able to achieve this, more types of bridges need to be designed with SBD, different road constructions need to be designed, different ground reinforcements need to be designed etc.

Prefabrication is something that could increase productivity, and that I believe it is necessary to consider more of it in the future.

Measuring productivity in the bridge-building industry is complex. Even though many improvements have been made, the final productivity has been hard to demonstrate. This makes it necessary to find alternative ways for these measurements. Comparing productivity over time is challenging since parameters change over time. If a more recent bridge has a higher load-carrying capacity compared to an older bridge, in interesting question is how these should be compared from a productivity and material perspective.

I think that it would be important to investigate how bridges could be classified based on load carrying capacity and climate impact. By doing that, clients could procure bridges with a certain classification.

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