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Sustainability-driven structural design using artificial intelligence

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1 Abstract

The construction industry is responsible for a large share of the global environmental impact. The need for addressing sustainability and increased competition calls for the development of innovative design methods that include sustainability in a transparent way. The aim of this work is to propose a framework to use machine learning and artificial intelligence (AI) for structural design optimization based on sustainability and buildability criteria. AI opens up new possibilities to optimize and assess structures early in the planning and design stages. In that way, it is possible to decrease the negative and enhance the positive environmental, economic and social impacts and create a more time- and cost-effective design process. The work is meant to serve as a first step toward the development of AI-based methods in the construction industry, which can bring digitalization in the construction industry to a new level and create new services and business models.

Keywords: Sustainability, structural design optimization, artificial intelligence, set-based design, life cycle sustainability assessment, multi-criteria decision analysis, construction.

2 Introduction

The construction industry is often depicted as a conservative industry relying on traditional methods. The European market for the construction industry is growing, and competition as well as the focus on sustainability is increasing. Authorities and municipalities responsible for the transport system and associated infrastructures are today in great need of addressing sustainability when upgrading and renewing the transport system. The same applies to both private and public residential builders. This together with the increased competition calls for an innovative design method that includes sustainability in a transparent way.

Simultaneously, the rapid development of artificial intelligence (AI) can lead to major changes in the

structural engineering process and opens up new possibilities to consider sustainability in the design stage. This can help reduce negative and enhance positive environmental, economic and social impacts, lead to a more efficient construction process, cost-effective solutions and new business models. With AI, the construction industry has the possibility to design, evaluate and optimize design concepts faster than ever. With the traditional calculation worksheets and design software used by structural engineers today, such optimization process would be costly and time-consuming.

The purpose of this study is to propose a framework to integrate AI with structural design and sustainability assessment methods and analyze the potential of this design framework in civil engineering applications. The proposed framework makes it possible to optimize the technical solution

with regard to sustainability and buildability aspects in an integrated way of working that facilitates collaboration between specialists. It is important to develop these types of cross-disciplinary, integrated ways of working to meet society's sustainability challenges. This requires integrated methods and tools.

This study focuses on the combination of three methods that catalyzes an integrated design approach: set-based design, life cycle sustainability assessment (LCSA) and multi-criteria decision analysis (MCDA); and a framework is proposed to use these methods together with AI.

3 Background

This section provides brief descriptions of the different aspects that are forming part of the proposed framework and some of their previous applications in building and civil engineering design.

3.1 Life cycle sustainability assessment

Sustainability can be assessed using the Life Cycle Sustainability Assessment (LCSA) model [1]. LCSA is a combined assessment using the tools: life cycle assessment (LCA), life cycle costing (LCC) and social life cycle assessment (SLCA). According to [1], the three separate life cycle assessments shall have consistent, ideally identical, system boundaries and there shall be no weighting between the sustainability domains (option 1 in [1]).

Today it is considered best practice to perform LCA for construction products in accordance with the EN 15804 standard [2]. This standard provides core product category rules (PCR) for all construction products and services. The standard classifies the life cycle stages of a product in modules; modules A1-A3 correspond to the product stage from raw material extraction to building material manufacturing, A4-A5 to the construction process stage, B1-B5 to the use stage relating to maintenance, B6-B7 to the use stage relating to operation, C1-C4 to the end-of-life stage and module D to the benefits and loads beyond the system boundary. In addition to the EN 15804 standard, there are specific product category rules for bridges, elevated highways and tunnels [3].

LCC for buildings should be performed according to the standards ISO 15686-5 [4] and EN 16627 [5],

which include both life cycle costs and incomes. There is not yet an ISO or EN standard on LCC for civil engineering works. The environmental cost of any product or activity can be calculated according to the ISO 14008 standard [6].

SLCA for buildings should be performed according to the standards EN 16309 [7] and EN 15643-3 [8]. The UNEP/SETAC Guidelines for Social Life Cycle Assessment of Products [9] and their Methodological Sheets [10] are also important documents to follow when performing SLCA and choosing social criteria, for any product. There is not yet an ISO or EN standard on SLCA for civil engineering works.

Furthermore, a life cycle sustainability assessment of a bridge can follow the EN 15643-5 standard [11]. This standard outlines a framework on specific principles and requirements for sustainability assessment of civil engineering works. In addition to the modules included in the EN 15804 standard, the EN 15643-5 standard includes the module A0, which is the pre-construction stage, and the module B8, which is the use stage relating to the user's utilization.

3.2 Buildability

It can be argued that aspects of buildability are included in the sustainability assessment of an infrastructure's life cycle. This is true with regard to analysis of existing structures, but less practical with regard to early stages of design and tendering activities. In initial stages of design, the risk of the construction engineering activities must be assessed and minimized. Therefore, it is important to give special attention to criteria related to buildability. This buildability awareness in the design stage can lead to seek design solutions that enable ease of construction and to implement platforms for construction products [12, 13].

