THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Sustainability-, Buildability- and Performance-driven Structural Design

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Abstract

The construction, maintenance and operation of infrastructure networks represent substantial impacts, both positive and negative, in all three dimensions of sustainability: economic, social and environmental. The greatest possibility to reduce the negative impacts and increase the positive ones is at the early design stage of construction projects. One way of achieving that is by using performance-based requirements. However, the use of performance-based requirements requires design processes and methods that support better-informed choices in design. The aim of this thesis is to propose a conceptual framework supporting well-informed choices in the early design stage of civil engineering projects. The thesis is based on a number of case studies related to the development of new structures, materials, construction methods, as well as structural engineering design and analysis methods. This provided a comprehensive view on the overall design process and allowed to identify potential for improvements in structural design. In addition, a set-based parametric design method was developed to meet the need to evaluate a large number of design alternatives according to criteria in the early design stage. The proposed framework integrates these advanced structural design methods and technologies with data-driven multi-criteria decision analysis. This supports better-informed choices in the early design stage taking into account the sustainability, buildability and structural performance of the design alternatives.

Keywords: structural engineering, civil engineering, design method, integrated design, structural developments, material developments, construction technology, requirements, sustainability, performance, buildability, constructability, finite element analysis, bridges, concrete structures.

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Preface

The research presented in this thesis is the result of the work carried out between November 2015 and May 2019 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. This work has been founded by the Swedish Wind Power Technology Centre (SWPTC), the Swedish Transport Administration (Trafikverket), Sweden's Innovation Agency (Vinnova) and NCC AB.

First and foremost, I would like to thank my academic supervisors, Mario Plos, and Rasmus Rempling, for their time and advices throughout this work. I also want to acknowledge my supervisor at NCC, Tobias Larsson and my manager at NCC, 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 wish to express my gratitude to my co-authors and my colleagues at NCC and Chalmers for the enjoyable working environment. Thanks also to the other researchers in the Swedish Wind Power Technology Centre for the interdisciplinary insights on wind turbine design from our meetings. I am also grateful to Prof. Steffen Marx and all his research group at the Institute of Concrete Construction at Leibniz University Hannover for the warm welcome and fruitful experience. Special thanks to Kristine Ek, Adam Sciegaj, Christian Koch, Jincheng Yang, Daniel Ekström, Jelke Dijkstra, Jesús Armesto Barros, Jonas Magnusson, Richard Malm and Marina Stümpel for interesting collaborations and discussions.

Finally, I want to thank my family for their love and support. To my parents, thank you for your unconditional support, and to my brother, thank you for being close despite the distance. To Teresa, thank you for being so supportive and for the daily joy of having you by my side. And to Elsa, thank you for helping me to wake up in the early mornings with a smile during the last weeks of writing this thesis.

Alexandre Mathern, Gothenburg 2019

List of publications included in this thesis

Paper A	Alexandre Mathern, Mathias Flansbjer, Ingemar Löfgren, Jonas Magnusson. Experimental study of time-dependent properties of a low-pH concrete for deposition tunnels. Published in *Proceedings of the 5th International fib Congress, "Better - Smarter - Stronger"*, The International Federation for Structural Concrete, October 7-11, 2018, Melbourne, Australia.
Paper B	Alexandre Mathern, Gautier Chantelot, Per-Ola Svahn, Per Kettil, Rasmus Rempling, Björn Engström. Enhanced strut-and-tie model for reinforced concrete pile caps. Published in *Proceedings of IABSE Symposium Vancouver 2017, Engineering the Future*, International Association for Bridge and Structural Engineering, September 21-23, 2017, Vancouver, Canada, pp. 608-614.
Paper C	Adam Sciegaj, Alexandre Mathern. Two-scale modelling of reinforced concrete deep beams: choice of unit cell and comparison with single-scale modelling. Accepted for publication in *Proceedings of the 7th International Conference on Structural Engineering, Mechanics and Computation* (SEMC) September 2-4, 2019, Cape Town, South Africa.
Paper D	Rasmus Rempling, Alexandre Mathern, Santiago Luiz Fernandez, David Tarazona Ramos. Automatic structural design by a set-based parametric design method. *Submitted to Automation in Construction*.
Paper E	Kristine Ek, Alexandre Mathern, Rasmus Rempling, Lars Rosén, Christina Claeson-Jonsson, Petra Brinkhoff, Malin Norin. Multi-criteria decision methods to support sustainable infrastructure construction. Published in *Proceedings of IABSE Symposium Guimarães 2019, Towards a Resilient Built Environment - Risk and Asset Management*, International Association for Bridge and Structural Engineering, March 27-29, 2019, Guimarães, Portugal.
Paper F	Christian Koch, Joseph Baluku, Issa Ibrahim Habakurama, Alexandre Mathern. The challenges of building inner sea offshore wind farms - the cases of Lillgrund and Anholt. Published in *Proceedings of the 9th Nordic Conference on Construction Economics and Organization*, June 13-14, 2017, Gothenburg, Sweden.

Author and co-authorship

In **Paper A,** Alexandre Mathern is the principal author with responsibility for data evaluation and writing of the paper. Jonas Magnusson was responsible for planning the tests, assisted by Alexandre Mathern. Mathias Flansbjer and Ingemar Löfgren were responsible for conducting the tests. All co-authors contributed to the evaluation of the test results and contributed with comments.

In **Paper B**, Alexandre Mathern is the principal author with responsibility for conducting the study and writing of the paper. Alexandre Mathern and Gautier Chantelot developed jointly the enhanced model. All other co-authors co-supervised the study and contributed with comments.

In **Paper C,** Adam Sciegaj is the principal author and responsible for the formulation and writing of the paper. Adam Sciegaj conducted the two-scale analyses. Alexandre Mathern conducted the single-scale analyses and contributed to writing of the paper. The two co-authors jointly initiated and planned the study and contributed with ideas and comments during the study and on the manuscript.

In **Paper D,** Rasmus Rempling and Alexandre Mathern shared the responsibility of formulation and writing of the paper. Santiago Luiz Fernandez and David Tarazona Ramos conducted the study and wrote the script used in the study. Alexandre Mathern initiated and defined the scope of the study. All co-authors contributed to the study and writing of the paper.

In **Paper E**, Kristine Ek and Alexandre Mathern jointly initiated the Paper and shared the responsibility of formulating and writing it. Petra Brinkhoff and Kristine Ek conducted the Norsholm case study. Alexandre Mathern defined and conducted the Rotebro case study. All co-authors contributed with ideas and comments on the manuscript.

In **Paper F,** Christian Koch is the principal author and responsible for the formulation and planning of the paper. Joseph Baluku and Issa Ibrahim Habakurama were responsible for conducting the study and the interviews under the supervision of Christian Koch and Alexandre Mathern. Alexandre Mathern was co-initiator and co-supervisor of the study and contributed to the writing of the paper.

Other related publications

Conference paper:

- Mathern, A., Rempling, R., Tarazona Ramos, D., Luis Fernández, S. (2018) Applying a set-based parametric design method to structural design of bridges. Published in *Proceedings of IABSE Symposium Nantes 2018, Tomorrow's Megastructures*, International Association for Bridge and Structural Engineering, September 18-21, 2017, Nantes, France.

Report:

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

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

- 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 on-shore 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.
- Ahlgren E., Grudic, E. (2017) Risk management in offshore wind farm development. Master's Thesis in Design and Construction Project Management.
- Ahlström, M., Holmquist, C. (2017) Assessment and comparative study of design method for onshore wind power plant foundations. Master's thesis in Structural Engineering.
- Habakurama, I. I., Baluku, J. (2016) The challenges in installation of offshore wind farms - A case of Lillgrund and Anholt wind farms. Master's thesis in Design and Construction Project Management.
- 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

AI	artificial intelligence
BIM	building information modelling
CAD	computer-aided design
CAPEX	capital expenditures
CFST	concrete-filled steel tubular
EN	European norm/standard
FE	finite element
FRP	fibre reinforced polymers
ICT	information and communications technology
LCA	life cycle assessment
LCC	life cycle cost
LCSA	life cycle sustainability assessment
LoA	level of approximation
MCDA	multi-criteria decision analysis
MEAT	most economically advantageous tender
PBD	point-based design
R&D	research and development
SBD	set-based design
SBPD	set-based parametric design
SLS	serviceability limit state
SSI	soil-structure interaction
ULS	ultimate limit state

PART I – EXTENDED SUMMARY

1 - Introduction

1.1 Background

Public infrastructure represents a crucial part of a country's economic and social development. It enables transport of people and goods, energy supply and communications, and supports employment directly and indirectly. At the same time, the construction, maintenance and operation of the infrastructure network represent very large impacts in all three dimensions of sustainability: economic, social and environmental. Nowadays, public authorities in most countries worldwide are struggling to maintain and develop infrastructures within the limits of their allocated budget and at the same time minimize the negative impacts of construction and maintenance activities on society and the environment.

The building and construction sector is responsible for 25-40% of the global anthropogenic greenhouse gas emissions [1, 2]. Construction materials account for a significant part of it as cement production alone represents more than 5% [3]. The construction sector is also by far the largest user of natural resources. Construction of infrastructure and building accounts for 60% of the global extracted abiotic and biotic resources according to the Worldwatch Institute, wherein infrastructure and building represent 60% and 40% respectively [4].

