THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Addressing the complexity of sustainability-driven structural design: Computational design, optimization, and decision making

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Department of Architecture and Civil Engineering

Division of Structural Engineering

Concrete Structures

CHALMERS UNIVERSITY OF TECHNOLOGY

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Abstract

Being one of the sectors with the largest environmental burden and high socio-economic impacts sets high requirements on the construction industry. At the same time, this provides the sector with great opportunities to contribute to the globally pursued sustainability transition. To cope with the increasing need for infrastructure and, at the same time, limit their sustainability impacts, changes and innovation in the construction sector are required. The greatest possibility to limit the sustainability impact of construction works is at the early design phase of construction projects, as many of the choices influencing sustainability are made at that point. Traditionally, an early choice of a preferred design is often made based on limited knowledge and past experience, considering only a handful of options. This preferred design is then taken on to the successive stages in the stepwise design process, leading to suboptimization.

Alternatively, many different design choices could be considered and evaluated in a more holistic approach in order to find the most sustainable design for a particular application. However, finding design solutions that offer the best sustainability performance and fulfil all structural, performance and buildability requirements, require methods that allow considering different design options, analysing them, and assessing their sustainability. The aim of this thesis is to explore and develop methods enabling structural engineers to take sustainability objectives into account in the design of structures.

Throughout this thesis, a number of methods have been explored to take sustainability aspects into account in the structural design process. As a first step, highly parameterized computer codes for sustainability-driven design have been developed. These codes interoperate with FE analysis software to automatically model and analyse design concepts over the whole design space and verify compliance with structural design standards. The codes were complemented with a harmonized method for life cycle sustainability performance assessment, in line with the state-of-the-art standards. Here, sustainability criteria were defined covering environmental, social, economic, buildability and structural performance for multi-criteria assessment of design concepts. To identify the most sustainable designs within the set, multi-objective optimization algorithms were used. Algorithms that address the high expense of constraint function

evaluations of structural design problems were developed and integrated in the parameterized computer codes for sustainability-driven design. To ensure the applicability and validity of these methods, case studies based on real-world projects and common structural engineering problems were used in this thesis. Case studies for bridges and wind turbine foundations as well as a benchmark case of a reinforced concrete beam were investigated.

The case studies highlight the potential of the methods explored to support the design of more sustainable structures, as well as the applicability of the methods in structural engineering practice. It is concluded that it is possible and beneficial to combine computational design, life cycle sustainability assessment, and multi-objective design optimization as a basis for decision making in the design phase of civil engineering projects. A wide adoption of such a sustainability-driven design optimization approach in structural engineering practice can directly improve the sustainability of the construction sector.

Keywords: structural engineering, civil engineering, life cycle sustainability assessment, parametric design, multi-objective design optimization, integrated design, construction, finite element analysis, bridge, wind turbine foundation, concrete structure.

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Preface

The research presented in this thesis is the result of the work carried out between November 2015 and April 2021 at the Division of Structural Engineering at Chalmers University of Technology. Between March and May 2017, the work was conducted at the Institute of Concrete Construction at Leibniz University Hannover, during a three-month research visit, followed by two additional visits during spring 2018 to participate in experimental campaigns. A second research visit was conducted between October 2019 and January 2020 at the Institute of Concrete Science and Technology (ICITECH) at the Polytechnic University of Valencia.

This work has been financially supported by the Swedish Energy Agency (Energimyndigheten) through the Swedish Wind Power Technology Centre (SWPTC), the Swedish Transport Administration (Trafikverket), Sweden's Innovation Agency (Vinnova), the Swedish research council for sustainable development Formas and the Swedish construction company NCC AB through the following projects:

- Innovative structural engineering approaches for design of offshore wind turbine foundations (SWPTC/Energimyndigheten)
- Sustainable design and construction planning (Vinnova)
- Design process for increased consideration of production methods, climate and environmental impact in the construction process (Trafikverket)
- Wind turbines under harsh operation conditions (SWPTC/Energimyndigheten)
- Sustainable and cost effective structural supporting system for onshore wind power plants (SWPTC/Energimyndigheten)
- Sustainability driven building design based on artificial intelligence (Formas)

The computations carried out in this work were enabled by resources provided by the Swedish National Infrastructure for Computing (SNIC) at Chalmers Centre for Computational Science and Engineering (C3SE) financially supported by the Swedish Research Council.

Many persons have accompanied me on this journey towards the completion of this doctoral thesis. I would like to express my appreciation to my academic supervisor and examiner, Professor Mario Plos, and assistant supervisor, Associate Professor Rasmus Rempling, for their time spent in following my progress during these doctoral studies and administrating the projects. Furthermore, I want to acknowledge my industrial supervisor at NCC, Dr. Tobias Larsson and my manager at NCC, Dr. Christina Claeson-Jonsson, for their continuous support and encouragements. I am sincerely grateful to the four of them for giving me the opportunity to embark on PhD studies. I also want to thank Associate Professor Magnus Gustafsson who provided me valuable writing advices in the final year. The first-class support form librarians at Chalmers in getting access to some hard-to-find publications was also most welcome.

I wish to express my gratitude to my colleagues at NCC and Chalmers for the enjoyable and enriching working environment. Thanks also to the other researchers in SWPTC for the interdisciplinary insights on wind turbine design from our meetings. I am also grateful to Professor Steffen Marx and all his research group at the Institute of Concrete Construction at Leibniz University Hannover, and to Professor Víctor Yepes Piqueras and the fellow researchers at ICITECH for the warm welcome and fruitful experiences during my research visits at their respective institutions. Special thanks also to Kristine Ek, Adam Sciegaj, Jincheng Yang, Jesús Armesto Barros, Daniel Ekström, Vicent Penadés Plà, Marina Stümpel, Jonas Magnusson, Karin Lundgren, Jelke Dijkstra, Richard Malm, Olof Skogby Steinholtz, and Anders Sjöberg for interesting discussions and pleasant collaborations over the last few years.

Last but certainly not least, I want to thank my dear family and friends across the globe. To my parents and my brother, I am deeply grateful for you always being there despite the distance that separates us. To Teresa, my most sincere thanks for your tremendous patience and support; without them, I never would have finished this thesis in time. Teresa, Elsa, I love you.

Alexandre Mathern, Gothenburg 2021

List of publications included in this thesis

Paper A	Alexandre Mathern, Christoph Von der Haar, Steffen Marx. Concrete structures for offshore wind turbines: current status, challenges, and future trends. *Energies* 2021 14(7):1995. DOI: 10.3390/en14071995.
Paper B	Kristine Ek, Alexandre Mathern, Rasmus Rempling, Petra Brinkhoff, Mats Karlsson, Malin Norin. Life Cycle Sustainability Performance Assessment Method for Comparison of Civil Engineering Works Design Concepts: Case Study of a Bridge. Trends in Sustainable Buildings and Infrastructure, *International Journal of Environmental Research and Public Health* 2020, 17, 7909. DOI: 10.3390/ijerph17217909.
Paper C	Rasmus Rempling, Alexandre Mathern, Santiago Luiz Fernandez, David Tarazona Ramos. Automatic structural design by a set-based parametric design method. *Automation in Construction* 2019, 108:102936. DOI: 10.1016/j.autcon.2019.102936.
Paper D	Alexandre Mathern, Olof Skogby Steinholtz, Anders Sjöberg, Magnus Önnheim, Kristine Ek, Rasmus Rempling, Emil Gustavsson, Mats Jirstrand. Multi-objective constrained Bayesian optimization for structural design. *Structural and Multidisciplinary Optimization* 2020. *DOI:* 10.1007/s00158-020-02720-2.
Paper E	Alexandre Mathern, Vicent Penadés Pla, Jesús Armesto Barros, Victor Yepes. Practical metamodel-assisted multi-objective design optimization for improved sustainability and buildability of wind turbine foundations. Submitted to *Structural and Multidisciplinary Optimization*.

Author's contribution to jointly published papers

In **Paper A,** The author, Alexandre Mathern (AM), took full responsibility for defining the work, conducting the research, and formulating, writing and editing the manuscript.
In **Paper B**, AM shared responsibility for conceptualizing the study, analysing and validating the results, and writing, revising and editing the paper.
In **Paper C,** AM initiated and defined the scope of the study and supervised the development and application of the script. AM shared the responsibility for formulating, writing, revising and editing the paper.
In **Paper D,** AM led the work and the preparation of the paper, and shared responsibility for planning the study, analysing the results, and formulating, writing, revising and editing the paper. AM took full responsibility for defining the case study, and developing the design and evaluation parts of the computer code.
In **Paper E**, AM led the work, and the writing and editing of the paper. AM shared responsibility for planning the paper, developing the computer code used to design the foundations and computing the optimization process.

The author has also actively participated in the definition and writing of the research proposals for the projects that financed the research conducted in the above-listed papers.

Other related publications

Licentiate thesis:

- Mathern, A. (2019) Sustainability-, Buildability- and Performance-driven Structural Design. Department of Architecture and Civil Engineering, Chalmers University of Technology.

Peer-reviewed journal and conference papers:

- Mathern, A., Yang, J., A practical finite element modeling strategy to capture cracking and crushing behavior of reinforced concrete structures. *Materials* (2021) 14(3).
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Technical report:

- Carlson, O. et al. (2018) TG0-21 Wind turbines under harsh operation conditions, Project report, Swedish Wind Power Technology Centre.

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- Nilsson, S., Öhman, P. (2019) Structural optimization for effective strut-and-tie models - Design of support crossbeams in single girder concrete bridges. Master's Thesis in Structural Engineering and Building Technology.
- Isaksson, J., Tenenbaum, D. (2018) The effect of soil-structure interaction on the behaviour of onshore wind turbines with a gravity-based foundation. Master's Thesis in Structural Engineering and Building Technology / Sound and Vibration.
- Jonsson, E., Tunander, E. (2018) Alternative evaluation methods for onshore wind turbines. Master's Thesis in Infrastructure and Environmental Engineering.
- Wiklund, D. (2018) Comparison of structural analysis methods for reinforced concrete deep beams. Master's Thesis in Structural Engineering and Building Technology.
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- Ahlström, M., Holmquist, C. (2017) Assessment and comparative study of design method for onshore wind power plant foundations. Master's thesis in Structural Engineering.
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- Halici, Ö. F., Mutungi, H. (2016) Assessment of simulation codes for offshore wind turbine foundations. Master's Thesis in Structural Engineering and Building Technology.

Miscellaneous:

- Ek, K., Mathern, A. (2018) Resursoptimering över livscykeln med hjälp av AI och sensorer [Life cycle resource optimization by use of AI and sensors] Innovationstävlingen Transformativ infrastruktur – banbrytande innovation för nollutsläpp.

Abbreviations

BOM	bill of materials
CAD	computer-aided design
EN	European norm/standard
EPD	environmental product declaration
FE	finite element
ISO	international norm/standard
LCA	life cycle assessment
LCC	life cycle cost
LHS	latin hypercube sampling
LoA	level of approximation
MCDA	multi-criteria decision analysis
NSGA-II	Non-dominated Sorting Genetic Algorithm II
PEF	product environmental footprint
SI	sustainability index
SLS	serviceability limit state
ULS	ultimate limit state

PART I – EXTENDED SUMMARY

1 - Introduction

This thesis builds on the work conducted in a series of studies, reported in **Papers A-E** [1–5], which have been published or are under review in international scholarly peer-reviewed journals. The thesis further develops the work published in a licentiate thesis [6] that constituted a mid-step towards the Degree of Doctor of Philosophy. In this chapter, the background, aim, and objectives of the thesis, as well as the research approach and methodology adopted are described.

1.1 Background

Modern society is highly dependent on functional and reliable infrastructure for its energy supply, communications, and its transport of people and goods. The infrastructure networks represent essential parts of any country's economic and social development and support employment directly and indirectly. With today's insight into sustainability, infrastructure is increasingly seen to play a key role in the transition towards a more sustainable society in a context where the global population is growing and urbanization expanding [7]; existing infrastructure is ageing [8]; and decarbonization of the expanding energy and transport sectors is on-going [9].

Countries worldwide are aiming to reduce their environmental impact, as reflected by the commitment made by more than 190 countries under the Paris Agreement in 2015 to reduce their greenhouse gas emission with the aim of limiting global warming below 2°C [10]. In line with this agreement, the European Union, has set the objective of becoming climate neutral by 2050 [11]. This objective implies a need for new infrastructure to support the decarbonization of the energy system, in particular to develop renewable energy sources (e.g. wind, solar and marine energy), upgrade electricity grids, and develop energy storage facilities. The installed capacity of offshore wind energy, for instance, is growing fast. It reached almost 30 GW globally by the end of 2019 [12] nearly three decades after its emergence. This capacity is expected to keep increasing exponentially in the coming decades, as illustrated by the European Union's target of reaching 60 GW of installed offshore wind capacity by 2030 and 300 GW by 2050.

The increasing population, urbanization, and intensification of exchanges and communications also require large infrastructure investments. At the same time, the infrastructure stock is ageing in many countries and there is an extensive need to repair, refurbish, or replace existing infrastructure, as well as to improve the resilience of existing infrastructure to climate change [13].

Beyond the necessary role of infrastructure works, their construction, maintenance and operation is also associated with large impacts in all three dimensions of sustainability: environmental, social, and economic that need to be addressed in order for such infrastructure to have a positive global contribution to sustainability goals. In the environmental dimension, the construction sector is by far the largest user of natural resources. Indeed, construction of infrastructure and buildings accounts for 60% of the global extracted abiotic and biotic resources according to the Worldwatch Institute, wherein infrastructure accounts for 60% and buildings for 40% [14]. The building and construction sector is also estimated to be responsible for 20-40% of the global anthropogenic greenhouse gas emissions [15–17]. Construction materials account for a significant part of it, as cement production alone represents more than 5% [18]. In the social dimension, health and safety, labour conditions, and stakeholders' satisfaction are particularly relevant given that the occurrence of work accidents has been historically high in the field and construction works are often associated with disturbances for local communities. Finally, in the economic dimension, construction represents large investments and public authorities in most countries worldwide are struggling to maintain and develop infrastructure within the limits of their budgetary allocations.

Being one of the sectors with the largest environmental burden and high socio-economic impacts sets high requirements on the construction industry, whilst providing the sector great opportunities to contribute to the sustainability transition. To cope with the increasing need for infrastructure and, at the same time, limit the associated sustainability impacts, changes and innovation in the construction sector are required. In fact, unexploited potential for improvement can be identified in many aspects of the construction process. This large potential for improvement relates to specificities of the construction industry that is primarily project-oriented in contrast to many other industries that are manufacturing standardized products.