3.3 Multi-criteria decision analysis

Multi-criteria decision analysis (MCDA) increases the transparency of the decision process and makes complex decision problems easier to understand. It is a method which takes into account multiple criteria to help decision makers organise information in order to make a confident decision [14]. It is a well-suited method for sustainability

assessment and has been used for this purpose in many cases in the field of structural engineering [15–18].

MCDA methods applied for sustainable bridge design were reviewed in [15]. The most common methods were identified for each life cycle stage in which they were used. For the design and planning stage and the construction stage, the Analytic Hierarchy Process (AHP) method [19] was most common. For the use stage (maintenance and operation), the AHP in combination with the Fuzzy method was most common, mainly because criteria often were subjective. In the end-of-life stage, the only method used is the Analytic Network Process (ANP).

Questions to help analysts choose a MCDA method adapted to the decision context were formulated in [20]. The crucial question to start with is: what type(s) of results is the method expected to bring?

3.4 Set-based design

The traditional structural design process in civil engineering is almost exclusively based on a so-called point-based design 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 possibilities are discarded already at an early stage. The ineffectiveness of this approach 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 [21]. In set-based design, the decisions involved in the design process are not made with a single design in mind; instead a set of designs is decided by the stakeholders and progressively narrowed down according to the requirements and choices of those involved in the project.

3.5 Artificial intelligence

Artificial Intelligence (AI) and Machine Learning are research areas where the goal is to develop models that can learn to perform predefined assignments, by observing large amounts of data. In recent years, a very rapid development has taken place in these areas, driven primarily by a sharp improvement in

computer hardware and by a massive increase in available data.

AI agents can be trained to perform the same tasks as engineers. Human intelligence comes from experience, more iterations of a certain task increase the experience, thereby learning to perform that task with increased precision. Experience can also be achieved by exploring adjacent areas and innovate from the learnings gained.

To train an AI agent for a structural design task, it is important to mimic the procedure that the engineer follows. There are several approaches to how the agent/agents should be organized and one of the most important questions is to decide if the agent should operate on a general or specific level, i.e. should the agent perform the design and propose a solution, or should specific interconnected agents support with specific design tasks, e.g. design the section of a structural member.

The short-term potential with an AI-supported design method is in the increased speed of the design tasks that enables to explore numerous solutions in a minimum time. In the long-term, the potential is in the possibility to include an endless number of criteria.

4 Proposed framework

The proposed framework combines parametric design, set-based design and life cycle sustainability assessment coupled with MCDA. The method is further complemented using AI. The method is intended to be used by consultants and contractors in the early stages of a construction project.

4.1 Set-based parametric design method

A set-based design approach allows to consider a large number of designs and to evaluate them according to many different criteria in the early design stage. Parameterization is used to allow varying a lot of parameters characterizing the different designs considered. These designs are based on different materials, different material properties for the same type of material, different sectional geometries and sizes, different reinforcement layouts for concrete elements etc.

4.2 Multi-criteria life cycle sustainability assessment method

In the proposed method four main criteria are suggested: the environmental, social and economic dimensions of sustainability, and buildability. The underlying method proposed for the sustainability assessment is option 1 in [1]; $LCSA = LCA + LCC + SLCA$, with minor alterations, addition of the buildability criterion, and coupled with MCDA. The life cycle sustainability assessment follows the framework outlined in the EN 15643-5 standard. The assessment is performed for the entire life cycle of a bridge; modules A0 to D including B8. Each main criterion is decomposed into lower-level criteria that are relevant for the specific project. A comprehensive list of lower-level criteria chosen as important for sustainability assessment of bridges is presented in Table 1. From this list, the most relevant criteria can be chosen for each case to be assessed, based on the site-specific conditions. Each life cycle stage has its own set of lower-level criteria and they are assessed separately for each life cycle stage. Buildability is assessed with lower-level criteria chosen with inspiration from [22], see Table 1. Finally, MCDA is used for the evaluation of designs based on the criteria included, see Figure 1.

4.3 Integrated framework based on AI

In the same way as human intelligence, AI uses experience and historical data, which means that AI has the potential to bring together a breadth of specialists in an integrated approach.

The development of parametric dimensioning that has taken place in recent years has created the conditions for starting to train intelligent algorithms. In the proposed framework, parameterized models are used in a set-based design approach, as developed in [24], to generate and analyze numerous design options, see Figure 1. This parametric set-based design method combines advanced parametric structural design with sustainability assessment and MCDA to evaluate the technical solutions' buildability and sustainability impact. This allows to study the influence of the various parameters. Inferior designs that do not fulfill the design requirements are filtered using several preselected filters (e.g. ultimate limit state (ULS) and serviceability limit state (SLS) checks according to Eurocodes [23]). The

Table 1. Main criteria and lower-level criteria (specific life cycle stages indicated in brackets when applicable).