Being one of the sectors with the largest environmental impact sets high requirements on the construction industry in a context where countries worldwide are aiming at reducing their environmental impact. The European Union, for instance, targets to reduce its greenhouse gas emission by more than 40% compared with 1990 and to reach a share of renewable energy of more than 30% by 2030 [5]. To reach current targeted goals in terms of environmental impact, material consumption in the construction industry needs to be minimized and more sustainable (e.g. more durable, renewable or recycled) materials need to be used to a larger extent. At the same time, the sector has a lot of potential to improve its efficiency in terms of efficient use of resources and sustainability of the products (production and service life, durability). This means that the construction sector is one of the sectors with the highest potential to contribute to reaching environmental targets, not only due to its large direct environmental impact, but also due to its large margin for improvement.

Additionally, and despite the technological progress in the last decades, productivity (here understood as the value added per hour worked) has been stagnating in the construction sector, especially in developed countries. This also points to an unexploited potential for improvement

in the sector. In the US, for instance, 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 [6]. Ways to improve the sector's productivity are identified in [6], and 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.

As often highlighted, it is in the early design stages that design choices have the greatest possibility to influence the sustainability impact of a project [7, 8], which is illustrated in Figure 1.1. However, in the early stages of a project, the data and information available are very scarce, which makes it difficult to assess the consequences of different design choices.

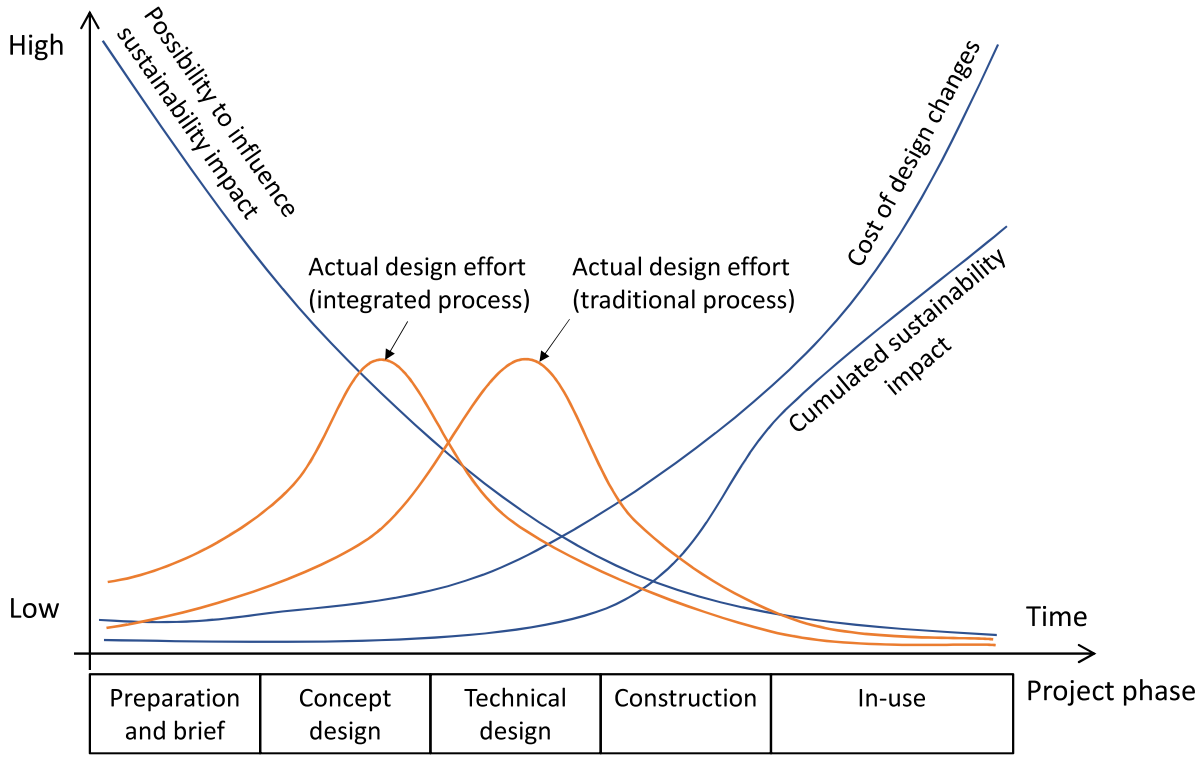

Figure 1.1. Evolution of the sustainability impact, of the possibility of influencing it, of the cost of design change and of the actual design effort with a traditional design process and with an integrated design process over the different stages of a construction project (elaborated from [7–9]).

Public authorities and clients need to provide effective incentives for encouraging the development of solutions performing well against environmental, social and economic sustainability criteria. To do so, they need to be able to value these solutions and to define clear requirements and criteria for a project according to their priorities and the specificities of the project. Engineers involved in the planning and design also need to have the knowledge and tools to make motivated choices in order to propose the most appropriate solutions.

To find, in the early design stage, the most sustainable structural solution that fulfils all performance and buildability requirements, research and development of new structures, materials and construction methods is often needed. Furthermore, structural engineering design and analysis methods supporting this need to be further developed. Design approaches different from those used today need to be developed to avoid making an early choice of a preferred design alternative based on too limited knowledge. This requires the development of methods for informed and transparent decisions applicable to the early structural design stages. To this end, information from previous experience is of great importance and needs to be incorporated.

1.2 Aim and objectives

The aim of this thesis is to propose an integrated conceptual framework that is applicable in the early design stage of civil engineering projects. The framework aims at achieving more efficient structures during their whole life cycle, considering their sustainability, buildability and performance. It integrates advanced structural design methods and technologies with data-driven decision making methods.

In this thesis, the proposed framework is described, and some methods that facilitate its implementation in engineering practice are developed. The main objectives of the work presented in this thesis are:

- to analyse requirements in structural engineering associated with today's demands on building and civil engineering structures, and their inclusion in a performance-based procurement process,
- to explore how existing structural engineering processes, methods and tools can be further developed and integrated to address today's demands,
- to propose a design method that allows to evaluate many design alternatives against various requirements in the early design phase, and
- to investigate suitable evaluation criteria and how they can be applied in the early design stage to assess sustainability, buildability and structural performance of design alternatives over their life cycle.

In addition, the following sub-objectives are addressed as case studies related to the development of new structures, materials, construction methods, as well as structural engineering design and analysis methods:

- to determine the time-dependent properties of a novel low-pH concrete for deposition tunnels (**Paper A**),
- to develop an enhanced strut-and tie model for discontinuity regions of reinforced concrete structures with a pronounced three-dimensional stress field (**Paper B**),
- to develop an approach for non-linear two-scale analysis of non-uniformly distributed concrete structures (**Paper C**), and
- to evaluate construction-related challenges in earlier major civil engineering projects as a base for experience feedback for early design (**Paper F**).

1.3 Research approach

The thesis builds on the work conducted in a series of studies, which have been partially published in scientific papers. The papers cover a variety of structural engineering methods for civil engineering applications (e.g. bridges, foundations, offshore wind energy, nuclear waste deposition). The applications are concerned by a broad range of requirements covering sustainability, structural performance and buildability and span different stages of a construction project. The relation of the papers to the sustainability-, buildability- and performance-driven structural design framework, that is proposed in this thesis, is illustrated in Figure 1.2, where **Papers A-F** are designated by their respective letters together with the corresponding aspect addressed (green boxes).

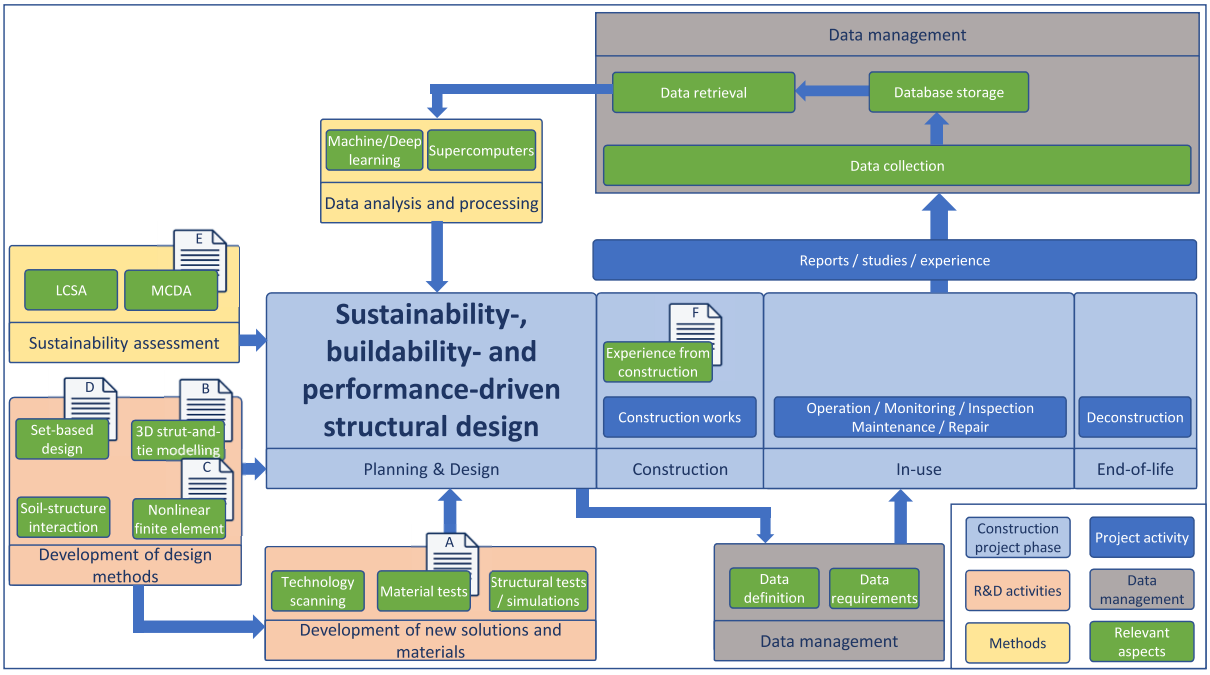

Figure 1.2. Overview of the sustainability-, buildability- and performance-driven structural design framework described and relationship to the papers included in this thesis.