Construction projects are often considered as being unique due to the fact that they are mostly built on-site and need to be adapted to the specific site conditions. In addition, the design process within a project is usually time-constrained and there is a lack of incentive to develop better solutions, for instance consuming less material [19]. Practitioners have highlighted that tremendously more material is needed to build a bridge or a tunnel today than 50-60 years ago, when considering the same loading conditions, i.e. more than 50% more concrete and more than double the quantity of reinforcing steel [19]. More conservative design codes and the preference towards simple non-optimized solutions that shorten both the design and construction times but are not material-efficient are suggested reasons for this increase.

Productivity (here understood as the value added per hour worked) has also been reported to have been stagnating in the construction sector in the last decades, especially in developed countries, despite the technological progress. For instance, in the US, the productivity of construction has not increased over the last 80 years, and has even declined in the last 50 years, while the productivity of other sectors such as manufacturing and agriculture has increased 10 to 15 times [20]. Ways to improve the sector's productivity are identified in [20], and they include rethinking the design and engineering processes with greater focus on constructability and standardization; changing the procurement process to base it on best value and past performance instead of only lower cost; and infusing digital technology, new materials, and advanced automation. With the right approach, these ways can also contribute to reducing the sustainability impact.

The unexploited improvement potential in the construction sector is probably even larger for civil engineering structures than for buildings. Indeed, infrastructure works consists to a lower extent of standardized parts, are usually more influenced by the terrain and geotechnical conditions, are subject to more complex loads, and less progress has been made in the field to take into account sustainability than in the building sector where it has been driven by various certifications programs. Additionally, large share of infrastructure is procured by public administrations, which means that an evolution of requirements and public procurement practice to support the development of more sustainable structures can have large impacts. Furthermore, while unique remarkable civil engineering structures, such as long span cable-stayed bridges, naturally attract a lot of interest, it is more ordinary structures that constitute the major part of the infrastructure stock. Given the large occurrence of these types of structures, even small improvements may have significant effects.

The design and construction of civil engineering structures involves a large number of choices that influence their sustainability, including choices on the design, the construction planning, the supply chain and the post-construction plan (see examples in Table 1.1). In most cases, the number of possible choices and their various consequences on the many facets of sustainability, requires making trade-offs. For instance, choosing a higher-strength concrete may improve durability but it has higher embodied energy and carbon due to a higher cement content. As illustrated in Figure 1.1, it is in the early design stages of a project, that many of these choices need to be made and that the possibilities to influence the sustainability outcome of a project are the greatest [21, 22]. However, time is often limited to perform the design tasks and data and information available are very scarce at this stage of a project, which makes it difficult to assess the consequences of different design choices. An early choice of a preferred design is often made based on limited knowledge and past experience, considering only a handful of options. This preferred design is then taken on to the successive stages in the stepwise design process, leading in the best case to suboptimization.

Table 1.1. Overview of aspects influencing the sustainability of civil engineering structures

Category	**Example**
Design choices	Design method
	Structural concept
	Materials
	Dimensions
Construction planning	Construction methods
	Construction equipment
	Level of prefabrication
Supply chain	Transport
	Material production
Post-construction plans	Use
	Maintenance
	End-of-life

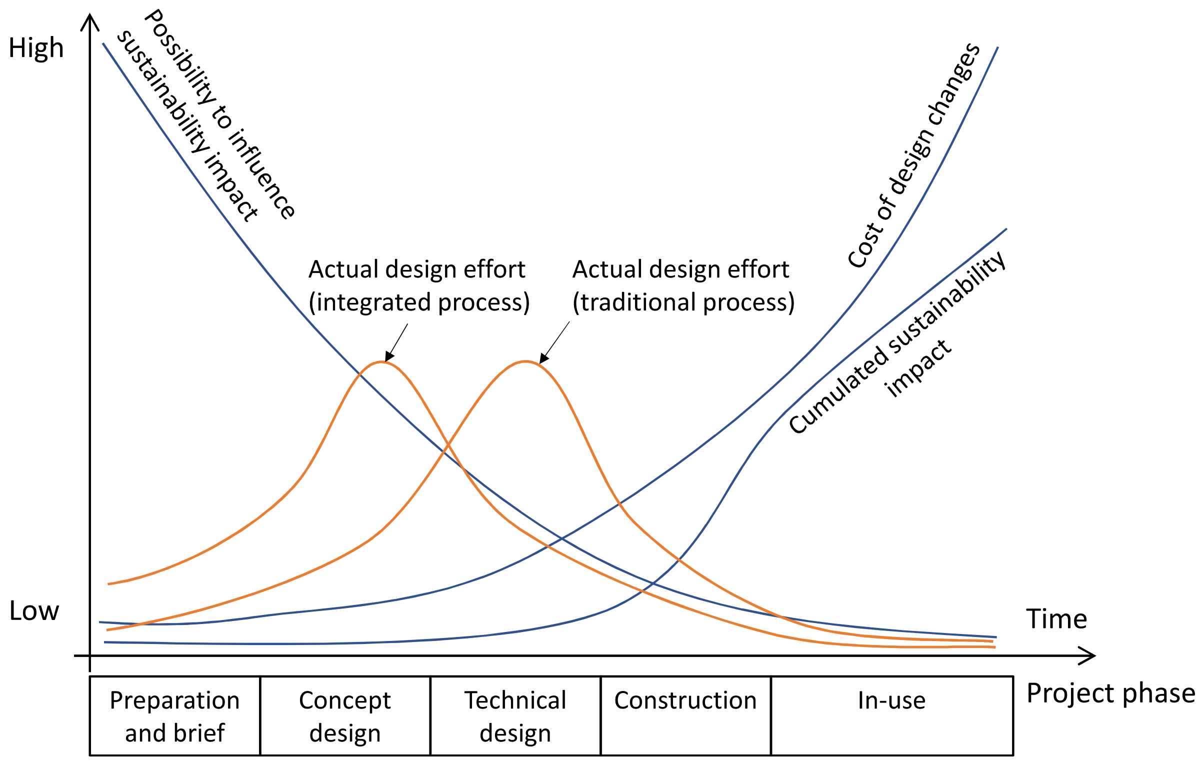


Figure 1.1. Evolution of the sustainability impact, of the possibility of influencing it, of the cost of design change and of the actual design effort with a traditional design process and with an integrated design process over different stages of a construction project (elaborated based on [21–23]).

A more adequate approach would be to consider many different design choices and evaluate these choices in a more holistic approach in order to find the most sustainable design for a particular application. Here, finding design solutions that offer the best sustainability performance and fulfil all structural, performance and buildability requirements, require methods that allow considering different design options, analysing them, and assessing their sustainability performance. Advances in computational design and optimization methods provide powerful tools, but there is still a big gap between the available design optimization methods used in other industries and in research and the common structural engineering practice.

Moreover, comprehensive indicators that can provide a clear picture of the sustainability performance of a solution over its life cycle need to be defined. Life cycle sustainability assessment methods are indicated to make better-informed decisions regarding the impact of design choices [24, 25] and many standards have been published in recent years to define the general principles and framework of these methods for civil engineering construction works [26–28]. However, there is a lack of guidelines on how to apply them and combining them with structural design process requires multidisciplinary knowledge and integrated methods. Therefore, new design methods need to be developed that are adapted to structural design and applicable in practice.

1.2 Aim and objectives

The aim of this thesis is to explore and develop methods enabling structural engineers to take sustainability objectives into account in the design of structures. This aim is broken down into four main objectives, which are:

- to identify and define relevant sustainability criteria, design concepts, and requirements that are adapted to specific structural design cases (**Papers A-E**),
- to develop and put into practice computational methods, that allow efficient design and assessment of structures (**Paper C-E**),
- to define and apply methods to assess and compare the life cycle sustainability performance of design concepts (**Paper B-E**),
- to assess the potential of multi-objective optimization methods adapted to structural design problems for reducing the computational times required to explore the design space and find optimal designs (**Paper C-E**).

In addition, the following sub-objectives are addressed in the different studies:

- to review the current status in the use of concrete structures in offshore wind projects, and identify and assess the potential of new solutions with focus on structural, buildability, knowledge, and sustainability aspects (**Paper A**),
- to identify critical sustainability indicators in different life cycle phases of a civil engineering works project as well as elements of the project with the greatest impacts (**Paper B**),
- to investigate the applicability of set-based parametric design in the early stage of structural design of bridges (**Paper C**),
- to study the efficiency of a state-of-the-art constrained Bayesian multi-objective optimization algorithm on a generic structural design case (**Paper D**), and
- to examine the potential of using kriging surrogate models to perform multi-objective design optimization of wind turbine foundations taking into account a comprehensive set of sustainability and buildability objectives (**Paper E**).

1.3 Research approach and methodology

The research carried out within this thesis is strongly interdisciplinary and therefore a wide variety of subfields and methods have been explored. The following fields have been approached in this thesis: structural analysis and design, bridge engineering, construction engineering, wind energy, offshore engineering, computational design, environmental assessment, decision making, and mathematical optimization and machine learning.

The research approach has been adapted to the interdisciplinarity nature of the thesis. To approach and deepen into the different subjects and methods, the author conducted literature reviews, and chose to collaborate with experts in the different studies, and to actively participate in specialised conferences and forums as a mean to obtain feedback from the relevant scientific community.

In a first stage, the author adopted a more theoretical and explorative approach that resulted in the formulation of a conceptual framework for sustainability-, buildability-, and performance-driven structural design [6]. The framework set the grounds for approaching the complexity of sustainable structural design and it provided direction to the rest of the work. This was presented and critically discussed at a licentiate seminar that was held in June 2019.

In the second part of the doctoral studies, the further research needs identified in the licentiate thesis were addressed. At this stage, the chosen approach was to work with case studies, as they were considered an appropriate way to investigate the practical application potential of the methods by using data from real-world projects. The subjects of the case studies were chosen to be representative of common and often occurring civil engineering structures so that their optimization could have a large overall potential impact. Therefore, the research was focused on common types of short- and medium-span bridges and on wind turbine support structures. The former represents a traditional and widespread civil engineering application, while the latter represent an emerging and fast-growing application.

The methodology followed in this work builds on four blocks (dark blue boxes), as visualized in Figure 1.2. Each block relates to one of the four objectives. The methods and tools applied in each block are represented in the light blue boxes. Achieving the aim of this thesis required both to examine and develop these methods individually and, more importantly, to propose processes to integrate them and facilitate their implementation in engineering practice.

The first block refers to the definition of the problem, which involves an advanced understanding of sustainability issues and challenges associated with a specific structural application and of the structural design process. These aspects were in focus in **Papers A-E**. Literature review and own engineering experience were the main sources of information for motivating design concepts, selecting design variables, their interval of variation, as well as defining criteria to assess the sustainability, buildability and structural performance of design alternatives. As part of the development process, different sets of criteria with varying levels of detail were deliberately chosen in the different studies. The ambition was to acquire experience and refine different criteria stepwise, as well as study the relevance of the level of detail. Additionally, requirements from design standards were included in line with structural engineering practice.

The second block deals with computational design by means of parametric design and finite element (FE) analysis (**Papers C-E**). The use of coding allowed automating the structural design process, build the FE models, control the numerical analysis, perform routine design tasks, and store the relevant results.

The third block addresses the assessment of the sustainability performance. This required to develop a harmonized method for life cycle sustainability assessment and comparison of the design of civil engineering works. The method was developed based on literature review and follows the principles and requirements given in the standards on sustainability performance assessment of construction and civil engineering works. The method is evaluated on a bridge case study in **Paper B**.

Finally, the need to explore many design options while keeping the computational time low called for the use of multi-objective optimization methods (fourth block). In this thesis, three alternative optimization approaches were developed and investigated. Based on the theories of integrated and parametric designs, a framework for set-based parametric design was defined and applied in **Paper C**. To explicitly exploit the features inherent to structural design problems, that is, expensive constraints and cheap objectives, possibilities of using surrogate modelling were investigated (**Paper D-E)**. In **Paper D** a Bayesian optimization framework was developed, which was evaluated on a generic case of structural design of a reinforced concrete beam. The Bayesian algorithm was benchmarked against two other common optimization algorithms: the Non-dominated Sorting Genetic Algorithm II (NSGA-II) and a random search procedure. In **Paper E**, kriging surrogate optimization was studied.

Paper B, Paper C and **Paper E** are based on case studies, which required data collection and analysis from the respective projects using project documents and personal communication with professionals involved in these projects.

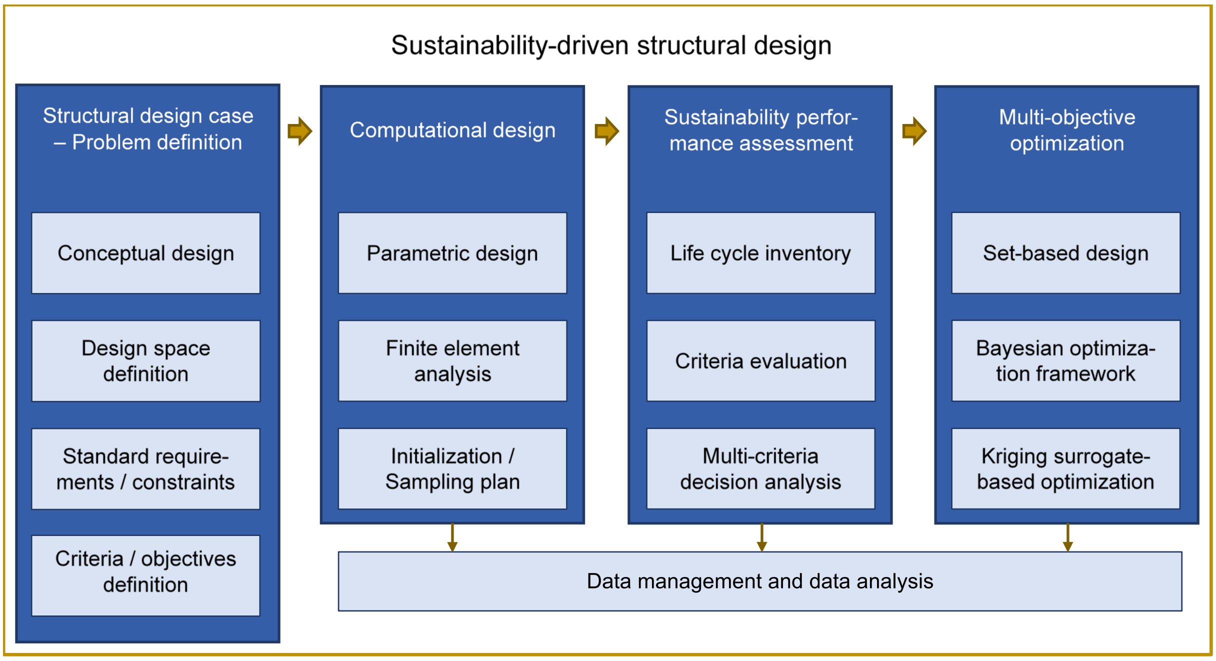


Figure 1.2. Overview of the methodology explored towards sustainability-driven structural design. The dark blue boxes indicate the four work blocks addressing each one of the objectives of the thesis. The light blue boxes indicate the tools and methods applied in each block.