The ambition by exploring different aspects related to the design process and its outcome is to achieve a comprehensive view on the overall design process. It also allows to identify potential for improvement of the design process by development and integration of these different aspects. The thesis presents an attempt to integrate the knowledge acquired in the studies in a common framework for sustainability, buildability- and performance- driven structural design (see central blue box in Figure 1.2).

Given the variety and interdisciplinarity of the studies included in this thesis, several research methods are used, both quantitative and qualitative: experimental studies, interviews, literature studies, conceptual analysis, analytical analysis, numerical analysis and multi-criteria decision analysis (MCDA).

A short summary of the appended papers is presented in Section 1.5.

1.4 Outline of the thesis

The thesis is structured as follows: requirements in the field of structural engineering associated with today's demands on building and civil engineering structures are described in Chapter 2. Chapter 3 deals with developments of new materials, structural systems and construction methods and Chapter 4 with developments of structural engineering design and analysis methods. In Chapter 5, methods are proposed to integrate the previously described developments with set-based design and decision making methods based on sustainability, performance and buildability criteria in the structural design approach. Concluding remarks and plans for future work are presented in Chapter 6.

1.5 Summary of appended papers

Paper A

The Swedish Nuclear Fuel and Waste Management Company developed a method for the final disposal of canisters for spent nuclear fuel in tunnels at depths of about 500 meters. The concept for closure of the deposition tunnels is based on a bentonite seal supported by a spherical concrete dome plug. In order to fulfil the requirements specific to the repository concept, a special mix of low-pH self-compacting concrete was developed. A series of large-scale castings and laboratory tests were conducted to gain experience on this low-pH concrete mix, in conjunction with the full-scale demonstration test of an unreinforced concrete dome plug in the underground hard rock laboratory in Äspö, Sweden. The laboratory tests aimed at studying the creep properties under high sustained compressive stresses of the low-pH concrete mix, its shrinkage properties and the properties of the rock-concrete interface. This paper provides an overview of these tests and analyses the latest results of the recently completed creep tests, which include 6 years of measurements. These results allow to improve understanding of the structural behaviour of the concrete plug and to assess the effects of the very high pressure acting on the plug on its deformations, cracking and water tightness.

Paper B

Strut-and-tie models provide a simple and rational way to design discontinuity regions in reinforced concrete structures. However, when it comes to three-dimensional concrete elements such as pile caps, enhancements are needed to ensure a reliable and not overly conservative design. This paper presents an enhanced strut-and-tie model adapted to the analysis and design of reinforced concrete pile caps. The model is based on consistent geometries of three-dimensional nodal zones and struts and integrates a strength criterion for confined bottle-shaped struts. An iterative process is used in order to optimize the position of the members by refining the dimensions of the nodal zones. The model is validated by experimental results from tests on four-pile caps reported in the literature, showing effective predictions of their ultimate capacities. This enhanced strut-and-tie model can lead to safe and less conservative design of pile caps.

Paper C

Two-scale and single-scale models are used to analyse the response of reinforced concrete deep beams with different reinforcement layouts. To this end, a novel approach of modelling non-uniformly reinforced structures in a multiscale manner is developed. Parameterized generation of suitable unit cells is described, and the subdivision of problem domain into regions with different substructures is presented. Three different reinforced concrete deep beams with available experimental data are analysed. Mid-span deflections are slightly underestimated by both models, while the maximum load is captured reasonably well.

Paper D

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 allow resolution of these challenges. The purpose of this work is to investigate the applicability of a Set-Based Parametric Design method (SBPD) 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 (SBD), parametric design, finite element (FE) analysis and 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 stage, against different sustainability criteria.

Paper E

The construction of infrastructure projects represents a large sustainability impact, both positive and negative. Increased positive and reduced negative impacts can be achieved through better design and planning of the construction. To make more sustainable choices, well-defined predictive sustainability assessment methods are required. MCDA is a well-suited method for predictive sustainability assessment. This paper evaluates two MCDA methods for sustainability assessment of infrastructure construction and exemplifies their application with two case studies. The aim of this paper is to discuss if the methods are suitable for identifying the most sustainable alternative during the procurement process of an infrastructure project. It is recommended that MCDA methods are further developed to comply with the recently published European standard (EN) on sustainability assessment of civil engineering works.

Paper F

Offshore wind power installation is a growing business within the construction sector as offshore wind represents large available renewable energy resources in locations where space is available. Offshore wind energy is however expensive due to the large capital expenditures (CAPEX). The construction of an offshore wind farm encounters many challenges throughout its construction processes. Therefore "inner sea" offshore wind farms receive increasing interest, due to their assumed attractive features of reduced costs of erection and operation. The aim of this paper is to identify the challenges encountered during the installation phase of offshore wind turbines at "inner sea" conditions, understood as the Baltic Sea region and neighbouring areas. Offshore wind farm installation is conceptualized as a building operation. Consequently, theories on construction management, operations management and strategy, supply chain, building logistics and concepts on offshore wind farm development were used. A qualitative approach using interviews and literature. Out of seven farms in operation in the southern Baltic, Øresund and Kattegat, two were selected. Interviews were conducted with professionals that were involved in installation of Anholt and Lillgrund, working for developers, contractors or service providers. The analysis showed that installation challenges can either be due to local natural conditions or technical issues related to equipment, planning, technology and work practices. At Lillgrund challenges were bad weather conditions and breakdown of a vessel, causing a delay of export cable installation and the tight tolerances for the bolts at the tower-foundation interface. At Anholt, a soft seabed necessitated the abandonment of some turbine positions. Irregular supply by the turbine supplier forced the vessel operator to change planning, and it was needed to handle gas leaks from the sea bed. Installation challenges grow as wind turbines are becoming bigger and heavier and locations go further from shore. Developers and contractors must continuously innovate processes and equipment to overcome these challenges.

2 - Sustainability, buildability and performance requirements in structural engineering

In this chapter, some of the new requirements affecting the structural engineering process are discussed. Current advances in structural engineering methods and technologies provide opportunities to develop better designs with respect to a broad set of requirements. These requirements, which are expected to become increasingly important in the early design process, have been categorized in this thesis under sustainability, buildability and structural performance and are defined in this chapter. Such requirements can be used in a performance-based procurement process.

2.1 New demands and advances in structural engineering

Some of the most important current demands and recent advances in methods and technologies that are characterising structural engineering of today, according to the author's experience, are listed in Figure 2.1. These demands and advances can be interpreted as an indication of current trends in the field of structural engineering. Some of these trends, related to aspects of structural engineering pertinent in this thesis, were confirmed by analysing the number of publications in Scopus. This is represented in Figure 2.2, where the keywords used in the search queries are those listed on the left-hand side of the figure. The root of the word was used in some cases to capture all relevant results and all results are limited to occurrences related to *Structural Engineering* in the area of *Engineering*. The accumulated numbers of publications over five-year periods for each aspect were normalized against the total number of publications related to structural engineering over the same period, as the number of publications is growing exponentially with time.

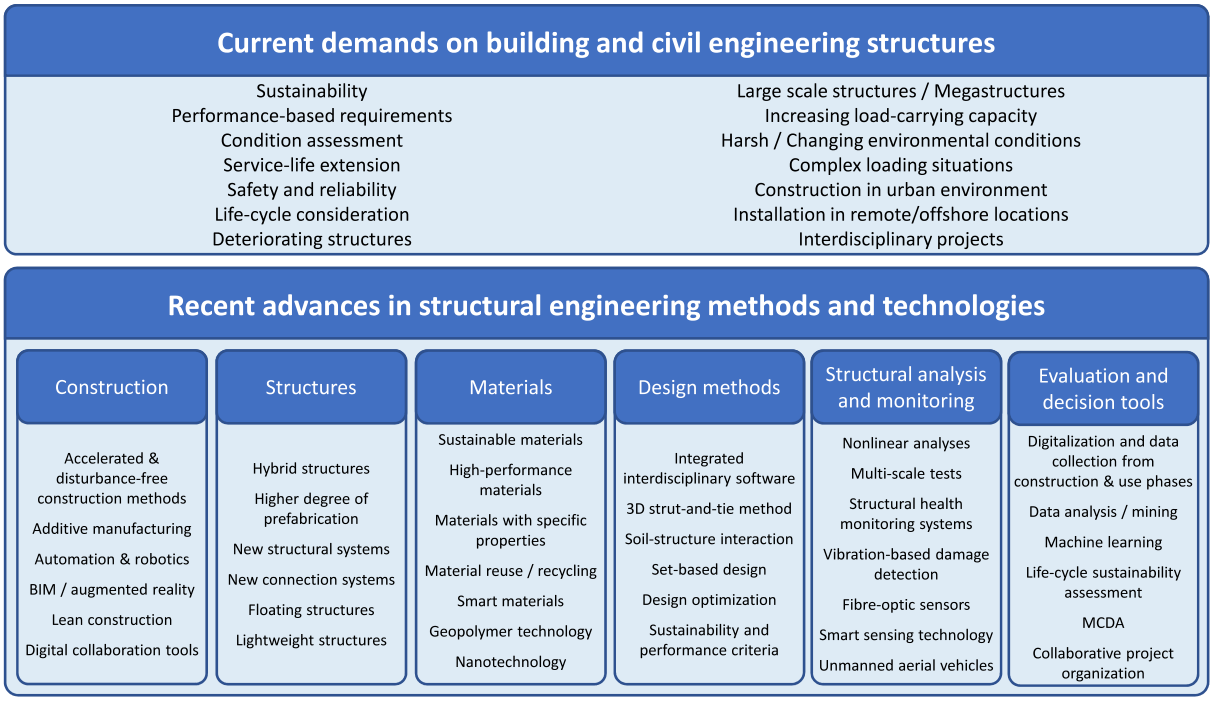

Figure 2.1. Selection of important current demands in the field of structural engineering (top panel) and recent advances in structural engineering methods and technologies (bottom panel) according to the author.