1.4 Outline of the thesis

The following chapters (Chapters 2-5) address the four above-described blocks (recall Figure 1.2). Given that each block builds on the outcome of the previous one(s), there is some level of interconnection between the blocks and consequently between the respective chapters. The structure of the thesis and interrelation between chapters is illustrated in Figure 1.3. The definition of structural design problems and inclusion of sustainability in engineering practice are presented in Chapter 2. Chapter 3 describes the computational engineering methods and tools applied in this work. In Chapter 4, life cycle sustainability performance assessment methods for civil engineering works and structures are presented and applied in a case study. In Chapter 5, different approaches are proposed to integrate the previously described developments with multi-objective optimization methods and the potential of these approaches is assessed. The potential, applicability, and challenges of sustainability-driven structural design are discussed in Chapter 6. Concluding remarks and recommendations for future work are presented in Chapter 7 and 8, respectively.

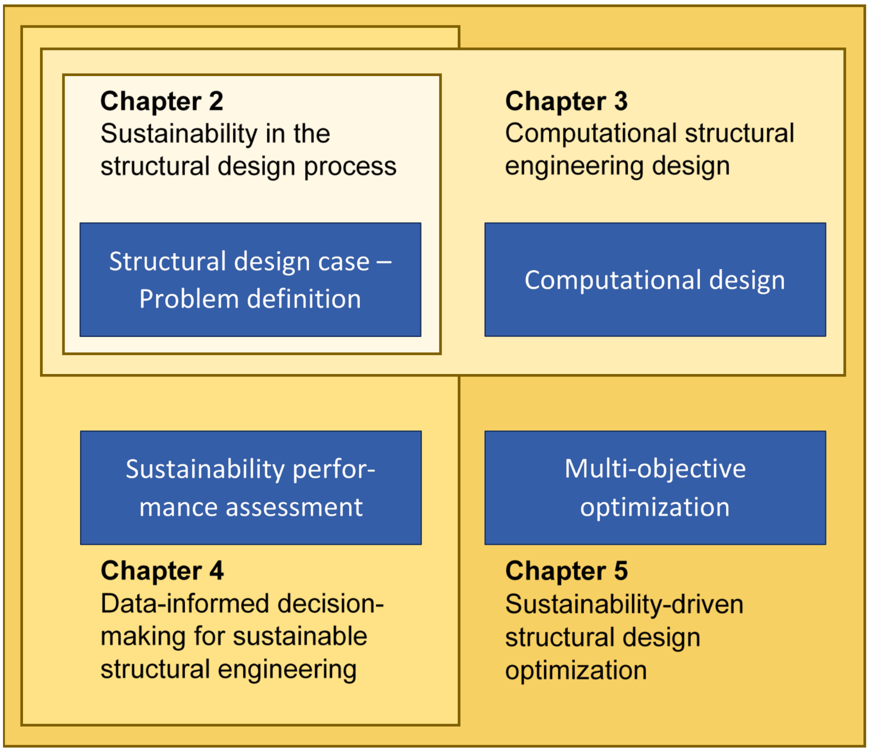


Figure 1.3. Outline of the thesis and relation to the corresponding work blocks (blue boxes).

1.5 Summary of appended papers

Paper A

Today's market of offshore wind turbine support structures is largely dominated by steel structures, since steel monopiles account for the vast majority of installations in the last decade and since new types of multi-leg steel structures have been developed in recent years. However, as wind turbines become bigger, and potential sites for offshore wind farms are located in ever deeper waters and ever further from the shore, the conditions for the design, transport, and installation of support structures are changing. In light of these facts, this paper identifies and categorizes the challenges and future trends related to the use of concrete for support structures of future offshore wind projects. To do so, recent advances and technologies still under development for both bottom-fixed and floating concrete support structures have been reviewed. It was found that these new developments meet the challenges associated with the use of concrete support structures, as they will allow the production costs to be lowered and transport and installation to be facilitated. New technologies for concrete support structures used at medium and great water depths are also being developed and are expected to become more common in future offshore wind installations. Therefore, the new developments identified in this paper show the likelihood of an increase in the use of concrete support structures in future offshore wind farms. These developments also indicate that the complexity of future support structures will increase due to the development of hybrid structures combining steel and concrete. These evolutions call for new knowledge and technical know-how in order to allow reliable structures to be built and risk-free offshore installation to be executed.

Paper B

Standardized and transparent life cycle sustainability performance assessment methods are essential for improving the sustainability of civil engineering works. The purpose of this paper is to demonstrate the potential of using a life cycle sustainability assessment method in a road bridge case study. The method aligns with requirements of relevant standards, uses life cycle assessment (LCA), life cycle costs and incomes, and environmental externalities, and applies normalization and weighting of indicators. The case study involves a short-span bridge in a design-build infrastructure project, which was selected for its generality. Two bridge design concepts are assessed and compared: a concrete slab frame bridge and a soil-steel composite bridge. Data available in the contractor's tender stage are used. The two primary aims of this study are (1) to analyse the practical application potential of the method in carrying out transparent sustainability assessments of design concepts in the early planning and design stages, and (2) to examine the results obtained in the case study to identify indicators in different life cycle phases and elements of the civil engineering works project with the largest impacts on sustainability. The results show that the method facilitates comparisons of the life cycle sustainability performance of design concepts at the indicator and construction element levels, enabling better-informed and more impartial design decisions to be made.

Paper C

Modern structural design faces new challenges, such as addressing the needs of several stakeholders and satisfying the criteria for achieving sustainability. The traditional design process does not enable addressing these challenges well. The purpose of this work is to investigate the applicability of a set-based parametric design method to the structural design process of bridges. The focus is on the early design stage of the design process, in which the design team should evaluate design alternatives against a chosen set of criteria. The main challenge in this stage of design is that the process should be cost- and time-effective while allowing comparison of the different alternatives and their evaluation in terms of the different design criteria. Certainly, structural design is often performed by a discussion between the different stakeholders involved in this process, i.e. the client, contractor, and engineering team. An evaluation of alternatives against criteria requires a more detailed design, which is contradictory to the early design stage when information is scarce. In the proposed method, a script was developed to generate information for decision-making, automate the structural design process, perform common routine design tasks, and control the numerical analysis. The method combined set-based design, parametric design, FE analysis and multi-criteria decision analysis (MCDA). Three existing bridges were used to demonstrate the applicability of the developed method. The method was successfully applied, and it was observed that it resulted in bridges that were more efficient in terms of material costs and carbon dioxide equivalent emissions. By delaying the decisions and developing the sets of alternatives, various alternatives can be assessed and evaluated, in the design phase, against different sustainability criteria.

Paper D

The planning and design of buildings and civil engineering concrete structures constitutes a complex problem subject to constraints, for instance, limit state constraints from design codes, evaluated by expensive computations such as FE simulations. Traditionally, the focus has been on minimizing costs exclusively, while the current trend calls for good trade-offs of multiple criteria such as sustainability, buildability, and performance, which can typically be computed cheaply from the design parameters. Multi-objective methods can provide more relevant design strategies to find such trade-offs. However, the potential of multi-objective optimization methods remains unexploited in structural concrete design practice, as the expensiveness of structural design problems severely limits the scope of applicable algorithms. Bayesian optimization has emerged as an efficient approach to optimizing expensive functions, but it has not been, to the best of our knowledge, applied to constrained multi-objective optimization of structural concrete design problems. In this work, we develop a Bayesian optimization framework explicitly exploiting the features inherent to structural design problems, that is, expensive constraints and cheap objectives. The framework is evaluated on a generic case of structural design of a reinforced concrete beam, taking into account sustainability, buildability, and performance objectives, and is benchmarked against the well-known Non-dominated Sorting Genetic Algorithm II (NSGA-II) and a random search procedure. The results show that the Bayesian algorithm performs considerably better in terms of rate-of-improvement, final solution quality, and variance across repeated runs, which suggests it is well-suited for multi-objective constrained optimization problems in structural design.

Paper E

In this work, we study the potential of using kriging surrogate modelling to perform multi-objective structural design optimization using FE analysis software and design standards while keeping the computational efforts low. A method is proposed that includes sustainability and buildability objectives and it is applied to a case study of reinforced concrete foundations for wind turbines based on data from a large Swedish wind farm project. The method is complemented with sensitivity analyses, which are conducted to investigate the influence of the penalty factor applied to unfeasible solutions and the size of the initial sample generated by Latin hypercube sampling. A multi-objective optimization is then performed to obtain the optimum designs for different weight combinations for the four objectives considered. Results show that the kriging-obtained designs from samples of 20 designs outperform the best designs in the samples of 1000 designs. The optimum designs obtained by the proposed method have a sustainability impact 8-15% lower than the designs developed by traditional methods.

2 - Sustainability in the structural design process: setting the scene

The need to take sustainability considerations into account in structural engineering is generally recognized. Yet the focus on sustainability and life cycle considerations in structural engineering is relatively recent and immature. These new conditions call for changes in the structural design process to address environmental, social, and economic impacts, in addition to structural performance and buildability requirements, already at the early stages of construction projects. In this chapter, the structural design process and the problem of taking sustainability into account in this process are revisited.

2.1 Structural engineering and the structural design process

Structural engineering is defined by the International Association for Bridge and Structural Engineering (IABSE) as "the science and art of planning, design, construction, operation, monitoring and inspection, maintenance, rehabilitation and preservation, demolition and dismantling of structures, taking into consideration technical, economic, environmental, aesthetic and social aspects" [29]. The definition reflects the many facets of structural engineering in relation to different types of structures: buildings, or civil engineering structures, such as bridges, tunnels, and dams. In addition, the structural engineering effort is conducted over different stages of a project and affects the outcome over all the whole life cycle of a structure from the early pre-construction stages to the end-of-life. Table 2.1 summarises design process maps representing the different work stages of a building project as they are defined by various international and national institutions. There is no general agreement on the definition of this complex process, and many of the stages are often overlapping. The process is influenced, for instance, by specific project requirements, and by the type of procurement. A similar mapping can be expected in civil engineering works. The design effort starts with the conceptual design, sometimes followed by the preliminary design, before moving on to the developed design, and finally the technical or detailed design.

Table 2.1. Comparisons of international design process maps for building projects. Reproduced from [30], with permission from the Royal Institute of British Architects (RIBA).

	Pre-Design		Design				Construction	Handover	In Use	End of Life
RIBA (UK)	0	1	2		3	4	5	6	7	
	Strategic Definition	Preparation and Brief	Concept Design	NOT USED	Developed Design	Technical Design	Construction	Handover & Close Out	In Use	NOT USED
ACE (Europe)	0	1	2.1	2.2	2.3	2.4	3		4	5
	Initiative	Initiation	Concept Design	Preliminary Design	Developed Design	Detailed Design	Construction	NOT USED	Building Use	End of Life
AIA (USA)			–		–	–	–			
	NOT USED	NOT USED	Schematic Design	NOT USED	Design Development	Construction Documents	Construction	NOT USED	NOT USED	NOT USED
APM (Global)	0	1	2		3	4	5	6	7	
	Strategy	Outcome Definition	Feasibility	NOT USED	Concept Design	Detailed Design	Delivery	Project Close	Benefits Realisation	NOT USED
Spain			–			–	–	–		
	NOT USED	NOT USED	Proyecto Básico	NOT USED	NOT USED	Proyecto de Ejecución	Dirección de Obra	Final de Obra	NOT USED	NOT USED
NATSPEC (Aus)		-	-	-	–	–	–		–	
	NOT USED	Establishment	Concept Design	Schematic Design	Design Development	Contract Documentation	Construction	NOT USED	Facility Management	NOT USED
NZCIC (NZ)		–	–	–	–	–	–		–	
	NOT USED	Pre-Design	Concept Design	Preliminary Design	Developed Design	Detailed Design	Construct	NOT USED	Operate	NOT USED
Russia			–	–	–	–	–			
	NOT USED	NOT USED	AGR Stage	Stage P	Tender Stage	Construction Documents	Construction	NOT USED	NOT USED	NOT USED
South Africa		1	2	3	–	4	5			
	NOT USED	Inception	Concept and Viability	Design Development	NOT USED	Documentation	Construction	Close Out	NOT USED	NOT USED

Traditionally in civil engineering projects, the structural design process follows a so-called point-based design approach, aiming at reducing costs while satisfying the constraints from the design standards and the detailed specifications drawn up by the client. In this approach, an early choice of a preferred design solution is made and then sequentially adapted in subsequent design steps by trial-and-error and designer's intuition (see e.g. [31, 32]). Therefore, many design alternatives are already discarded at an early stage. This approach often results in the sub-optimization of this early-chosen solution when new information is available as the project advances and stakeholders better define or modify their respective requirements. The ineffectiveness of the traditional point-based design approach has motivated the development of alternative design approaches in manufacturing industries [33], such as set-based design or set-based concurrent engineering. Set-based design and its application to case studies are described in Section 5.1.

The structural design of civil engineering structures must follow design codes and standards. In the European Union, the Eurocodes, a series of ten European Standards, provide the general rules for the structural design of buildings and civil engineering works for common structural materials, as well as for geotechnical design and earthquake resistance. The Eurocodes are completed at the national level by application documents that define national choices for nationally determined parameters and provide complementary information. Other standards need to be used in combination with the Eurocodes for special structures, e.g. wind turbine support structures and dams. The four case studies in **Papers B-E** are based on the use of the Eurocodes, together with the relevant Swedish application documents [34, 35]. In **Paper E**, specific rules and guidelines for the design of wind turbine were also used in complement (e.g. [36, 37]).

2.2 Definition of design concept, design parameters, and design constraints

In this thesis, various structures have been considered: foundations for both onshore (**Paper E**) and offshore (**Paper A**) wind turbines, different types of bridges (**Paper B** and **Paper C**), and reinforced concrete beams that represent basic one of the basic constitutive structural elements of many types of structures (**Paper D**). **Papers B, C and E** are based on real-world construction projects. Therefore, the design concepts that were chosen and developed in these respective projects have been considered in this work to evaluate the potential of the proposed methods to optimize these concepts. In **Papers C-E** parametric design thinking was used (see Section 3.2) to generate different design alternatives.

In **Paper A**, various concepts of concrete support structures for offshore wind turbines that are under development were studied using SWOT analysis. Different aspects were qualitatively assessed in the analysis: sustainability; application range and experience; structural behaviour, durability and design; and buildability and supply chain.

In the short-span road bridge project used as case study in **Paper B**, two alternative design concepts were developed in the tender stage of a design-build road project by one contractor: a concrete slab frame bridge and a soil-steel composite bridge. These two detailed tender estimates included supplier information and cost calculations.