It can be seen in Figure 2.2, that safety and reliability have been given significant attention that has been relatively constant over the last five decades. The focus on sustainability, life cycle and performance is more recent, and studies related to these keywords appear to have grown significantly in the last fifteen years. Buildability and the related term of constructability appear to have a very low frequency of occurrence to date. This seems to indicate that there is still a very low focus on related aspects in structural engineering research. It may also be partly explained by the fact that these terms are not well-established yet and called differently in studies dealing with such issues.

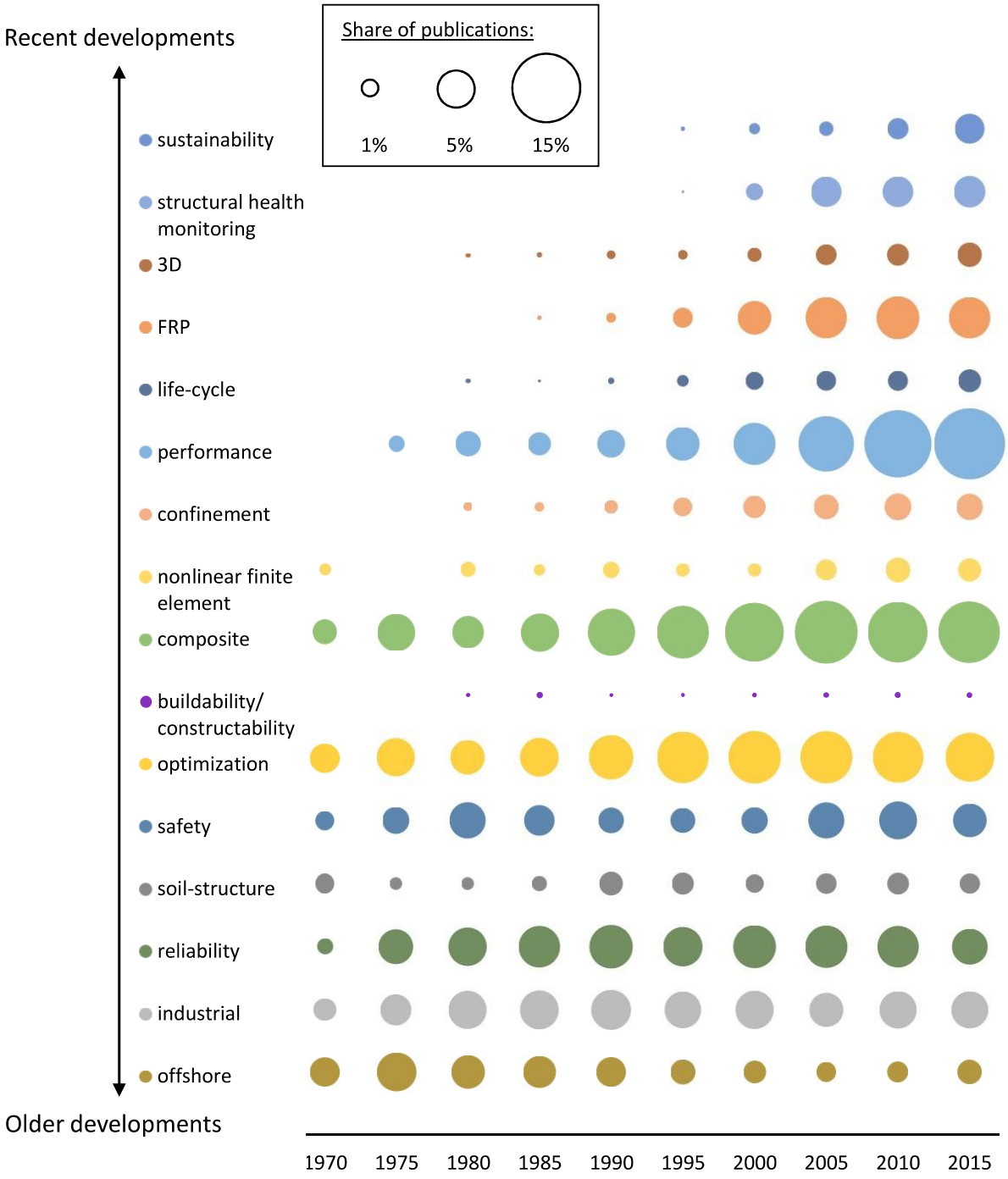

Figure 2.2. Evolution of the number of publications, referenced in Scopus, associated with different keywords. The area of the disks represents the share, over a five-year period starting at the year indicated, of the number of publications associated with a keyword in the total number of publications related to structural engineering in the area of Engineering.

These new demands on buildings and civil engineering structures require solving unconventional structural challenges that call for new construction concepts and new materials. In this thesis, such structural challenges are exemplified by the current critical need for nuclear waste disposal solutions (**Paper A**), the recent development of offshore wind energy and its need for infrastructure (**Paper F**), and construction methods for disturbance-free bridge construction and maintenance (**Paper E**). The focus on sustainability, buildability and structural

performance is supported by the fact that all demands identified in Figure 2.1 can easily be associated with these three categories of requirements.

2.2 Performance-based requirements: hierarchy and terminology

In this thesis, the hierarchical structure shown in Figure 2.3 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 objectives. The objectives and requirements can also correspond to the ones 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 performance-based requirements for a specific structure or structural component. To assess performance-based requirements, they need to be broken down into performance-based criteria that are predictable and verifiable. Examples of sets of performance-based criteria for the three domains of sustainability to use in the procurement stage for civil and infrastructure projects is given in **Paper E** (in which they are called key performance criteria).

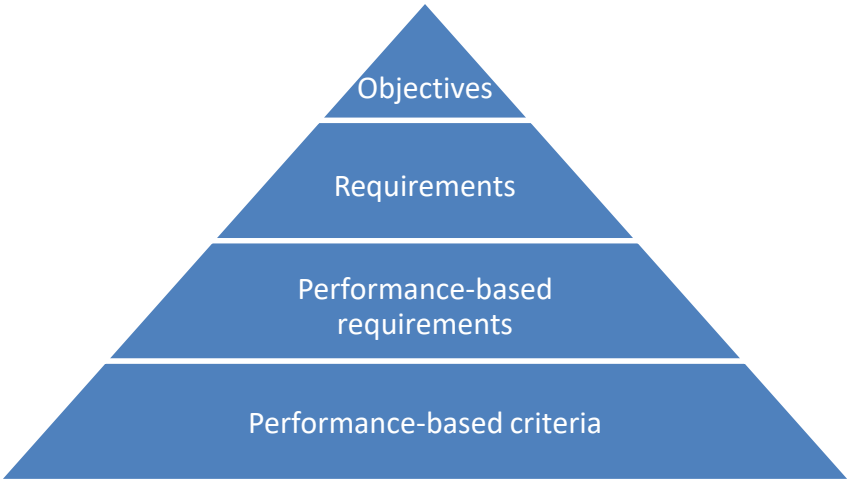

Figure 2.3. Hierarchical structure adopted in this thesis for definition of performance-based requirements.

Note that, 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 structural performance of a structure, i.e. 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 requirements/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 [10]. Therefore, in the latter it encompasses all three categories of requirements described in this thesis, i.e. sustainability, buildability and structural performance.

2.3 Sustainability, buildability and structural performance requirements

In order to improve the sustainability of structures during their entire life cycle, to maintain their performance during their service life, and to minimize disturbances associated with

construction activities, it is necessary to clearly define related specific requirements for their construction at the beginning of a project.

In this thesis, the requirements considered are divided into three categories: sustainability, buildability and structural performance. 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" [11]. 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.

In this thesis, sustainability requirements are considered in **Paper E** and **Paper D**, buildability requirements in **Paper F** and **Paper E**, and structural performance requirements in **Paper A** as well as to some extent in **Paper B** and **Paper C**.

2.4 Performance-based procurement

A broad vision, taking into account sustainability, structural performance and buildability requirements, should be adopted during the design stage of a project to elaborate better designs. This requires a procurement process that encourages more sustainable solutions and evaluates them in an adequate way. A design that is somewhat more expensive to build but that leads to consequent cost savings during its life cycle or to lower negative sustainability impact, must have a chance to be selected. This has seldom been the case, as most often the lowest initial price has been the only criteria considered in the procurement process.

In the procurement stage, the evaluation of tenders can be conducted taking into account different criteria. However, this sets high requirements on the method and the process used for the evaluation. Because of this, clients procuring infrastructure projects almost always base the choice on the lowest price quotation from the contractor according to detailed specifications drawn up by the client. This traditional tender procedure therefore constitutes one of the most important barriers to achieve sustainable projects.

Today, the greater focus on sustainability and life-cycle thinking and the will to encourage innovation, creativity and competitiveness in the construction industry, is leading to a wider use of new contract and procurement forms with performance or functional requirements. The European Directive 2014/24/EU, which describes the procedures for public works procurement, encourages the use of performance specifications. It specifies that the award of contract must be based on the most economically advantageous tender (MEAT) to the authority [12]. This can include assessments based on price only, or other methods such as the "best price/quality ratio" that can take environmental and social requirements into account. It allows to take into account the full life-cycle costing. The contracting authority can also ask for certification and labels, or other evidence of social and environmental characteristics and refer to aspects directly linked to the production process.

An example of a contracting authority considering environmental aspects in procurement is the Swedish Transport Agency. Since 2015, they require a climate calculation and declaration for all investment projects and climate reduction measures to be taken [10]. The climate declaration is a single-issue life cycle assessment (LCA) tool considering global warming potential (GWP). If contractors succeed to meet the climate impact reduction goals based on this declaration, they receive a bonus. A fine may be issued if the Swedish Transport Agency is judged to be harmed because the climate performance is not reached.

3 - Development of new materials, structures and construction methods

This chapter highlights the development of new structures, materials and construction methods that can help to meet sustainability, buildability and performance requirements in structural engineering. They are exemplified by specific cases studied in this thesis.

3.1 New materials and materials for specific applications: the case of a low-pH concrete for closure of deposition tunnels

The choice of innovative or less conventional materials is most often governed by a search for cost-reductions, performance, durability or buildability. For instance, when it comes to the choice of concrete materials, cost issues often set limit to the strength of the material, buildability issues can call for use of a self-compacting concrete, shrinkage issues for using high-performance concrete or even prepact concrete, and finally, sustainability concerns for using inorganic geopolymers (such as ground granulated blast-furnace slag or fly ash) [13] or recycled aggregates in concrete [14].

The development of new materials is often driven by new demands or specific requirements in a project large enough to accommodate the time and cost required for the development activities. An example of this is the development and testing of a low-pH concrete mix to be used for closure of deposition tunnels for final disposal of spent nuclear fuel at depths of about 500 m (**Paper A**). The concept for closure of the deposition tunnels is based on a bentonite seal supported by a spherical concrete dome plug. Due to the specificities of this application, a long list of performance-based requirements was imposed on the materials used and the construction methods. For instance, in order to avoid possible negative effects from leachate from the concrete on the swelling properties of the bentonite, a low-pH concrete was required (i.e. with a pH below 11), which can be obtained by replacing part of the cement content by silica fume. The concrete mix B200, originally developed by [15], is characterized by a binder content of 200 kg per m^3 of concrete with addition of limestone powder and superplasticizer to make it self-compacting. Besides, a series of laboratory tests and large-scale castings were conducted in order to study mechanical, functional and production related aspects of this special low-pH concrete mix, as described in **Paper A,** in which new results obtained from creep tests until six years after loading are reported and analysed. The results of these tests can be divided into four categories: hardened concrete properties, shrinkage, creep, and interaction between concrete

and rock. These tests also comprised a full-scale demonstration test of the plug system, with an unreinforced concrete dome plug (DOMPLU) of more than 8 m in height, conducted under realistic underground conditions in the Äspö Hard Rock Laboratory located in the south east coast of Sweden [16]. These tests were conducted between 2010 and 2018, which illustrates the long time that may be required to gain understanding on the functionality and performance of a new material.

An extensive experimental campaign is possible in this type of project with a very long-term perspective but is usually not an option in more common infrastructure projects due to both time and cost limitations. Data obtained through experiments is valuable to predictively assess the specified performance-based criteria of the materials and structural systems, e.g. using numerical models. A small-scale or full-scale demonstration can be necessary for unvalidated complex structural systems to gain insights on their performance under realistic conditions and validate the chosen performance-based criteria in line with the performance-based requirements for the project.

3.2 Development of structural engineering systems: the case of support structures for offshore wind turbines

As for new materials, new structural engineering systems are being continuously developed to answer to new needs and tackle associated requirements and challenges. Their development can also be associated to material developments. Today, composite structures are being used and developed for many structural applications since the combination of different materials (e.g. reinforced or prestressed concrete, structural steel, fibre reinforced polymers) allows to optimize structures by using the different properties of each material in an efficient way. Such types of structures are of particular interest for steel-concrete composite bridges [17], concrete-filled steel tubular (CFST) columns for high-rise buildings [18] or hybrid support structures for offshore wind turbines in concrete and steel or concrete and ductile cast-iron [19]. The design of composite structures requires more knowledge: on the structural behaviour of each material, the ways to connect them and the interaction between the different parts.

Wind energy, and in particular its offshore applications, is associated with special challenges, requiring the development of structures to support wind turbines. Wind energy has grown exponentially in the last decades. The size of wind turbines has also increased exponentially in recent years to increase their capacity and take advantage of steadier winds. The hub height and rotor diameter of a wind turbine installed today can both reach more than 150 m. Offshore wind farms are also progressively located further from shore and in deeper waters, which sets new requirements on support structures. Support structures are being scaled up in order to support the larger turbines in these water depths, and monopiles (which constitute by far the most common type of support structure for offshore wind turbines) with diameters as large as 8 m are nowadays used. In addition, wind turbines are exposed to high and complex wind loads that vary in amplitude and direction. Support structures for offshore wind turbines need to be designed for a very large number of load combinations taking into account these wind loads as well as wave, current and ice loads.

Often new developments are driven by construction issues, and this is especially true in the field of offshore wind as transport and installation of structures in offshore environment represent critical phases in the construction of an offshore wind farm (**Paper F**). Many recent developments in the field are aiming at shortening or facilitating the activities associated with these phases. One example of this is the development of self-buoyant gravity-based concrete foundations that can be towed to the installation site and then positioned and installed by standard tugs without the use of costly heavy-lift vessels [20].

3.3 Development of construction methods: the case of accelerated bridge construction

A considerable proportion of today's bridges in Europe, especially on the railway side, is obsolete and needs to be either repaired or replaced [21, 22]. With a history of increasing allowable loads and traffic on road and rail networks, the need for maintenance and construction works increases at the same time as the sensitivity of the transportation networks to traffic disturbances. In addition, many of today's bridge projects are situated in urban environment or at heavily trafficked crossroads where the work areas are cramped, or at railway lines where the traffic cannot be hindered. In these conditions, the available space for construction works is often very limited and traffic rerouting or disruptions are not easily granted. Furthermore, several studies pointed out the important costs for society as a result of traffic congestion [23, 24].

To tackle these challenges, accelerated bridge construction projects have generated significant interest [25, 26]. The use of prefabricated elements produced off-site and transported to the construction site for assembly can be beneficial in terms of costs, construction time and social impact [27]. Many methods are available to transport and install large prefabricated elements or even entire bridges (e.g. launching gantry or self-propelled modular transporters). Such an example of installation of an entire bridge, constructed in the immediate vicinity of the bridge, and being first used in a temporary position before being laterally launched into its final position was studied in **Paper E**. These methods set high requirements on the assembly process. When using prefabricated elements flexibility decreases compared to traditional on-site construction and late changes become harder to implement, therefore requiring a good planning to have an even flow at the site and to avoid unexpected events.

4 - Development of structural engineering design and analysis methods

The development of structural engineering design and analysis methods is driven by several factors. The four main factors motivating it are to improve the accuracy or reliability of existing methods, to develop adequate methods adapted to new materials or structural systems, to integrate methods from different disciplines to enhance accuracy, and to develop flexible and reusable methods. Examples of development of methods that contribute to these factors are given in this chapter.

4.1 Reliable and less conservative design methods

In engineering practice, the design of common structural elements, such as beams, slabs or walls, is most often performed using hand calculations or a spreadsheet or another numerical analysis software (e.g. Excel or Mathcad), and applying simple theoretical or empirical formulas or using user-friendly linear elastic FE software. When confronted with more complex structures or cases, these methods are still often applied, even outside the limits for their application. 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, would be more adequate but are more time-consuming and require specific knowledge that is not always available in design offices. Further developments and dissemination of these methods are required for them to become more used in engineering practice.

It is important to keep in mind that the predicted cost and performance of a design alternative also depend on the design and assessment method used. Indeed, the analyses conducted to determine the load effects and the capacity of structural members are approximations of reality, which are obtained with different levels of accuracy [10]. To achieve a reliable comparison between different structural alternatives, it is important that they are designed with similar levels of accuracy, which is often difficult to ensure. Especially in preliminary design, the differences in terms of accuracy between the simplified methods used can be significant. One may conclude too prematurely that an alternative is less interesting only because an overly conservative method was used for its design. A levels-of-approximation approach (LoA) has been introduced in Model Code 2010 [10] for the design and assessment of concrete structures. The choice of the LoA involves a trade-off between the level of accuracy of the method used and the time required in the design stage, as shown in Figure 4.1.

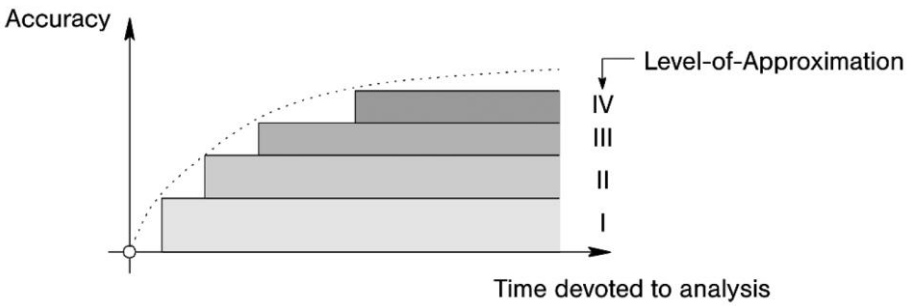

Figure 4.1. Relation between accuracy and time devoted to the analysis for different levels of approximation [10].