In **Paper C**, the design parameters controlled the cross-sectional configuration of the superstructure of the bridges (e.g. number and dimensions of girders, thickness of the slab, diameter of reinforcement bars). Three common types of medium-span road bridges were investigated: a concrete beam bridge, a steel-concrete composite bridge and a concrete frame bridge. The design constraints included the main necessary verifications for the ultimate limit state (ULS) and the serviceability limit state (SLS) under permanent loads and traffic loads and covering both the construction and the operation phases, with the exception of fatigue limit state that was not included. Not accounting for fatigue was motivated by the fact that, in practice, fatigue verification is commonly not conducted before the last detailed design stage for road bridges. Fatigue is also not included in most similar structural design optimization studies. In a previous study, Perea et al. [38] found that not including deflection and fatigue verifications in the optimization of a concrete frame bridge led to a reduction of the cost of construction about 4%. In contrast, they also observed that not including fatigue verifications had no further impact when deflections were included.

In **Papers D-E**, the design parameters encompassed the dimensions of a reinforced concrete beam and a wind turbine foundation, respectively, and the material properties of the concrete. In addition, the layout of the bending and shear reinforcement of the concrete beam in **Paper D** was also predefined parametrically. In contrast, the reinforcement quantities necessary for the concrete elements are determined through the design in **Papers C-D**. Relevant design constraints were taken into account in **Papers D-E**. Bending and shear design constraints in ULS, and geometrical and buildability constraints were included in both studies, as well as verification of deflections in SLS in **Paper D**. A set of relevant geotechnical design constraints was also imposed in **Paper E**.

2.3 Performance-based sustainability indicators: terminology and definition

Defining requirements at the beginning of a construction project is key to improve the sustainability of structures over their entire life cycle (i.e. from cradle to grave). In this thesis, the hierarchical structure shown in Figure 2.1 is adopted for the definition of requirements and criteria for a project. Requirements refer to general requirements for a project in line with the client's aims. The aims and requirements can also correspond to those from another stakeholder depending on the type of project, contract form, and the phase and perspective considered, e.g. from users, owner, developer, or contractor. Requirements are expressed as functional requirements for a specific structure or structural component.

To assess the compliance of a structure with the functional requirements, these requirements need to be translated to performance-based criteria that are quantitative, verifiable, and predictable. Criteria are called objectives when used in the context of optimization. These criteria/objectives are based on indicators, which measure specific impacts in the different dimensions (environmental, social, economic, buildability, structural performance). Examples of sets of performance-based criteria and indicators for the three domains of sustainability to use in the procurement stage for civil and infrastructure projects is given in [39].

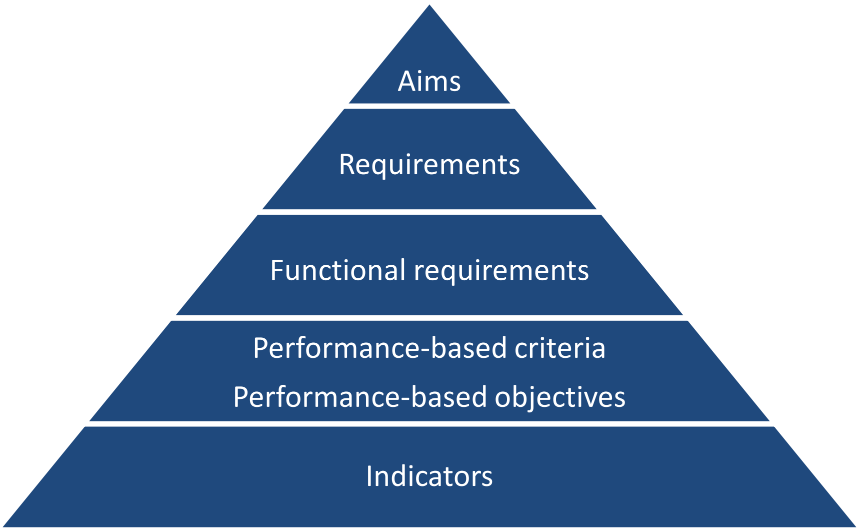


Figure 2.1. Hierarchical structure adopted in this thesis for definition of performance-based criteria and indicators.

In this thesis, the term performance may have a broader or a more specific meaning depending on the context in which it is used. In “structural performance”, “performance of a structure” and “performance-driven structural design” it refers to the ability of a structure to fulfil its function in a safe manner during its service life. In “performance-based procurement” or in “performance-based criteria” it refers, in a more general manner, to the “fulfilment of the essential demands of the stakeholders (i.e. owners, users, contractors, society) during the intended lifetime of structures or structural elements” according to the definition in [40]. Therefore, performance-based criteria encompass all three categories of requirements described in this thesis, i.e. sustainability, buildability and structural performance.

It is important that assessments are performed in a harmonized way and can be compared impartially. Standards have been published in recent years about the sustainability assessment of civil engineering works and buildings, as reviewed in [41]. These standards require that sustainability assessments are performed with a life cycle perspective. Current standards provide the general framework for the sustainability assessment of civil engineering works but do not give detailed guidance on the calculation of indicators and their aggregation [28, 42]. In most studies on sustainability-based design and optimization of bridges, for instance, simplifications are used, and the assessment is based on one or two selected indicators and only covers certain life cycle phases [25], e.g., CO_2 emissions and the cost of construction materials [3] and of transport and installation [43] or embodied energy of construction materials [44].

A civil engineering work’s life cycle includes several stages according to EN 15643-5:2017 [45] that classifies them in so-called information modules: pre-construction stage (Module 0), product stage from raw material extraction to construction material manufacturing (Modules A1 to A3), construction process stage (Modules A4 to A5), use stage relating to maintenance (Modules B1 to B5), use stage relating to operation (Modules B6-B7), use stage relating to the user’s utilization (B8), end-of-life stage (Modules C1 to C4) and benefits and loads beyond the system boundary (Module D), as illustrated in Figure 2.2. This standard has been followed in the sustainability assessments conducted here, and therefore the results are presented and discussed in terms of the standard life cycle information modules A-D.

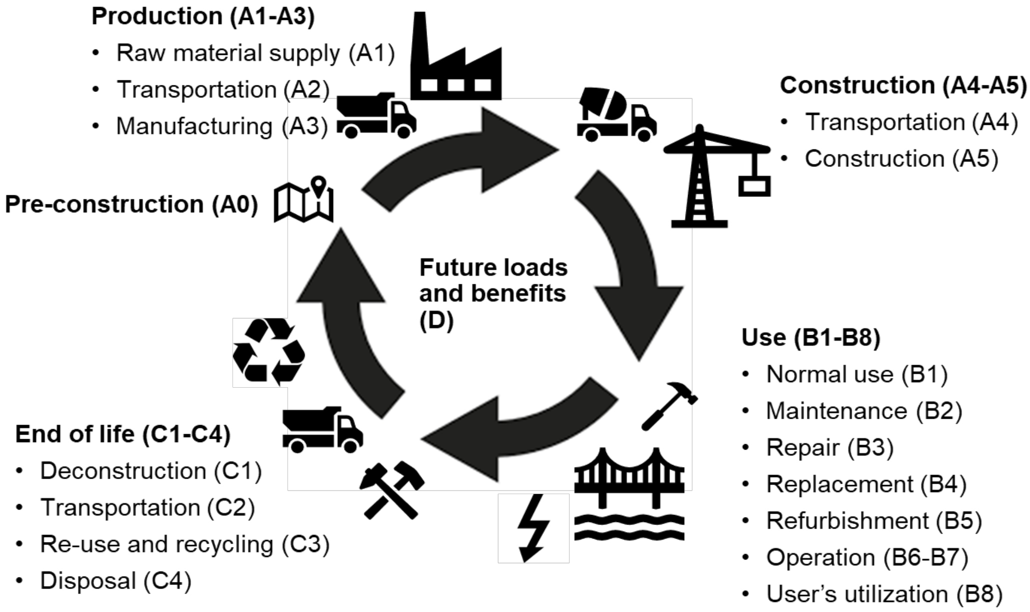


Figure 2.2. Schematic overview of the life cycle stages of a civil engineering works project and their classification in modules according to EN 15643-5:2017 [45], reproduced from **Paper B** [2].

In this thesis, the assessment criteria considered can be divided into three categories: sustainability, buildability, and structural performance. Sustainability criteria have been considered in **Papers A-E**, buildability criteria in **Papers A, D and E**, and structural criteria in **Paper A and C-E**. Sustainability refers to economic, social and environmental impacts that are associated with the constructed object during its life cycle. For buildability, the definition proposed by CIRIA was adopted: "the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building" [46]. As already mentioned, performance refers to structural performance, i.e. the ability of a structure to fulfil its function in a safe manner during its service life.

Requirements for buildability and structural performance may overlap with each other and with sustainability requirements in terms of consequences. However, the division in these categories is justified by the fact that they are connected to different objectives for different stakeholders and by the fact that different information is needed to assess aspects related to these categories. For instance, both buildability and the economic part of sustainability are connected to construction costs. Buildability is more directly connected to the objective of reducing risks for cost-overruns while economic sustainability concerns an estimate of the probability and size of these costs. In general, the buildability criteria require information mostly based on experience and reports from the construction phase and its outcome, while structural performance criteria require information from the operation phase. Sustainability criteria require information from all phases, in general.

Based on the criteria defined in a project, multi-criteria decision analysis (MCDA) methods are used by decision makers to take into account multiple criteria and organise the information in order to make a confident decision [47]. MCDA is well-suited for predictive sustainability assessment and has often been used for this purpose [48–51].

3 - Computational structural engineering design

Technological developments in the last few decades are constantly reshaping structural engineering practice. Today, FE analysis is widely used in practice to compute the load effects used to design structural elements. The development of computer programs and parameterization offers great possibilities to test and evaluate many different design or modelling choices in an automated and time-effective manner. Useful information can be generated in this way and used in the design process. The basis for the computational tools and methods applied in this thesis are described in this section.

3.1 Computational tools for structural design

In engineering practice, the design of common structural elements, such as beams, slabs or walls, was until not long ago mostly performed by hand calculations. The use of computer programs has been developing in the last decades, and the design is now usually done in a similar manner but with help of a spreadsheet program (e.g. Microsoft Excel) or a mathematical notebook program (e.g. Mathcad) using standard equations. Dedicated structural engineering computer programs, that are usually user-friendly, have also been extensively developed in the last decades to calculate the load effects for common structural elements based on analytical or linear elastic FE software that integrate standard design verifications (e.g. FEM-design and Robot Structural Analysis). FE modelling is also useful to analyse the response of unconventional structural elements, for which it may be difficult to use analytical methods. FE modelling allows considering the interaction between different parts and materials and determine complex stress distributions. For more complex structures, structural details, and cases, other methods, such as limit analysis methods (e.g. strut-and-tie models and stress fields for reinforced and prestressed concrete) and nonlinear FE methods, are more adequate but are more time-consuming and require specific knowledge that is not always available in design offices.

The FE simulations, in **Papers C-E**, were performed using the commercial FE package Abaqus/CAE [52], which is a general-purpose FE simulation software application, widely used globally both in research and industry [53]. Further technical details of the models can be found in the respective papers, and they are also briefly described in the following sections.

3.2 Automated parametric design

Since the development of computer-aided design (CAD) tools, parametric design is often used to some extent in today's design process. For instance, some parametric features are often included by structural engineers in their calculation worksheets and are offered by structural design software, leading to some degree of automation. Previous research has shown that the automation of the routine design tasks is a key to a more effective design and construction [54, 55]. However, current structural engineering software most often only offer limited parameterization possibilities. A further step in parameterization and automation, was undertaken in this work by developing parametric design tools that automate the generation, design and analysis of all design alternatives that need to be evaluated. This was achieved in **Papers C-E**, by developing purpose-written scripts using the object-oriented programming language Python. In **Paper C** and **Paper E**, Python scripts were also used to build and analyse FE models of bridges and wind turbine foundations, respectively. This was realized by using the application programming interface (API) of the FE software Abaqus. Other FE software offer this possibility, for instance using programming in Matlab to control the specialized bridge analysis and design software CSiBRiDGE [56].

An important step in parametric design is the definition of the intervals of variation for the different design parameters and of their possible values. In **Paper C**, the possible values assigned to the 3-6 design parameters governing the dimensions of bridge elements, for the three types of bridge considered, led to a few hundreds or thousands of alternatives. When taking into account more parameters with more possible variations, the number of alternatives increases tremendously. In **Papers D and E**, 6 and 8 design parameters were considered, respectively, together with a larger number of possible values, which led to hundreds of millions of possible combinations. Such large number of alternatives makes it clearly unviable to calculate every single case. Statistical sampling methods can be used to calculate a number of them, while ensuring that all design variables are represented along their respective ranges. For instance, in **Paper E**, initial samples were obtained by Latin hypercube sampling (LHS) [57], which allows using different predefined sample sizes. The size of the design space increases exponentially with the number of parameters. For larger design spaces, the use of optimization algorithms becomes necessary to search the whole design space in an efficient manner, as treated in Chapter 5.

To cope with the computationally intensive nature of the series of FE simulations required in this work, the computations were carried out on computer clusters by making use of parallel processing capabilities and resource availability.

3.3 Data management

Automated parametric design generates large amounts of data which needs to be handled carefully to achieve a fine balance between data availability and adequate use of memory and disk resources. On the one hand, only sufficient and necessary data at each step of the analysis and design process should be kept to avoid consuming unnecessary large memory resources with superfluous data. On the other hand, missing data that would have been required for postprocessing and verification may impose to restart the whole process with the consequent additional use of time and computation effort. As a rule of thumb, in automated parametric design, it is a good practice to save specific data not only for the structural design but also for verifications (i.e. testing, debugging and proving) of the programs and models. While the data required in the design is usually well-known in advance, data required for various verifications is more unforeseeable. In this regard, it was helpful, in this work, to gain knowledge and experience of data management and verification by starting with simpler cases and smaller design spaces.

4 - Data-informed decision-making for sustainable structural engineering

A prerequisite to achieving sustainable structures is to be able to make informed and trustworthy decisions in the early design stage when the available information in a project is commonly still limited. In the design phase, defining indicators that best represent each dimension of sustainability is a complex task and efforts have been limited to including a few simplistic indicators so far. The definition and use of more comprehensive sustainability criteria and tools such as life cycle assessment (LCA) databases and methodologies is necessary to enable sustainability-based decision-making by evaluating the consequences of design choices and comparing the performance of different design alternatives in terms of the criteria considered. In this chapter, life cycle sustainability performance assessment methods for civil engineering works and structures are presented and applied in a case study.