4.1.1 The case of three-dimensional strut-and-tie modelling

Strut-and-tie models provide a simple and rational way to design discontinuity regions in reinforced concrete structures. The method allows to take into account all load effects simultaneously, by using a hypothetical equivalent truss to represent the complete transfer of forces in the structure. The truss consists of struts (concrete) and ties (reinforcing steel), which carry compressive and tensile stresses, respectively, and are connected at the nodes.

However, when it comes to concrete elements that are large in all three dimensions (i.e. length, width and height), such as concrete foundations, there is a lack of guidelines in standards and in the literature on how to design them with strut-and-tie models. Most often, three-dimensional design cases are solved using a combination of two-dimensional models or using improper three-dimensional models based on two-dimensional analogy. Enhancements are needed to ensure a reliable and not overly conservative design. An enhanced and generic three-dimensional strut-and-tie model was proposed in **Paper B** for the design of reinforced concrete pile caps and validated against experimental results from tests on four-pile caps found in the literature. Enhancements included in the model are: (1) that it is based on consistent and compatible three-dimensional geometrical definitions for all members of the strut-and-tie model, ensuring an accurate verification at the nodal zones; (2) that the sizes of nodal zones are refined according to the state of stress in the nodal zones; and (3) that the geometry of the strut-and-tie model is improved by an automated iterative process to decrease internal forces and better utilize the strength of the nodal zones (see Figure 4.2). Furthermore, the model integrates a strength criterion to check bottle-shaped compressive struts confined by plain concrete. As illustrated in Figure 4.3, the proposed model led to accurate predictions with low scatter of the ultimate capacity for the four-pile caps studied, indicating that the enhanced model developed can lead to more reliable and less conservative design for concrete elements in which the stress distribution is predominantly three-dimensional.

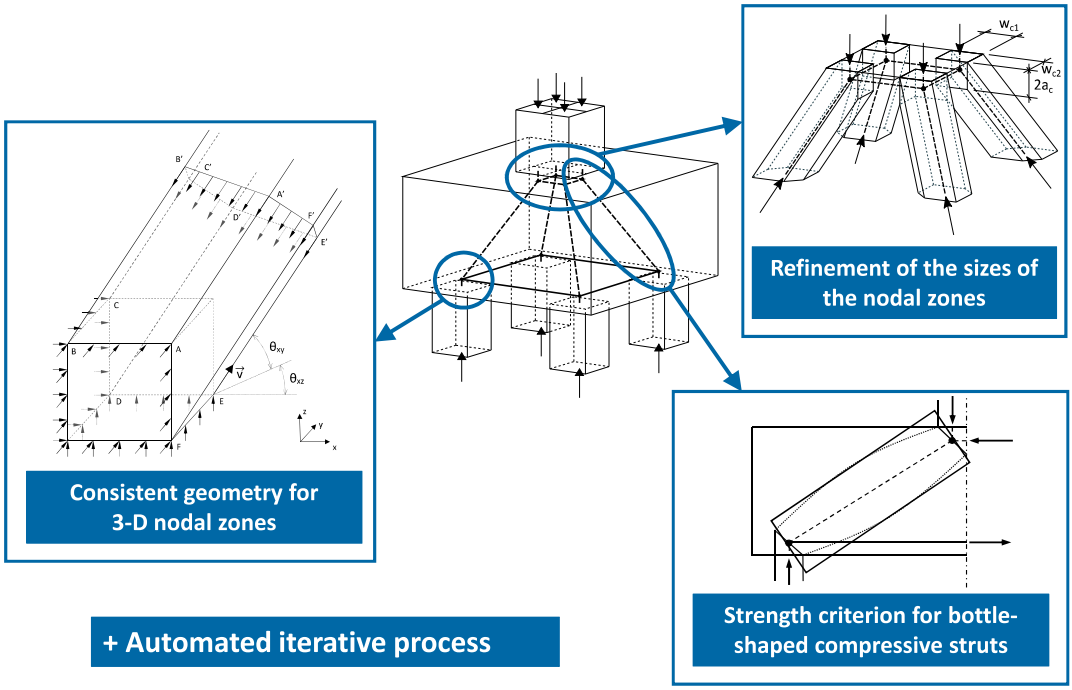

Figure 4.2. Features of the enhanced strut-and-tie model (**Paper B**).

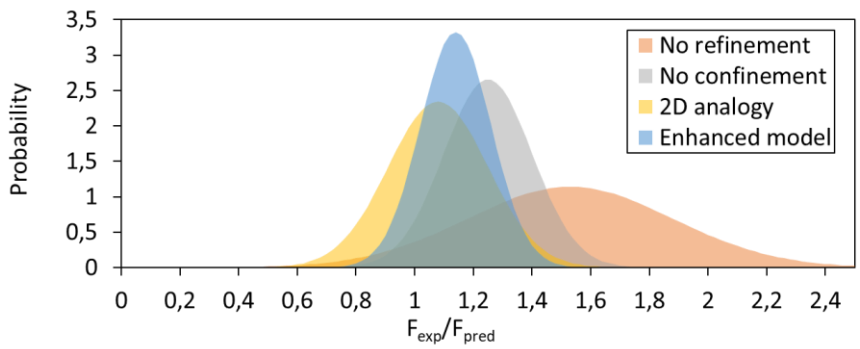

Figure 4.3. Influence of the features implemented in the enhanced strut-and-tie model, elaborated from results presented in **Paper B**.

4.1.2 The case of single-scale and two-scale nonlinear finite element modelling of reinforced concrete deep beams

Another way to analyse discontinuity regions in reinforced concrete structures is to use finite element (FE) modelling. As concrete structural elements are characterised by a complex nonlinear behaviour under loading, the use of nonlinear FE analyses is often required. Multiscale modelling, specifically the FE_2 method, can constitute an interesting alternative to conventional single-scale modelling in terms of modelling complexity and computational time for large reinforced concrete structures. In **Paper C**, several deep beams with available experimental data were analyzed with both two and single-scale models. The two-scale model was based on a model developed in [28], which takes into account the cracking of concrete,

plasticity of reinforcement and bond-slip interaction between the materials. However, the response of beams with non-uniform reinforcement layout had not been previously investigated. The model was also not validated by comparison with available experimental data.

4.2 Design methods adapted to new materials or structural systems: the case of confined concrete in hybrid structures

FE modelling is also useful to analyse the response of unconventional structural elements. In complex cases, it may be very difficult to use analytical methods, e.g. it is not always possible to determine an appropriate strut-and-tie model. In this instance, more advanced numerical modelling becomes necessary. FE modelling allows to consider the interaction between different parts and materials and determine complex stress distributions. The ability to simulate the structural response of a structure is particularly important when developing a new structure to reach a good understanding of its behaviour and be able to optimize the structure and its details. This is particularly true in the case of offshore wind energy, where structures are subjected to very complex loading conditions. Moreover, the cost and difficulty of offshore operations to install or repair these structures, as highlighted in **Paper F**, call for reliable structural design and analysis models. FE modelling is also often needed to assess a structure's condition during its lifetime, especially if degradation is identified or in case the structure needs to be refurbished or to withstand higher loads (e.g. in the case of a change of traffic situation on a bridge resulting in higher loads, replacement of a wind turbine, etc.).

Modelling composite structures made of concrete is a challenging task. In particular, several studies have highlighted the difficulty of modelling the behaviour of steel-concrete or fibre reinforced polymers (FRP)-concrete assemblies with significant confinement effects from the steel or the FRP on the concrete, for instance in the case of concrete-filled steel tubular columns [29–32] and lately FRP-confined concrete columns [33–38]. Lately, grouted joints between monopiles and transition pieces for offshore wind turbines have raised similar issues [39, 40]. Good results have often been obtained using nonlinear finite element modelling in these studies, but they also highlighted the importance of adapting the model to specific applications, e.g. special cross-section geometries or a certain range of concrete grades. For instance, it often requires modifying the hardening or softening rule depending on the level of confining pressure [38, 41].

4.3 Interdisciplinary methods for more holistic structural analysis: the case of wind turbine analysis

In order to find the most efficient structure and to avoid sub-optimization it is necessary to develop holistic approaches that allow considering the whole structure in the design process. One field in which these considerations received special attention in the last years is the field of wind energy.

Wind turbines are subjected to very complex loading situations with wind loads that vary in amplitude and direction and whose load effects depend on the control system of the wind

turbine and rotation of the blades. Furthermore, for offshore wind turbines numerous load combinations need to be included taking into account complex loads from wind, waves, current and ice. Under these conditions, support structures need to provide the stability to ever larger wind turbines.

A common approach for the design of foundation is that the turbine and foundation are analysed separately, and the loads used to design the foundation are calculated assuming a rigid foundation. This way of designing has its limitations and will influence the design loads crucially for stability/durability, especially for larger wind turbines and poorer soil conditions. As current wind turbines are becoming ever larger structures, it becomes even more important to take into account the soil-structure interaction in the analysis of the dynamic response of the whole wind turbine and the design of the foundation. To do so, it is necessary to know the dynamic parameters of the soil, as well as the behaviour of the turbine under working conditions and the loads transmitted from the turbine to the foundation. Current codes and standards only offer limited guidance on the assessment of the dynamic behaviour of soils (especially for undrained soils subjected to cyclic loading). A rotational spring and a lateral spring derived from the foundation are often used to reflect the interaction between the tower and the foundation. The foundation stiffness can influence the dynamic response of wind turbines due to the soft soils surrounding the tower base.

4.4 Flexible and reusable design methods: application of parametric design models

Parametric design is often used to some extent in today's design process. Since the use of computers and the development of computer-aided design (CAD) solutions, some parametric features have most often been included by engineers in their calculation worksheets and are offered by structural design software. However, current structural engineering software most often only offer limited parameterization possibilities. A step further in parameterization, consists in developing and parameterizing the design model in a way that allows the generation of all design alternatives that need to be evaluated, as was applied in **Paper B** and **Paper D**.

5 - Proposed framework for sustainability-, buildability- and performance-driven design

In order to base choices in the early structural design stage on sustainability, buildability and structural performance criteria, it is necessary to develop and apply methods that allow to evaluate the consequences of choices made in the early design stage and to compare different alternatives in terms of the considered design criteria. In this chapter, a set-based parametric design method developed in this work is presented. The possibilities to combine this method with advanced structural analysis methods, MCDA and artificial intelligence (AI) in an integrated framework is discussed.

5.1 Set-based parametric structural design

Taking into account criteria from different stakeholders in the early design stage imposes a number of adaptations in the planning of design process. The traditional structural design process in civil engineering fails to address these challenges as it is almost exclusively based on a so-called point-based design (PBD) approach. In this approach, the development of the design is based on an early choice of a preferred design solution followed by its sequential improvement, which means that many design alternatives are already discarded at an early stage.

The ineffectiveness of PBD has motivated the development of alternative design approaches. Toyota was one of the first companies that started using a novel concept, based on parallel and delayed decision-making processes called set-based design (SBD) [42]. In SBD, the decisions involved in the design process are not made with a single design in mind, instead a large set of alternatives is explored and progressively narrowed down according to the requirements of the client and the stakeholders involved in the project.

The potential of applying a set-based parametric design (SBPD) method to the early stage of structural design of bridges was investigated in **Paper D**. The framework for the proposed SBPD method includes the theories of integrated design proposed by the American Institute of Architects [43] and parametric design with regard to geometrical and material parameters. Integrated design, which is closely related to the conceptual design proposed in [44], integrates different engineering disciplines and all stakeholders, while parametric design utilizes computer algorithms to consider variations of design parameters in an automated process. Combining

these two approaches may provide the construction community a cost-effective process to evaluate alternatives against common decided criteria, which address materials, structural system and member size.

The method proposed in **Paper D** integrates SBD, parametric design, FE analysis and MCDA. 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 automatization 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 and generating information for a large number of bridge alternatives. A flow chart of the script, developed in **Paper D**, is presented in Figure 5.1.

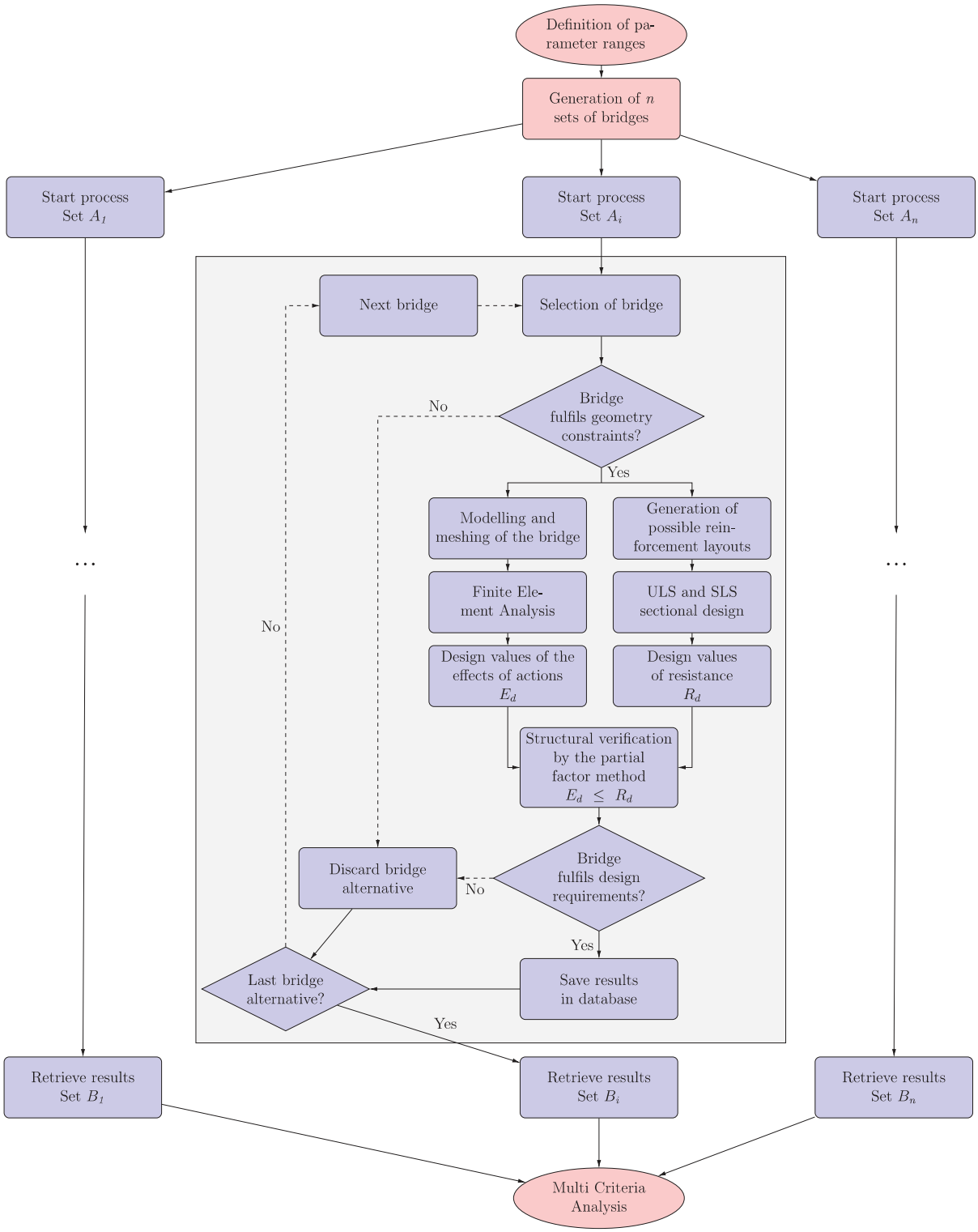

Figure 5.1. Flow chart of python script performing the numerical analyses and controlling the SBPD (**Paper D**).

The method was successfully applied, in **Paper D**, 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. The use of the method led to a reduction in material cost and CO_2 equivalent emissions by 20-60% compared to the existing bridges, which were

designed using a traditional point-based design approach. This is illustrated in Figure 5.2 for one of the three design cases: a 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 a MCDA method.

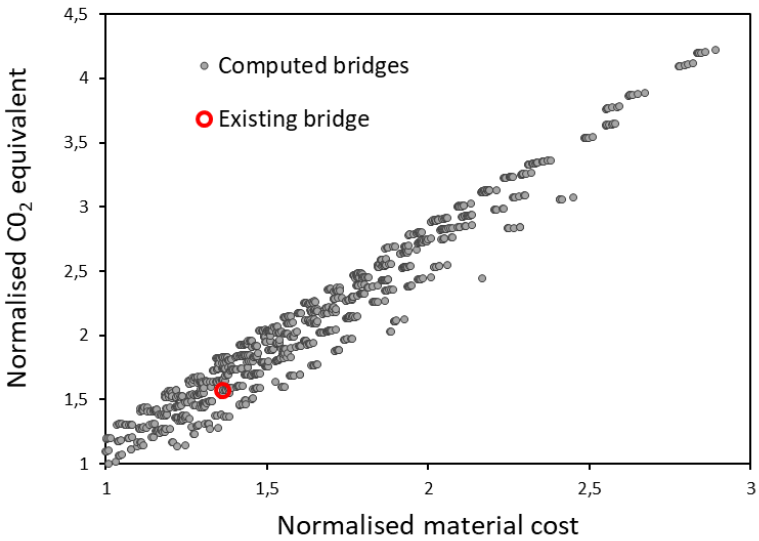

Figure 5.2. Estimated material cost and CO_2 equivalent emissions for several hundred variations of a concrete beam bridge. Results have been normalised by dividing all values by the minimum value obtained for each criterion. The red mark indicates the corresponding values for the existing bridge. Elaborated from results in **Paper D** and published in [45].

5.2 Multi-criteria sustainability assessment

Sustainability, buildability and structural performance aspects can be considered early in the project using suitable MCDA methods, as described in **Paper E**. MCDA methods take into account multiple criteria to help decision makers organise information in order to make a confident decision [46]. MCDA is well-suited for predictive sustainability assessment and has often been used for this purpose [47–50]. It can be used in different project stages; in the client's design, in procurement and in the contractor's production planning, or for follow-up. In the procurement stage, MCDA methods can be used to evaluate tenders. However, as discussed in Section 2.4, this sets high requirements on the method and the process used for the evaluation, which leads to clients almost always procuring infrastructure projects based on lowest price only.

To be applicable in the procurement stage, a MCDA method used should satisfy the following characteristics [51]:

- Flexibility: The method should be usable with different sets of performance-based criteria and for diverse projects with minor adjustments.
- Consistency: The results of the assessment should be coherent and reproducible with low variation.
- Transparency: The method needs to be pre-defined and described in the tender documents. The way the results are obtained should be transparent.

- Measurability and verifiability: The assessment should be based on measurable and verifiable information provided by the contractor. Thereby, the contracting authority can check that the performance level announced in the tender has been satisfied.