4.1 Sustainability-driven decision-making in civil engineering projects

The traditional practice in the design process is to focus almost exclusively on reducing the initial costs, see, e.g., [58–60]. The application of sustainability-driven design in civil engineering projects should be supported by procurement strategies and contract forms based on performance or functional requirements, which encourage and facilitate more sustainable solutions to be developed and values these solutions in an adequate way. Indeed, the most sustainable designs developed need to have a chance to be selected in a procurement process that has traditionally focused on lowest bid prices. MCDA methods can be used to evaluate tenders [39]. However, MCDA is not standard practice as it is challenging to implement, and it is regarded as a source of risk for disputes. As described in [61], to be applied in the procurement stage, assessment methods should be:

- consistent, i.e. the results of the assessment should be coherent and reproducible with low variation;
- transparent, i.e. the method should be predefined, and the assumptions and underlying data used in the calculations should be clearly specified;
- measurable and verifiable, i.e. the assessment should be based on measurable and verifiable information to enable checking the achievement of the performance levels announced;
- flexible, i.e. the method can be used with different sets of performance-based criteria and for diverse projects with minor adjustments.

Although the procurement and its requirements were outside the scope of this thesis, they were taken into account in the development of the harmonized sustainability assessment method applied in **Paper B** (see Section 4.2), so that it could be used in the planning, design and tender phase of civil engineering works projects by the different stakeholders involved [41], e.g. clients or developers, architects, designers or contractors. It is desirable to converge to common sustainability assessment indicators and methods that are applicable by the different stakeholders in the different stages of a project in order to improve comparability, efficiency, and collaboration, and to avoid a proliferation of differently defined indicators and methods.

In today's practice, the inclusion of sustainability in the procurement stage is still limited. For example, Swedish Transport Administration introduced, in 2016, climate requirements, based on life cycle climate calculations and declarations, in the procurement of large construction projects (over SEK 50 million), as well on construction materials in smaller projects and in maintenance projects [62]. Further, the Swedish Transport Administration require since 2015 a climate calculation and declaration for all investment projects is a single-issue LCA tool considering global warming potential. The evaluation of tenders is still based on price but it is complemented by a system of bonus and fines to incentivise contractors to achieve the required reductions in greenhouse gas emissions in line with the predefined baseline set by the Swedish Transport Administration [63].

4.2 Harmonized method for life cycle sustainability performance assessment of civil engineering designs

In most studies on sustainability-based design and optimization of bridges, simplifications are used, and the assessment is based on one or two selected indicators and only covers certain life cycle stages [25], e.g., CO_2 emissions and cost of construction materials, transport and installation [43], and embodied energy of construction materials [44]. The use of simplified and non-harmonized indicators reflects the current difficulty and lack of guidelines for a broader assessment of life cycle sustainability. This situation also raises the question of how well these simplified indicators represent the environmental or sustainability performance of a solution.

To address the need for clear and applicable implementation procedures, a harmonized method for life cycle sustainability assessment and comparison of civil engineering works design concepts was conceptually defined in a preliminary work [41]. The method was further detailed and applied to the case study of a road bridge in **Paper B**. The method includes guidelines for the calculation of environmental, social and economic indicators, using LCA, life cycle costing (LCC) and external costs, following the principles and requirements of methods for sustainability performance assessment given in the standards EN 15643-5 [28] and ISO 21931-2 [42]. The indicators included in the method are presented in Table 4.1.

Table 4.1. Indicators included in the harmonized life cycle sustainability performance assessment method for civil engineering design concepts used in **Paper B**.

Dimension	Category	Indicator
Environ-mental	Acidification	Acidification potential
	Biodiversity	Eco-toxicity potential (freshwater)
		Potential soil quality index
	Climate change	Global warming potential total (fossil + biogenic + -land use and land use change)
	Depletion of abiotic resources—minerals and metals	Abiotic depletion potential for non-fossil resources
	Depletion of abiotic resources—fossil fuels	Abiotic depletion potential for fossil resources
	Eutrophication	Eutrophication potential (freshwater)
		Eutrophication potential (marine)
		Eutrophication potential (terrestrial)
	Ozone depletion	Ozone depletion potential
	Photochemical ozone creation	Photochemical ozone creation potential
Social	Health and comfort	Potential ionizing radiation—human health
		Human toxicity potential—cancer effects
		Human toxicity potential—non-cancer effects
		Particulate matter emissions
		Water user deprivation potential
Economic	Life cycle economic balance	LCC and incomes
	External cost	Environmental externalities

The indicators used in the environmental and social dimensions correspond to the ones currently declared in Environmental Product Declarations (EPD:s) in accordance with the European standard EN 15804 [64]. The indicators are categorized into environmental and social indicators proposed in [41]. All these environmental and social indicators have different units, which requires a way to normalize them and assign them weights defining their relative importance in order to define aggregated scores for the environmental and social performances that are easier to interpret. Aggregation was achieved using the Product Environmental Footprint (PEF) method in which normalization and weighting factors [65] are defined for these indicators. The normalization factors represent the total global impact per person in the world in 2010, based on the EF 2017 method [65] and updated in 2019 [66]. The weighting factors express the severity of the indicator's impact according to Sala et al. [67]. Following the categorization of the environmental and social indicators, the weighting factors were scaled up to a total of 100 for the environmental and social dimensions, respectively. Normalizing and weighting the indicators values in this way to calculate the aggregated environmental and social scores ensures that the performance values obtained for a design concept are not dependent on the performance of other concepts considered, which is important for comparability and optimization purposes.

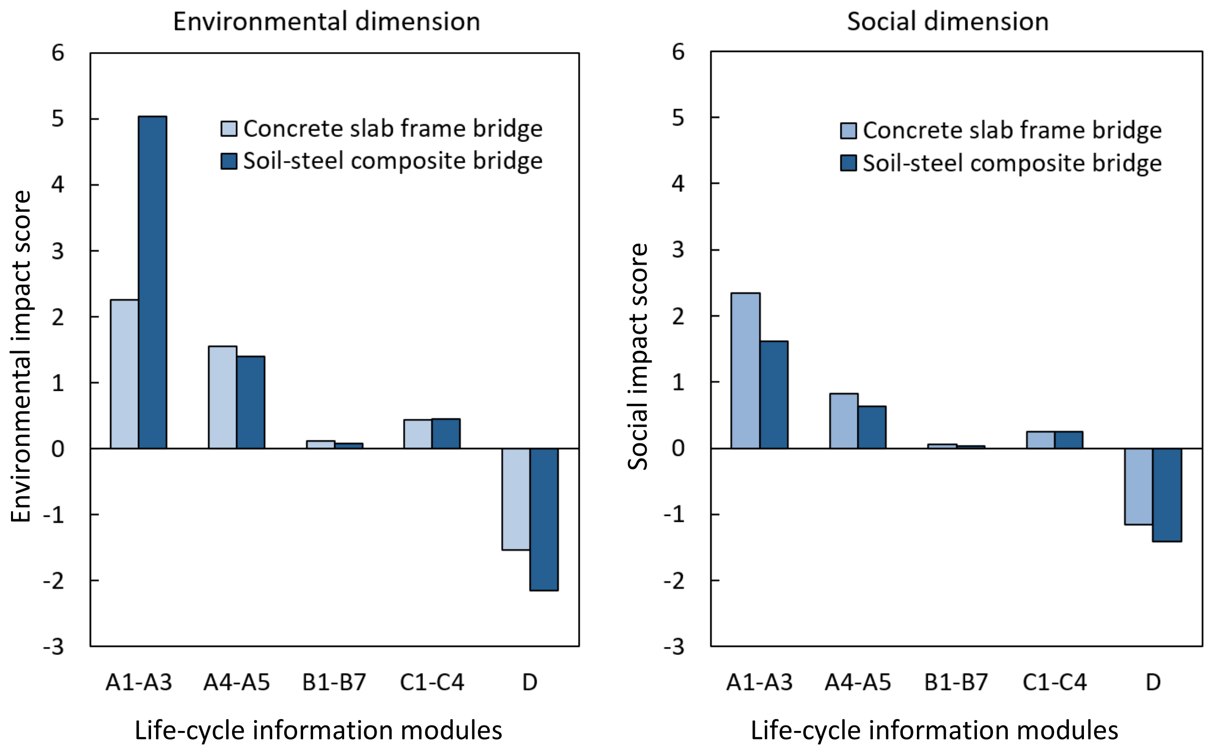
In the economic dimension, the life cycle costing (LCC and incomes) is calculated according to the standard EN 15686-5 [68], and environmental externalities are calculated in accordance with ISO 14008 [69]. These two economic indicators are presented separately as net present value using a discount rate of 3% in line with the prescription of EN 16627 [70] for calculation of economic performance of buildings. Environmental externalities were calculated using the EPS 2015dx method [71].

4.3 Comparison of design concepts for a road bridge

The harmonized method for life cycle sustainability assessment of civil engineering works design concepts was applied in **Paper B** to study and compare the sustainability impacts of two design concepts for a short-span road overpass: a concrete slab frame bridge and a soil-steel composite bridge. The information used in the assessment of these two concepts comes from two detailed tender estimates that were prepared as part of a design-build road project, located between Jönköping and Mullsjö, in southern Sweden. The soil-steel composite bridge concept constituted the basis for the bridge that was later constructed. This case study was selected for its generality and the fact that it built on data available in the tender stage, which allowed evaluating the practical application potential of the method in carrying out predictive sustainability assessments of design concepts in the early planning and design stages.

The assessment of the indicators was done using a life cycle inventory (LCI) in the form of bills of materials (BOMs) for each design concept. These BOMs were based on the tender information for the product and construction stages (modules A1–A5, recall the construction stages in Figure 2.2), completed by defining realistic and representative scenarios for the use (modules B1–B8) and end-of-life (modules C1–C4) and re-use, recovery, and recycling potential (module D) stages, as well as transport modes and distances for resources and wastes. As far as possible, the scenarios were based on project documentation and literature data, if available, as well as expert knowledge. LCA was performed using the LCA software GaBi [72] and selecting the most appropriate LCI datasets available. For the LCC, project data was used consisting in the average market prices for the resources included. The underlying BOMs, scenarios, and datasets used for the assessment are detailed in **Paper B**.

The comparison between the two bridges showed that the concrete slab frame bridge was associated with a considerably lower environmental impact and lower LCC and incomes than the soil-steel composite bridge but with a larger social impact and much larger environmental externalities. Figure 4.1 shows the environmental and social impacts decomposed into life cycle stages for the two bridges. More detailed results are given in **Paper B**. The two impact categories that were found to contribute the most to the environmental impacts were the abiotic depletion and the global warming potentials. Particulate matter emissions were found to represent the main contribution to the social impacts. However, most of the other indicators had significant impacts too. The study highlighted the importance of taking into account all relevant indicators simultaneously in the environmental assessment to obtain a comprehensive assessment of environmental performance over the entire life cycle. For instance, if only the indicator "global warming potential" had been considered in this case study, the soil-steel composite bridge would have performed only 7% worse than the concrete slab frame bridge, while taking into account all environmental indicators, its environmental performance became 60% worse.



(a) **(b)**

Figure 4.1. Comparison of the two bridge design concepts per life cycle stage in **(a)** the environmental dimension and **(b)** the social dimension. Module B8 is not included in the comparison. Reproduced from **Paper B** [2].

When analysing the impacts in the different life cycle stages, results for this case study indicated that the traffic on the bridge during the use phase (module B8) contributed to 38-50% of the total environmental impact, 66-73% of the total social impact, and only 3-17% of the economic impacts over the life cycle (modules A–C) of the two bridges studied. This demonstrated that a significant share of the environmental and social impacts and most of the economic impacts were connected to the bridge itself, i.e. to the type of bridge, its dimensions, the choice of materials, the production method, the need for maintenance and repair, etc. Most of these impacts were found to occur in the production and construction stages (modules A1–A5). The results obtained in this study highlighted the importance of the material production method on the environmental performance of a solution. Non-renewable elements and non-renewable energy resources were found to be the major contributors to the environmental externalities in this case study.

5 - Sustainability-driven computational design optimization

In this chapter, applications of integrated methods for sustainability-driven design optimization of bridges and wind turbine foundations are presented and their potential is evaluated. The methods integrate multi-objective design optimization, structural design based on FE analysis, and multi-criteria assessment in a way compatible with common engineering practice. Several methods are developed using different optimization approaches.

5.1 Set-based parametric design

Set-based concurrent engineering, or set-based design, is a design approach that forms one of the pillars of the lean product development philosophy popularized by the Japanese car manufacturer Toyota [33, 73]. In contrast to the traditional point-based design approach, set-based design relies on postponed commitment to a specific design [32, 73]. The decisions involved in the design process are not made with a single design in mind, instead a large set of alternatives is explored in parallel and progressively narrowed down according to the requirements of the client and the stakeholders involved in the project. In this process, the decision-making is delayed, and it takes place after sufficient information about different design alternatives has been generated. In practice, to implement a set-based design approach, the structural engineer needs to define the initial set of alternatives, as well as to design them. This has been done, in **Papers C-E**, using parametric algorithms. In addition, in a sustainability-driven design approach, the designs need to be evaluated against numerous criteria simultaneously, which results in trade-offs between conflicting objectives.

In **Paper C**, a set-based design method based on parametric design in a multi-objective setting was developed and applied to the design of bridges. The proposed set-based parametric design method follows the theories of integrated design proposed by the American Institute of Architects [74]. Integrated design is closely related to the conceptual design proposed in [75] and it integrates different engineering disciplines involving all stakeholders.

5.2 Multi-objective optimization

Exploring the design space in the search of the designs that simultaneously maximize the utility values of multiple objective functions constitutes a multi-objective optimization problem [76], which requires multi-objective optimization methods. The objectives in a multi objective optimization problem are often conflicting, for instance, the initial cost of a structure can often be reduced at the expense of a longer construction time or higher maintenance cost. Therefore, there is usually no unique solution and the challenge is to reach at a set of solutions providing a human decision maker with a set of diverse objective trade-offs [77]. Additionally, in real-world optimization applications, constraints are generally imposed on the candidate solutions, which may render individual solutions unfeasible despite exhibiting favourable objective values [78]. In structural design, the requirements defined by the design codes and standards such as the Eurocodes [79] form such constraints. The problem to be resolved can be mathematically formulated as follows,

$$\min_{x}\big(f_1(\boldsymbol{x}), \dots, f_m(\boldsymbol{x})\big) \tag{1a}$$

$$\text{subject to} \quad g_j(\boldsymbol{x}) \leq 0, \tag{1b}$$

$$\boldsymbol{x} \in \mathbb{R}^D, \tag{1c}$$

where f_i, $i = 1,...,m$, are objective functions, g_j, $j = 1,...,n$, are constraint functions, and the variable $\boldsymbol{x}$ is a D-dimensional real valued input.