5.3 Collection and use of experience from construction and service life

Assessing the consequences that design choices, made in the early planning and design stage of a project, will have during the construction and whole life cycle of a structure requires information to evaluate or compare alternatives according to different criteria. 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 gather experience and knowledge from these phases from other projects in order to reuse them to motivate choices in following projects.

Adopting a sufficiently broad approach to plan and compare alternatives is also necessary. For instance, while an alternative may appear more economical to build, it may end up having a larger life cycle cost (LCC) due to its need for maintenance during its service life or having greater negative societal impacts during construction due to a longer construction time or due to construction activities generating more disturbances. Therefore, when comparing alternatives, it is important to consider aspects such as the construction methods used and the predicted performance of the structure and its components during their entire life cycle. This has been exemplified in **Paper E** through the study of a bridge replacement project for which two different construction methods were considered. Besides the respective construction costs associated with each of these methods, it was shown that the chosen construction method has an impact on the traffic delay costs, the time of construction and the LCA considering global warming potential.

In **Paper F**, for instance, interviews were conducted to learn from two completed offshore wind farm construction projects in specific “inner sea” conditions. This allowed to identify challenges encountered in the installation phase of these projects. This kind of knowledge and experience is very useful to mitigate risks in future projects. This information can also be used to refine predictions in the early stage of subsequent projects for better planning and for comparing different design alternatives, e.g. information on the actual transport and installation times required for the different components to be assembled offshore and how these were affected by weather conditions. One difficulty lies in spreading this information across projects and persons involved in different stages and activities to be able to reuse it in future projects. This may require analysing and recording this type of data in a systematic and quantitative manner. For example, one installation challenge identified in **Paper F**, which necessitated unplanned work offshore at one of the wind farms, was due to too tight tolerances for bolts at the interface between the concrete foundations and the towers of the wind turbines. This experience can be used to define appropriate values and limits for tolerances to enhance buildability for future applications of specific solutions and methods.

It is also important to have reliable information from the construction outcomes and the actual performance during the use and operation phase of solutions used in previous project. For instance, there are numerous reports from Sweden and abroad of cracked concrete foundations of wind turbines but there is lack of details on their causes and consequences [52, 53]. This kind of feedbacks would be required in the design stage for designers to make informed buildability-oriented choices that may appear more expensive but could reduce risks of construction defects and need for expensive remedial measures. Therefore, it is important to gather information and experience from the construction stage and its outcome in form of observations and recommendations of measures that can be taken into account in the design stage for preventing the repetition of these quality issues in future projects.

5.4 Integration of optimization and artificial intelligence methods

In the proposed framework, SBPD is used to generate a large number of design alternatives that are then iteratively filtered to remove undesirable and inferior alternatives. The automated method that has been developed and applied is also well suited for training AI. Using AI, suitable alternatives can be directly suggested without having to make the heavy calculations required to find out if a design meets the requirements from building standards or not. Systems using AI can, by observing large amounts of generated design alternatives, draw their own conclusions regarding which additional options fulfil building codes requirements and are suitable from a sustainability, structural performance and buildability perspective. AI-based models can be used in complement to the SBPD method proposed in this thesis to speed up the process and to be able to provide additional suggestions for options that were not initially generated in the SBPD method.

6 - Concluding remarks and outlook

The overall aim of this thesis was to propose an integrated conceptual framework that is applicable in the early design stage of civil engineering projects. The thesis is based on a number of case studies related to the development of new structures, materials, construction methods, as well as structural engineering design and analysis methods. This allowed to achieve a comprehensive view on the overall design process and to identify potential for improvement. Concluding remarks are given in this chapter and suggestions for further work are presented.

6.1 Concluding remarks

The review of current demands on building and civil engineering structures indicates a growing focus on sustainability and life-cycle considerations and on buildability issues, as well as needs for new structures and materials tailored for specific applications (e.g. new types of energy structures and offshore structures). Performance-based requirements, such as sustainability, buildability and structural performance requirements, should be used in the structural design process and encouraged by a performance-based procurement process.

As shown in this thesis, existing methods and tools can be adapted to meet the demands on structural engineering of today. Special attention should be given to choices made during the design stage of a project, as they have the potential to give significant improvements in sustainability and performance of structures and in their ease of construction. To find and enable an appropriate solution requires adequate choices and development at different levels:

- materials, e.g. more sustainable materials or well-performing materials for specific applications,
- structural engineering systems, e.g. efficient structural solutions and structural solutions for new applications,
- construction methods, e.g. low disturbance or accelerated construction methods,
- design and analysis methods, e.g. reliable and not overly conservative design methods using strut-and-tie models and nonlinear finite element analysis,
- interdisciplinary methods, e.g. holistic analysis of wind turbines considering the entire structure and soil-structure interaction at once, and
- flexible and reusable design methods, e.g. by use of parameterization.

The proposed conceptual framework integrates advanced structural engineering methods and technologies with data-driven decision making methods, as illustrated in Figure 6.1. It supports better-informed decisions in the early design stage taking into account the sustainability, structural performance and buildability of the solutions. To this end, performance-based requirements need to be broken down to performance-based criteria that can be assessed predictively and controlled at a later stage. Methods for assessing the consequences of design choices in terms of relevant criteria are essential for the construction sector as it is early in the projects that the possibilities to positively impact the outcome of a project are the greatest.

To meet the need to evaluate design alternatives against criteria, a set-based parametric design method was developed. The method combines set-based design with parametric design, advanced structural analysis methods, and criteria-based decision making. It has been demonstrated that this method is suitable to assess a large number of design alternatives based on different dimensions, materials, structural systems and even structural analysis methods. In addition, the method is flexible and can account for different criteria in different stages in order to identify the most advantageous solution for a project in the early design stage. In the cases studied, the proposed method led to designs that were significantly more efficient in terms of material cost and CO_2 equivalent emissions, compared to a traditional point-based design approach.

It was shown in this work that multi-criteria decision analysis can be used in the early design stages to assess the sustainability, buildability and structural performance of design alternatives over their life cycle. Nevertheless, it has also been identified that the identification, definition, and quantification of performance-based criteria at the beginning of a project is essential. This is a challenge for the construction sector as detailed information on performance requirements is scarce at this stage.

Information from the life cycle and value chain of the structure (e.g. related to material, structural system, methods of construction, environmental conditions) must be reliable to be able to predictively evaluate relevant criteria for different design alternatives. For the conceptual stage, this information may be obtained from tests, experience, and by gathering and analysing data from the construction and operation stage of building and civil engineering projects.

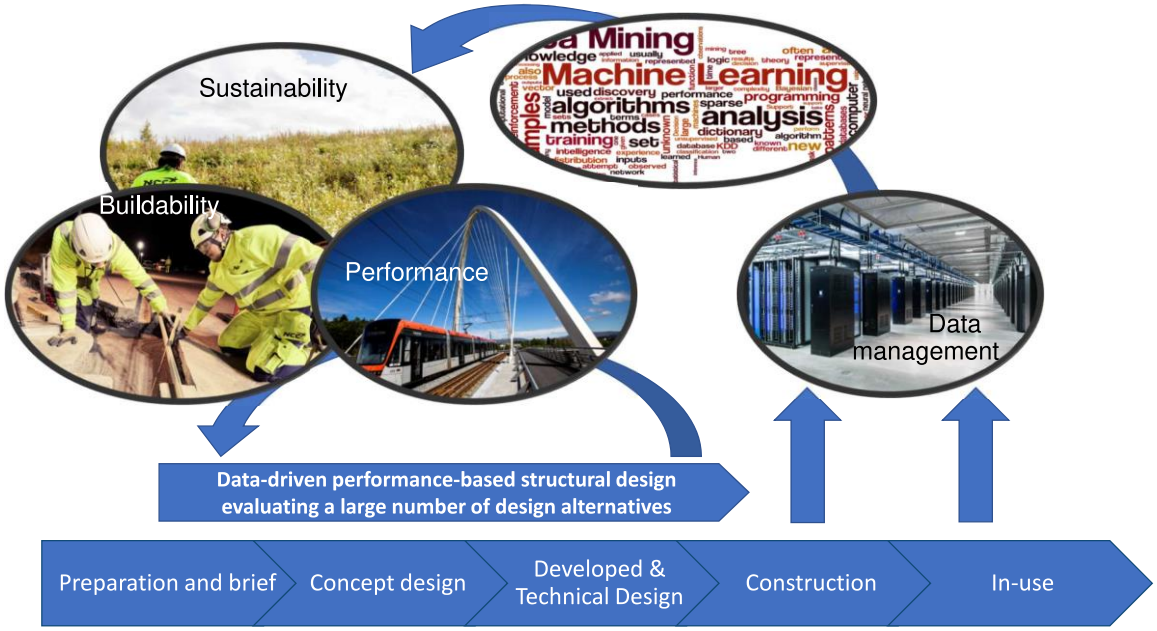

Figure 6.1. Overview of the sustainability-, buildability- and performance-driven structural design framework proposed in this thesis.

6.2 Future work

Possible directions for future studies and recommendations for further research have been identified. Methods based on the integrated framework proposed in this study should be developed further and put into practice by applying them on design cases. The use of optimization methods and artificial intelligence are promising to keep the calculation time low and to analyse large amounts of data to predictively assess performance-based criteria.

More criteria should also be taken into account in the assessment in as accurate, comprehensive and rigorous a manner as possible. This requires gathering and analysing data and information from completed and on-going projects. In this respect, it is necessary to determine what kind of information is needed and how it should be used. To achieve a holistic assessment of the sustainability, buildability and structural performance of designs, effects over the whole life cycle and value chain of the infrastructure should be included. It will also enable comparability of the results of assessments of similar projects.

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