Given a set of multi-objective solutions retrieved in a search procedure, the quality of individual solutions is often classified in terms of Pareto optimality. Again, assuming minimization of m objectives subject to n constraints according to (1), a feasible solution $\boldsymbol{x}^*$ is said to be Pareto optimal, or equivalently, non-dominated, if there does not exist another feasible $\boldsymbol{x}$ such that $f_i(\boldsymbol{x}) \leq f_i(\boldsymbol{x}*)$ for all $i \in \{1, 2,...,m\}$ and $f_j(\boldsymbol{x}) < f_j(\boldsymbol{x}^*)$ for at least one j [80]. In order to determine the quality of a solution set in a multi-objective optimization problem, the hypervolume indicator measure is commonly employed [81].

Structural optimization of reinforced concrete structures tends to be computationally expensive because of the expensive constraint function evaluations using FE simulations and the need to analyse different load cases, especially in the case of bridges and wind turbine support structures. Various evolutionary algorithms have been studied [82, 83], however without explicitly dealing with the computationally expensive parts of the problem. In this context, the use of surrogate models (also called metamodels) has the potential to reduce the computational expense associated with the constraint function evaluations. A surrogate model is a mathematical response surface approximation that is used to predict an output from a set of inputs [84]. There are different types of surrogate models, some of the most notable ones being polynomial models, moving least-squares, radial basis functions, support vector regression, gaussian process regression and kriging, and artificial neural networks [85].

Gaussian process regression and kriging [86, 87] are increasingly popular surrogate models, which are known for their versatility and efficiency in providing accurate predictions [85]. These types of models are also less computationally expensive than artificial neural networks as they usually require less function evaluations [56, 84, 88]. Although kriging has often been applied in other fields, applications for structural optimization of civil engineering structures are still limited but have indicated good potential to handle the standard design constraints typical of structural engineering design problems [88, 89]. In particular, Penadés-Plà et al. [44] constructed and optimized a constraint-weighted surrogate model, based on prior evaluations sampled from a latin-hypercube, to find the best design for a concrete bridge design case. Their results showed that kriging-based heuristic optimization could reduce the computational time by more than 90% compared to conventional heuristic optimization without unduly affecting the quality of the obtained solutions [44].

Building on the surrogate-based heuristic optimization process presented in [44], **Paper E** extends it by integrating FE modelling for the structural analysis and design, and a comprehensive set of sustainability and buildability criteria assessed in a life cycle manner, while focusing on a different type of structure: onshore gravity wind turbine foundations. In contrast to this approach, Bayesian optimization, as investigated in **Paper D**, allows surrogate models to be constructed sequentially, utilizing information from prior evaluations at each iteration, while guiding the search procedure, which should decrease the sensitivity to poor initialization.

Bayesian optimization has emerged as a capable approach to optimizing expensive functions by iteratively constructing a probabilistic surrogate model of the underlying target function, and has had many previous successful applications, e.g. [90–92]. It makes use of an acquisition function to convert the surrogate model to a metric reflecting the potential for improvement, which is in turn used to guide the optimizer toward a promising new query point.

5.3 Set-based design of three types of road bridges

The method proposed in **Paper C** combines set-based design, parametric design, FE analysis and multi-objective optimization. The method is based on the generation of numerous design alternatives by varying design parameters (e.g. dimensions, material properties, etc.) based on predefined ranges of variation. The automation of the method is based on a script, developed in Python, capable of performing the routine design tasks, controlling the numerical analysis as well as the MCDA process, and generating information for a large number of bridge alternatives. This approach allows for user-defined parallelization of the computations by grouping the design configurations in sets analysed independently. A flowchart of the script, developed in **Paper C**, is presented in Figure 5.1.

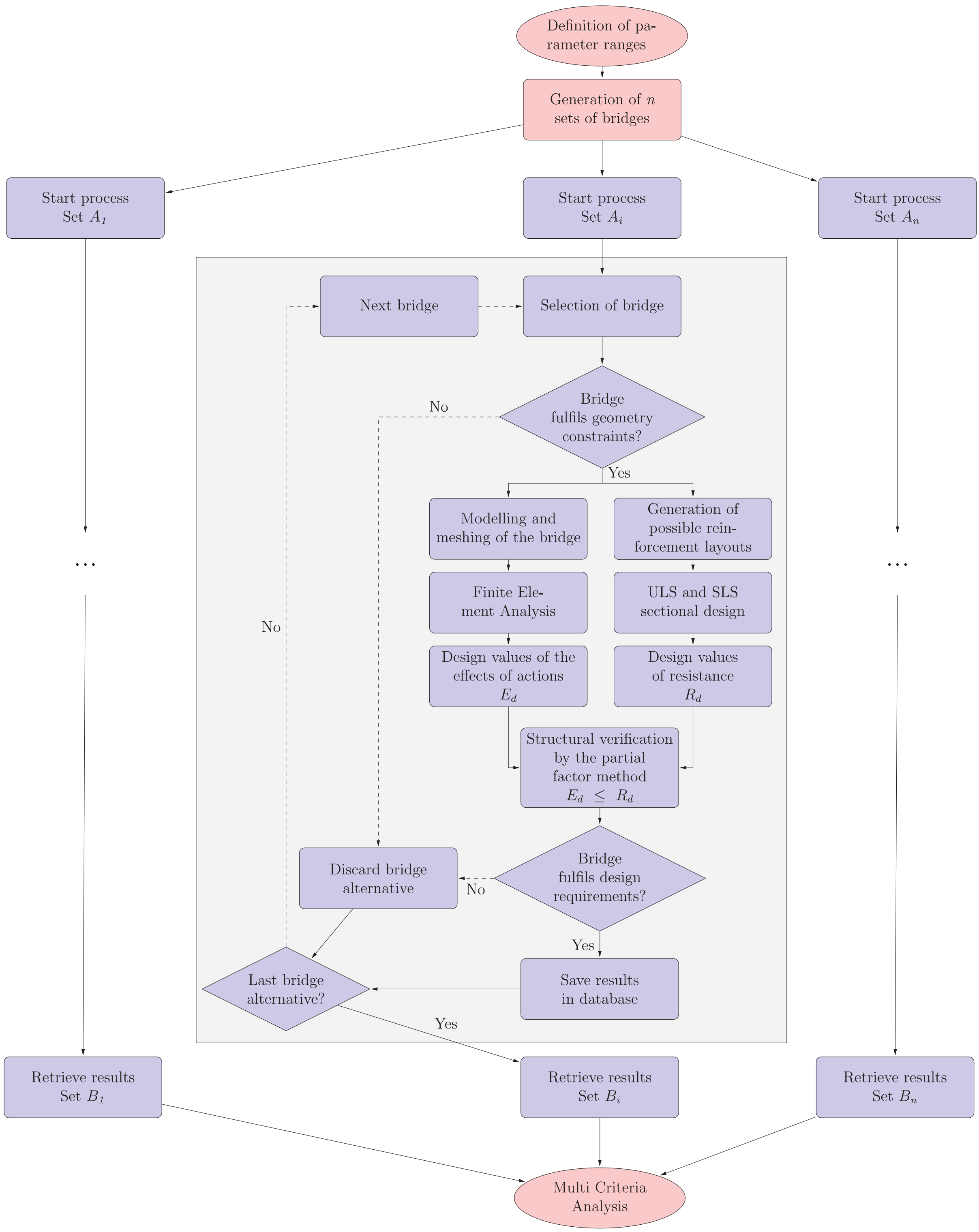


Figure 5.1. Flowchart of the set-based parametric design method, reproduced from **Paper C** [3]**.**

The method was applied, in **Paper C**, to three different bridge design projects to assess the feasibility of a large number of alternatives and to generate information about these alternatives in order to compare them. Three bridges were considered, using data from real-world projects conducted in Sweden. These bridges correspond to three common types of medium-span road bridges: a concrete beam bridge, a steel-concrete composite bridge, and a concrete frame bridge.

The number and types of parameters were similar in the three cases: five for the concrete beam bridge, six for the steel-concrete composite bridge, and three for the concrete frame bridge.

The proposed method allowed automating the design process to a high level in the three design cases in order to evaluate numerous alternatives. Results showed that the best designs obtained with this method had a 20-60% lower material cost and embodied carbon compared to the existing bridges designed using a traditional point-based design approach. This result is illustrated in Figure 5.2 for the design case of the concrete beam bridge. The data generated can be used in an integrated design process to support decision making in the early design stage based on all relevant sustainability, structural performance or buildability criteria using an MCDA method.

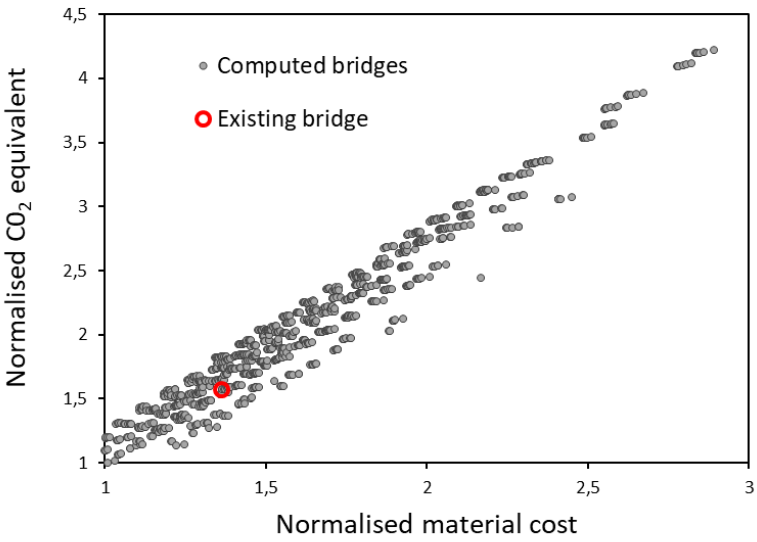


Figure 5.2. Estimated material cost and CO_2 equivalent emissions for several hundred variations of a concrete beam bridge. Results have been normalised by dividing all values by the minimum value obtained for each criterion. The red mark indicates the corresponding values for the existing bridge. Elaborated from results in **Paper C** and reproduced from [93].

5.4 Bayesian optimization of reinforced concrete beams

In **Paper D**, a state-of-the-art constrained Bayesian optimization algorithm was proposed, that was specially adapted to structural engineering design optimization problems incorporating multiple objectives. The algorithm explicitly utilizes the fact that objective functions are cheap to evaluate while constraint functions have expensive evaluations, which is common in structural engineering design problems, as constraint function evaluations commonly require expensive numerical computations.

The proposed algorithm builds on the Bayesian optimization approach for expensive, unknown-constraint optimization proposed for one-dimensional optimization problems by Gelbart et al. [94]. The authors suggested a constraint-weighted acquisition function based on the expected improvement criterion [95] using separate Gaussian processes [96] to model both the objective function and each constraint functions. It is further developed in **Paper D** to handle the multi-objective setting while taking advantage of the cheap objective evaluations, by replacing the expected improvement by the actual hypervolume improvement. A pattern search [97] algorithm was used to optimize the acquisition function. A flowchart of the proposed Bayesian algorithm is shown in Figure 5.3

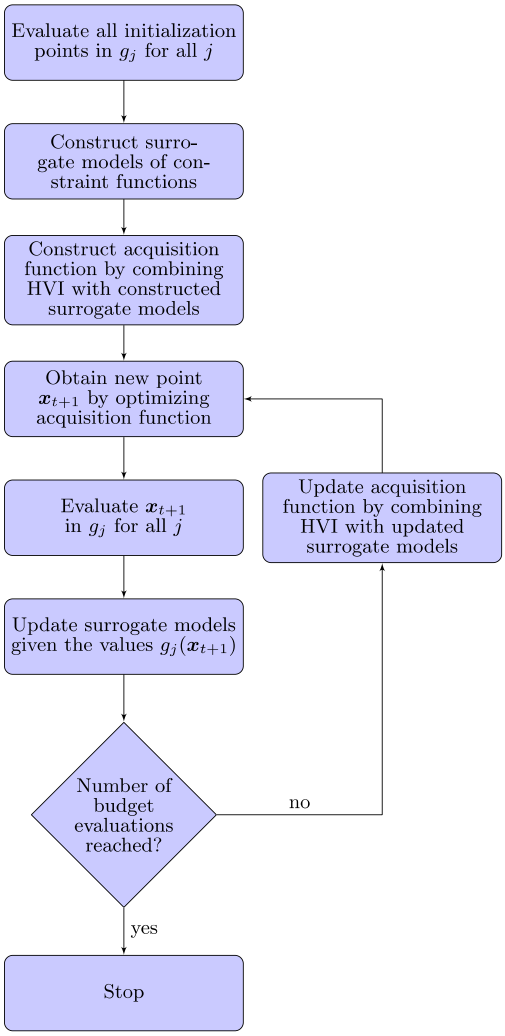


Figure 5.3. Flowchart of the proposed Bayesian optimization algorithm, reproduced from **Paper D** [4]**.**

A benchmark problem was defined to examine the efficiency and applicability of the proposed Bayesian optimization algorithm on a generic structural design case. The problem consisted in optimizing a doubly reinforced concrete beam over eight design parameters (corresponding to the dimensions of the beam, the reinforcement layout and the concrete strength class) with respect to five relevant objective functions (covering economic, environmental, social, buildability, and performance aspects of the design options), while fulfilling four structural design constraints (including verifications in ULS, SLS according to design codes and a buildability constraint for placing of the reinforcement).

The proposed Bayesian algorithm was benchmarked against two other optimization algorithms: an adapted random search algorithm and the commonly applied NSGA-II algorithm [98], which is a genetic algorithm specifically targeting multi-objective problems. The three algorithms were compared by running 25 independent optimization runs with an allowed budget of 1000 expensive constraint evaluations.

Results showed that the Bayesian algorithm exhibited by far the best performance, as shown in Figure 5.4. It could be observed that the Bayesian algorithm yielded considerably larger hypervolume than both the random search and the NSGA-II algorithms. It surpassed the end-of-run results of both these algorithms already after 150 constraint evaluations. In addition, the hyperparameter tuning procedure applied to the NSGA-II algorithm prior to algorithm evaluation is not desirable for practical applications in expensive constraint evaluation settings.

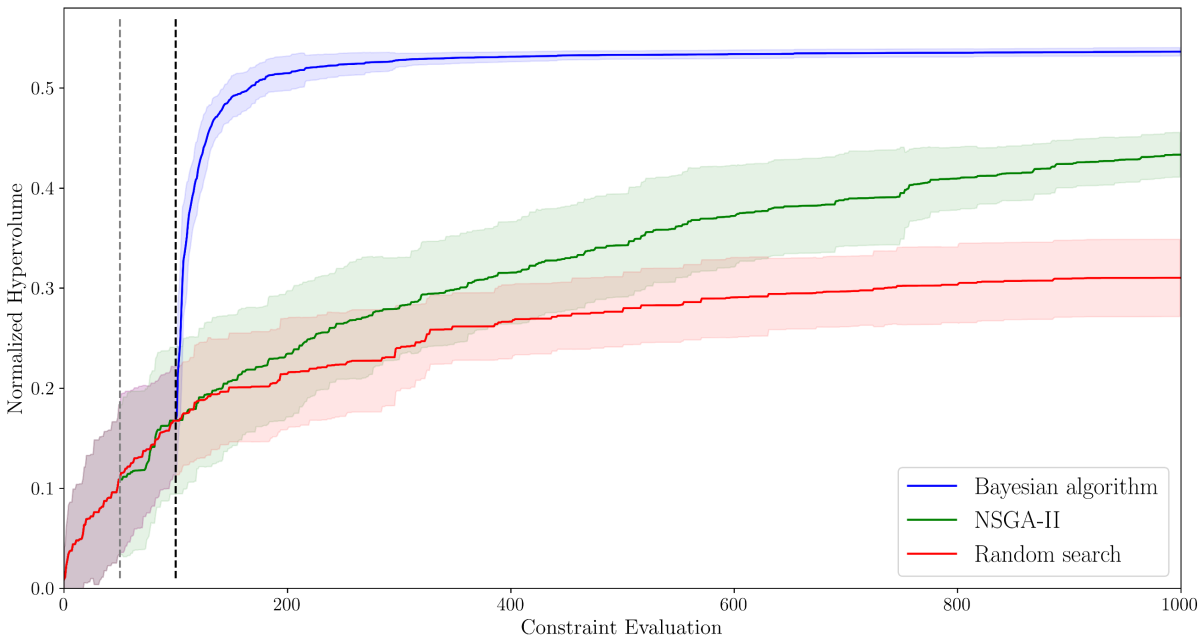


Figure 5.4. Normalized hypervolume improvement as a function of the number of constraint evaluations for the three examined algorithms in **Paper D**. The solid lines indicate the average, obtained from 25 runs with seeded initialization. The upper/lower limits of the shaded areas represent ±1 standard deviation from the average. For the Bayesian and the random search algorithms, each run was initialized with 100 inputs generated by seeded randomized sampling (marked by the dashed black line). For the NSGA-II algorithm, only the first 50 inputs per seed (marked by the dashed grey line) were used due to its population-size hyperparameter being set to 50. Reproduced from **Paper D** [4].

5.5 Kriging surrogate-based optimization of wind turbine foundations

In **Paper E**, the potential of using kriging-based surrogate modelling to achieve structural design optimization taking into account sustainability and buildability objectives was investigated. This work sought to propose a practical application of a multi-objective optimization method with a reasonable trade-off between accuracy and complexity. The method was intended to be compatible with real world engineering practice, i.e. integrating structural analysis with the FE method, verifications according to design codes, and requiring a limited number of the expensive constraint function evaluations while keeping the optimization procedure relatively simple.

The proposed method was applied to a case study dealing with the design optimization of wind turbine foundations of a Swedish wind farm project, where information from the product and construction process stages was accounted for in a life cycle approach. The optimization problem consisted in optimizing a circular reinforced concrete gravity foundation over six design parameters (dimensions of the foundation and concrete strength class), with respect to four objective functions (covering environmental, social, economic and buildability aspects), under six geometrical and geotechnical design constraints.

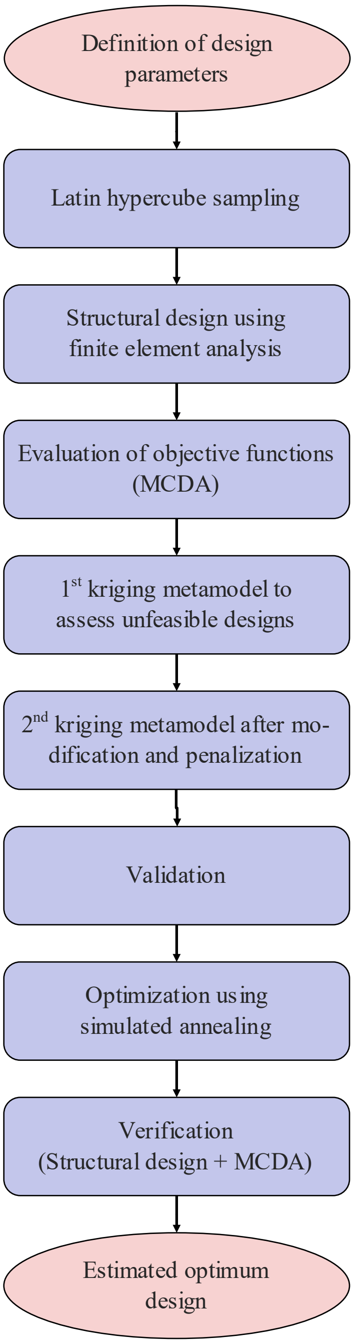


Figure 5.5. Flowchart of the kriging surrogate-based optimization process proposed in **Paper E**.

The optimization was conducted in two steps. First, sensitivity analyses were performed in a mono-objective optimization setting to study the influence of the sampling size and of the penalty factor applied to unfeasible solutions. To do so, a sustainability index was defined and used as single objective function by considering the four objectives considered equally important. Second, a multi-objective setting was adopted by repeating the optimization process several times for different combinations of the relative weights of the four objectives to obtain a Pareto set of designs that forms a preferred trade-off between the sustainability and buildability objectives considered.

As it is often the case, in the real-world industrial project on which this case study was based, the technical design was first conducted using the design configuration developed in the predesign stage of the project due to limited time. This design was then refined in a trial-and-error manner inspired by engineering judgment in an attempt to reduce material quantities. In this second step, around ten solutions were investigated. However, the configuration used in the predesign had a definite influence on these results as the iterations started from it, which is mostly explained due to time limitations to select a design to be further developed (e.g. to produce the full technical design, the technical drawings and specifications, etc.). As a consequence, many possibly better-performing configurations were obviously disregarded at this stage.

Using parametric design allowed calculating a much larger number of design configurations, i.e all the initial LHS-generated design configurations. Additionally, the use of surrogate models allowed exploring the whole design space without computing the expensive constraint functions. The sustainability performances of the designs obtained using the different design approaches are represented in Figure 5.6. This comparison revealed that the optimum design obtained by kriging had a sustainability index 15% lower than the original predefined design and around 8% better than the best design obtained by trial-and-error improvement. This rate of improvement certainly depends on the quality of the predesign and of the engineer's experience and judgment in the trial-and-error improvement process. It also usually requires a larger effort to be implemented (see Figure 5.7). However, it clearly appears that the use of parametric design and kriging-based optimization can lead to substantial improvement of the sustainability of the structure.

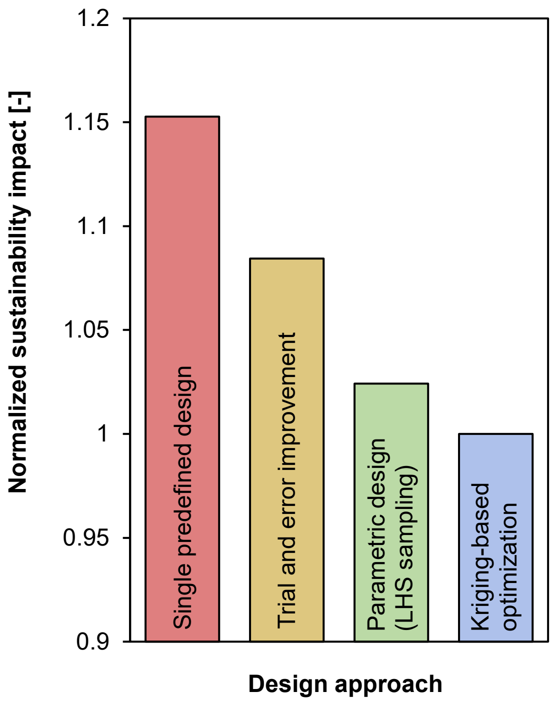


Figure 5.6. Comparison of the sustainability performance of the optimum design obtained using the different design approaches. The sustainability impact values are normalized by the lowest impact value (obtained using kriging-based optimization). Elaborated from results from **Paper E** [5].

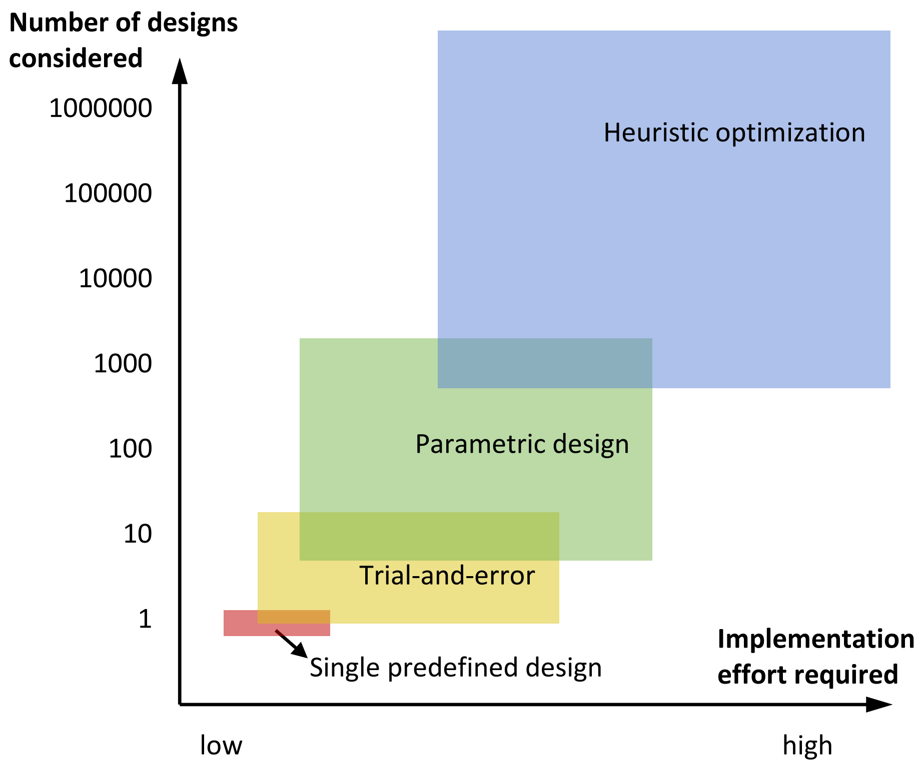


Figure 5.7. Description of different design approaches and corresponding approximate number of design configurations considered, and implementation effort required.

6 - Discussion

The focus of this thesis has been on developing methods that enable taking sustainability objectives into account in the design of structures. The methods should not only allow assessing the sustainability impact of design solutions over their entire life cycle but also using the outcome of the assessment to drive the design process towards more sustainable designs. For these methods to have a significant impact in practice, it is important that they are applicable for structural engineering practitioners. This means that the methods should follow standard requirements, be compatible with structural design tools, and make use of available information for criteria assessment. The four case studies included in this thesis provided insight into the potential, applicability, and challenges of the methods, which are discussed in this section.

6.1 On the potential and applicability of the explored methods

When it comes to sustainability-driven design optimization methods, it is challenging to fairly assess their potential, which includes both the sustainability improvement potential of the structural designs and the performance of the optimization methods. The potential of the explored methods was evaluated, in this work, in different manners and at different levels. In **Paper C**, the potential of the proposed set-based parametric design method was assessed by comparing the best theoretical designs found with the ones that were built in three real-world bridge projects. In **Paper D**, a representative benchmark problem was defined to compare the performance of the proposed Bayesian optimization algorithm with that of two other commonly applied algorithms. In **Paper E**, the potential for sustainability improvement (8-15%) of a foundation element was evaluated by comparison to the foundation design originally developed in a real-world wind farm project. The performance of the optimization method was also evaluated against those obtained through the initial sampling. **Paper C** highlighted that the use of a set-based parametric design approach to automate the design process in order to find optimum designs could lead to significant reductions in terms of cost and greenhouse gas emissions. Reductions of more than 20% were achieved for the three types of bridges included in the study. A similar potential for improvement (10-15%) in terms of material and labour costs and environmental impact was found by Chalouhi et al. [99] using heuristic optimization on a multi-span reinforced concrete beam bridge. In both cases, the improvement potential was estimated by comparing the optimized designs to the bridges that were built in the respective real-world projects that constituted the basis for these case studies. The above-mentioned studies confirmed a clear potential for sustainability improvement, yet the actual magnitude of that improvement inevitably depends on the quality of the reference design used for comparison.

Paper A exemplifies, for the specific case of offshore wind turbine foundations, the wide variety of conceptual designs available, which represents the first level of design choices in the search for sustainability improvements. It is not possible to state which type of structural concept is the best for different applications, due to the different conditions encountered (loading conditions, soil and terrain, environmental conditions, etc.), which influence the choice of a structure, its design, and its production and installation methods. Hence, the choice of the initial set of reasonable design concept needs to be decided on a case-by-case basis. Once the initial design concepts are selected, their sustainability performance can be quantified and compared with the proposed methods regardless how different the design concepts are. This process and the resulting potential for sustainability improvement in the early phase of the project was illustrated in **Paper B**, by comparing the sustainability of two design concepts developed in the tender stage of a bridge project. The analysis of the two bridges concepts was done using exclusively data that is available in the early planning and design stages of a project, which demonstrated that the life cycle sustainability assessment method applied could be effectively used to transparently assess and compare the sustainability performance of civil engineering works design concepts even in such an early stage.

Additionally, the analysis of the results obtained in **Paper B** provided understanding of the types of impacts over the different life cycle phases and their relative magnitude. A key outcome was the identification of the critical components of the civil engineering works project that contribute the most to these sustainability impacts. This information indicates where to focus in the planning and design process to make effective adjustments or take special measures to achieve more sustainable design concepts. The case study supported that to reduce the overall negative impact on sustainability, mitigation measures should primarily address the production and construction phases of civil engineering construction works.

An important feature of the harmonized sustainability method applied in **Paper B** is that it is built to facilitate automated assessments. The method makes use of quantitative indicators, and the result obtained for one case does not depend on the results of other cases, since fixed standard factors are used in the aggregation of environmental and social indicators. Therefore, the assessment does not require human judgment, allowing a calculation process in the form of a fully digitalized automated system. New design concepts can be assessed without affecting the results of previously calculated ones, which is particularly interesting for using the method in combination with design optimization algorithms, such as those proposed in **Papers C-E.** Moreover, the use of multi-objective optimization methods, as investigated in this thesis in **Papers C-E**, is especially interesting for uncoupling the determination of the relative weights of the objectives from the design and optimization process. This separation allows solving the multi-criteria decision-making problem in parallel or after the design stage and do not make the structural engineer dependant on this information, which usually involves subjective judgments and may be subject to late changes during the design process. Therefore, although it takes longer implementation time, it has the potential to reduce rework and delays in the design phase. In the decision-making process, it is possible to aggregate the different sustainability dimensions using an MCDA method to obtain an overall sustainability score [39, 47, 50].

In order to search a larger design space, while keeping the computational time low, surrogate-based optimization approaches were explored in **Papers D and E**. In both cases, satisfactory results were obtained in terms of computational time and quality of the trade-offs. The limited number of function evaluations required in both cases is particularly interesting to enable performing structural calculations using an FE analysis software, whose computational cost usually limits the number of possible evaluations and hinders their application in structural design optimization problems. In **Paper E**, the complexity of the kriging metamodel was kept low to facilitate its practical applicability. In more complex structural design optimization problems, further improvements can be included in the method, for instance by updating the kriging metamodel with infill points during the optimization process, in a manner similar to the one proposed in the Bayesian optimization algorithm in **Paper D.** It is worth mentioning that recommending a specific optimization algorithm, on the grounds of performance comparisons derived from specific problems may be dubious. Care should be exercised when doing such generalisations, in respect to the "no free lunch" theorems [100]. In this work, choices made in the optimization strategies were motivated by structural design problem-specific aspects, therefore, good performance of the optimization algorithms applied here are expected for other structural design problems.

In this work, the design parameters considered when optimizing designs in **Papers C-E** were related to geometrical dimensions of the structure, the type and quantity of reinforcement bars, and the concrete material strength. The methods were applied to common design concepts as they are representative for a large share of the infrastructure stock. The sustainability-based structural design methods studied in this thesis can be applied in all stages of the design process, from the conceptual design to the detailed/technical design (recall Table 2.1). When applied in earlier stages in the design and decision process, broader planning and design choices may be included and progressively narrowed down in a set-based design approach using these methods. Different structural concepts could be optimized in parallel, for instance the two bridge design concepts considered in **Paper B**, or some of the traditional and more innovative concepts of support structures for offshore wind turbines identified in **Paper A**. Materials and products from different suppliers could also be considered as design parameters, since, for instance, different mechanical characteristics, prices, geographical location and EPD would influence the results. The optimization of the different design concepts allows their fair comparison provided that similar levels of detail are used for their analysis and design. The comparison may provide valuable insight on the relative performance of structural engineering solutions or their domain of applicability, and ensures a good basis for decision.

6.2 On the level of detail in the structural design process

A critical question that needs to be addressed early in the process of sustainability-driven design optimization is, how detailed do the structural analysis and design need to be? Indeed, simplifications are ineluctable in the structural design process, as the structural analysis models used to determine the load effects and the design methods used to determine the capacity of structural members are approximations of reality, which are associated with different degrees of accuracy. In the design optimization process, it is important to keep in mind that the sustainability performance of the optimum designs found, depends, beyond their optimization, on the accuracy and level of conservatism of the structural analysis and design methods used. It is common to justify the simplifications and assumptions made in the structural design process by the fact that they are on the safe side. While the contrary would be inappropriate, too conservative simplifications lead to over-consumption of materials, which has a direct impact on the sustainability of the structures. In addition, when comparing significantly different design concepts, it is also important to seek that they are designed with similar degrees of accuracy, which is often difficult to ensure. Especially in the conceptual or preliminary design stages but even for detailed designs, the differences in terms of accuracy between the simplified methods used can be significant. Such differences may lead to the premature conclusion that an alternative is less interesting only because an overly conservative method was used.

A strategy called the levels-of-approximation (LoA) approach was introduced in Model Code 2010 [40] for the design and assessment of concrete structures. The choice of the LoA involves a trade-off between the level of detail of the method used and the time required for its implementation. It is recommended in [40] to progressively increase the accuracy over the successive stages of design, which is often limited in the early design stages. When doing so in combination with sustainability-driven design optimization, there is a risk that some optimized solutions are no longer feasible when including additional design verifications, as optimized solutions can be expected to often be found near the boundaries of feasibility regions. This challenge was recently observed by Skoglund et al. [101], when optimizing the girders of a composite steel-concrete bridge under ULS and SLS design constraints, which indicated that the use of high-strength steel had the potential to lead to better designs in terms of the objectives considered (weight, cost and CO_2 equivalent emissions). However, when including fatigue verifications, the authors found that none of these optimum designs fulfilled the verifications [101]. In practice, it is not always possible to know in advance which verifications are the most limiting or when additional details will reduce the set of feasible solutions. The experience of the designer supported by preliminary tests can help to identify the adequate level of detail in the analysis of the solutions. The use of an adapted set-based design approach in the optimization process can also overcome this issue by retaining a larger number of designs in the successive design stages.

The use of refined models and analysis methods, for instance non-linear analysis has the potential to lead to further improvements but it is often accompanied by high computational costs and added complexity. The development of computing power and practical application guidelines [53] may support the wider use of such methods in the future. The development of alternative methods, such as two-scale FE (FE_2) methods [102], may also help reduce computational time and modelling complexity for large reinforced concrete structures.

6.3 On the need for comprehensive and evidence-based sustainability indicators

Both simple and more refined assessment criteria have been used in the studies conducted in this work. The methods developed are relatively flexible as they can accommodate new criteria, either to adapt to a specific project or stakeholder's preferences, or to take into account the new scientific knowledge and developments in life cycle sustainability assessment. Sustainability assessment methods need to follow the state-of-the-art knowledge related to the different impacts and their consequences, as fulfilled by the harmonized method proposed for sustainability assessment of civil engineering works in **Paper B**.

Simple indicators can help to improve specific aspects of a design, yet they only allow reaching an incomplete picture of the sustainability performance of a solution. For instance, it was found in **Paper B**, that the relative environmental performance of the two bridges compared would have been significantly different if only the global warming potential had been considered instead of all the environmental criteria included in the method. This observation is important, corroborating previous studies [103], as today, it is common practice to solely consider global warming potential (or one other indicator such as embodied energy) in order to assess the environmental performance [44, 103, 104]. Additionally, too simplified sustainability indicators can lead to inaccurate correlation between them, for instance due to an overestimated dependence on the quantities of materials. When using simplified indicators in **Paper C**, a strong linear positive correlation between CO_2 equivalent emissions and cost was found, as also argued by other authors [43, 105]. This type of correlation implies that improving the performance for one of these indicators would indirectly improve the other one, which was not the case when more detailed sustainability indicators were used in **Paper B** to compare two markedly distinct bridge design concepts. This discrepancy can be attributed to the fact that the assessment presented in **Paper B** covers more sustainability impact categories with a more accurate life cycle inventory over the whole life cycle of the bridges. Similar observations have been made in previous studies, e.g. [106].

Sustainability assessment is complex due to many conflicting aspects that need to be accounted for; the difficulty to define aggregated impact indicators; and the fact that environmental and social impact results are highly dependent on the LCA datasets chosen for the calculations. As the LCA in the method applied in **Paper B** is done in accordance with the EN 15804 + A2 standard [64], it makes it possible to use data sources that follow this standard i.e. both generic datasets from LCA databases, and Environmental Product Declarations (EPDs). Generic datasets were used in this case study, since supplier specific EPDs that follow EN 15804 + A2 [64] were not yet available. However, the use of supplier EPDs instead of generic datasets is recommended, as EPDs would further increase the accuracy of the environmental and social assessment results for a specific construction project. Indeed, EPDs contain supplier-specific declarations, while generic datasets do not take into account the specific production processes and transport distances for the resources purchased in the project and may therefore be less representative. Easy access to LCA and EPD data is an important prerequisite for a more widespread use of the method and of LCA in the construction sector. LCA and EPD data sources are becoming increasingly available, global databases regrouping different sources are being developed, and the use of the machine-readable ILCD format is becoming more common [107].

A current limitation of the method is the small number of social indicators currently included and the non-inclusion of social externalities. This limitation is due to the fact that until now less focus has been given to the social dimension for which indicators and data are not as well-defined and available as for the environmental and economic dimensions. However, as the proposed method follows the principles of published standards, it can easily be further developed when new or updated standards or indicators are published. Besides, open-access EPDs and LCA data are sufficient to apply the method, which promotes a widespread use as well as fair competition. Due to its general character, the method can be also applied to other types of civil engineering works, not only bridges, or even to buildings provided that appropriate scenarios are used to define the specific processes, for instance related to the operational use of energy and water during the use phase.

Assessing the consequences that design choices, made in the early planning and design stages of a project, will have during construction and the whole life cycle of a structure requires information to evaluate or compare alternatives according to different criteria and scenarios. While some aspects depending mainly on material consumption and equipment used can be relatively easily assessed, other related to buildability and structural performance may require information from the construction or operation phase that is not yet available in the design phase. To this end, it is important to collect data from the construction, use, and end-of-life phases of ongoing projects in order to reuse this knowledge and experience to verify and refine scenarios, and to motivate choices in future projects [24]. Sensitivity analysis could help to assess the influences of different scenarios and datasets whose uncertainty is considered important for the evaluated impacts.

6.4 Prospects of sustainability-driven structural design

The case studies in **Papers C-E** focused on the potential and applicability of sustainability-driven design optimization methods. This focus motivated the inclusion in the studies of a limited number of structural design parameters of ordinal type (dimensions, reinforcement layout, concrete material strength). Consequently, the revealed room for improvement only reflects a part of a larger unexploited improvement potential that can be reached using sustainability-driven structural design methods. The alternative structural concepts studied in **Paper B** and the scanning for innovative technologies in **Paper A** exemplify a wider spectra of design alternatives that can be considered in sustainability-driven design. The methods offer unlimited possibilities to cover the comparison of different concepts (e.g. different structural systems and innovations), different materials (e.g. concrete with supplementary cementitious materials), different material production methods (e.g. materials from different suppliers), or different project requirements (e.g. service life). A set-based design approach could here play a key role in broadening the variety of initial design options. Optimizing these different design options, could be done in parallel or by including categorical values (e.g. structural element or material types), or even conditional ones (e.g. dimensions dependent on the choice of structural element) in the optimization problem settings, for instance building on the achievements by Sjöberg et al. [108] for hyperparameter optimization in Bayesian optimization.

Multi-criteria sustainability assessment methods are not yet common practice in the procurement of infrastructure projects, but some contracting authorities already include environmental aspects in their procurement strategy, as previously mentioned in Section 4.1. Further dissemination of these methods, and development of implementation tools and guidelines are necessary before they become more commonly used in engineering practice. Testing these methods in ongoing real-world civil engineering projects is probably necessary to identify implementation challenges related to interdisciplinary teams, information flows, and project timelines.

Furthermore, the question of who should develop the tools supporting the application of such methods remains open. Structural design software and LCA software are developing independently of each other. Structural design software packages integrate limited parameterization and optimization functionalities, and LCA tools are usually even more restrictive. The development of open-source solutions would offer more flexibility and faster development possibilities, as well as facilitate collaboration. Collaboration and information sharing in the early stages of structural design and construction planning are keys to shifting the design efforts and decision-making processes earlier in the project timeline, which is fundamental to enable making appropriate choices and ensuring a successful project outcome. This is particularly challenging in construction projects, since the project teams are usually unique for the duration of a project, leading to a fragmented transmission of information and learnings from a project to the next one [21]. Strategies such as partnering and early contractor involvement have been recognized to be beneficial for construction projects by integrating construction knowledge in the design phase [109]. The implementation of such methods and the development of adequate tools, such as computer programs supporting them, within project is hampered by the fact that every construction project is traditionally considered and addressed as being unique.

Finally, who decides what is sustainable enough for a design to be chosen? As in traditional cost-based procurement, the quantification of the sustainability performance allows the choice of the most sustainable project among tenders. However, the multi-dimensionality of the assessment makes this choice and its motivation more complicated. In the future, such strategies could be complemented by clients of infrastructure projects having their own environmental and social budget, in the same way as in the economic dimension, and defining a sustainability budget for a project for each sustainability dimension. Such environmental and social budgets could be determined by the client´s corporative sustainability goals and targets, which in turn should reflect national or international policies. Such specific policies dictating project-based environmental budgets are not yet in place but could resemble, for instance, the current schemes for greenhouse gas emissions.

7 - Summary and conclusion

The ambition of this work has been to contribute to the improved sustainability of the built environment. Throughout this thesis, a number of methods have been explored to take sustainability aspects into account in the structural design process. Both developments of specific aspects of these methods and processes to integrate them and facilitate their implementation in engineering practice were proposed. The main developments have been:

- highly parameterized computer codes for sustainability-driven design that interoperate with modern FE analysis software, automate modelling and analysis of design concepts over the whole design space, and verify compliance with structural design standards;
- the definition and inclusion of a wide range of criteria covering environmental, social, economic, buildability and structural performance for multi-criteria assessment of design concepts;
- a harmonized method for life cycle sustainability performance assessment, in line with state-of-the-art standards;
- multi-objective optimization algorithms that address the high expense of constraint function evaluations in structural design problems, as well as their integration in the parameterized computer codes for sustainability-driven design;
- application and validation of the above-mentioned developments through real-world case studies for bridges and wind turbine foundations, and through a benchmark case of a reinforced concrete beam.

The main findings of this thesis are summarized below:

- Environmental and sustainability performance is clearly dependent on various indicators, life cycle phases and the accuracy of the life cycle inventory. Care should be exercised when generalising results obtained in assessments that only take into account indicators covering one or a few impact categories (typically global warming potential) or that disregard important elements of the civil engineering works.
- The proposed harmonized method for life cycle sustainability performance assessment of civil engineering works was found to be suitable for transparent comparisons of design concepts based on data available in the early design and planning stages of a project. The method is easily automated thanks to its use of quantitative indicators and fixed weighting and normalization factors.
- The developed set-based parametric design algorithm proved to be satisfactory in automating the FE-based design process and evaluating numerous design alternatives.

> The application of the principles of set-based design to three real-world bridge projects revealed obvious improvement potentials as compared to the constructed designs. The foreseeable extensive computational time was overcome using optimization methods. Both the kriging surrogate-based and the Bayesian optimization algorithms proposed in this work allowed finding high-performance designs in terms of the sustainability indicators considered, whilst markedly limiting the number of computationally expensive FE simulations.

Finally, this thesis shows that it is possible and beneficial to combine computational design, life cycle sustainability assessment, and multi-objective design optimization as a basis for decision making in the design phase of civil engineering projects. A wide adoption of such sustainability-driven design optimization approaches in structural engineering practice can directly improve the sustainability of the construction sector.

8 - Future research in sustainability-driven structural design

The different studies conducted in this thesis provided an overall view of the need, possibilities and challenges to achieve sustainability-driven structural design. The challenges and directions for future research identified through this work are the following:

- There is a need to develop evidence-based data from the construction, use, and end-of-life phases of civil engineering projects to make the sustainability assessment of projects more accurate.
- Social indicators need to be further researched and defined as the social dimension is the less mature of the three sustainability dimensions.
- The application of the sustainability-driven structural design methods in ongoing civil engineering projects would reveal implementation challenges such as interdisciplinary collaboration needs, information flows between the stakeholders, and potential deviations from project timeline.

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