Environmental	Social
Biodiversity impact	Safety of construction site workers
Water management	Safety/ security/ resilience of area of influence
Abiotic depletion potential-minerals & metals	Stakeholder participation
Abiotic depletion potential-fossil	Aesthetic perception of users (<i>only B8</i>)
Acidification potential	Accessibility/mobility
Global warming potential (fossil/ biogenic/land use)	Time of disturbance
Eutrophication potential	Protection of cultural heritage
Soil quality	Noise
Waste disposed	Vibration
Ozone depletion potential	Job creation
Photochemical ozone creation potential	Equality
Use of primary renewable energy resources	Water deprivation potential
Use of primary non-renewable energy resources	Human toxicity potential
Components for reuse	Particulate matter emissions
Materials for recycling	Buildability
Materials for energy recovery	Simplicity of design details
Exported energy	Material supply reliability
Economic	Technological risks of methods used
Life cycle cost (<i>not B8</i>) (incl. costs and incomes)	Specific construction work experience
Environmental cost	Repetition on global structural level
Users cost (<i>only B8</i>)	Innovative construction methods and tools

remaining options undergo an evaluation routine based on selected LCSA criteria and MCDA methods. This provides a knowledge- and information-based decision-aiding tool for the early stages of a construction project.

Set-based design relies on the generation of a large number of designs that are then iteratively filtered to remove undesirable ones. However, there is no well-defined procedure to generate the initial designs. By adapting and training AI algorithms, suitable designs can be directly suggested without having to conduct the potentially 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 designs, draw their own conclusions regarding which additional options are permitted according to building standards and suitable from both a sustainability and a buildability perspective. The AI-based design method will be used as a complement to set-based design method to speed up the process and to be able to provide additional suggestions for options that were not generated in the initial set-based design process. In the final step, a human verification allows to validate the preferred design option.

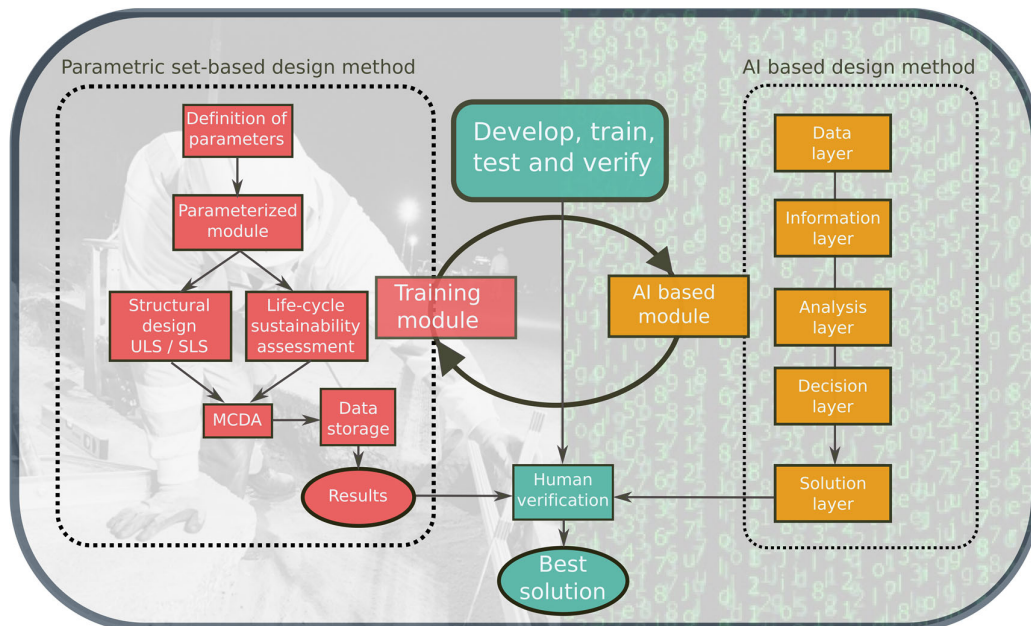


Figure 1. Proposed integrated framework based on AI and the set-based parametric design method developed in [24].

5 Discussion

The development of AI offers new opportunities to optimize construction projects already at the design stage. In the same way as human intelligence, AI uses experience and historical data. With today's computing power and easily accessible advanced algorithms, the construction industry can gather, evaluate and transfer experience and knowledge regarding the effect of design choices on the entire life cycle of a construction work, see Figure 2. This is an innovative way of avoiding today's "memory gaps" between projects and sharing knowledge and competence between generations. Great opportunities are opened up to take into account the experiences of previously built structures, from their design, construction and use stages, and to

optimize future structures with respect to sustainability criteria.

A SWOT analysis has been conducted to identify the strengths, weaknesses, opportunities and threats of the proposed framework, as presented in Table 2.

The proposed framework does not constitute a solution in itself, but rather a tool for designers to perform repetitive design tasks and achieve better structures. Depending on how it is implemented and used this way of working can either lead to too similar and repetitive solutions or free time for designers to express their creativity. Interrogations that the use of AI may raise on responsibilities are not so critical as long as a traditional complete technical design is required to check the adopted design option.

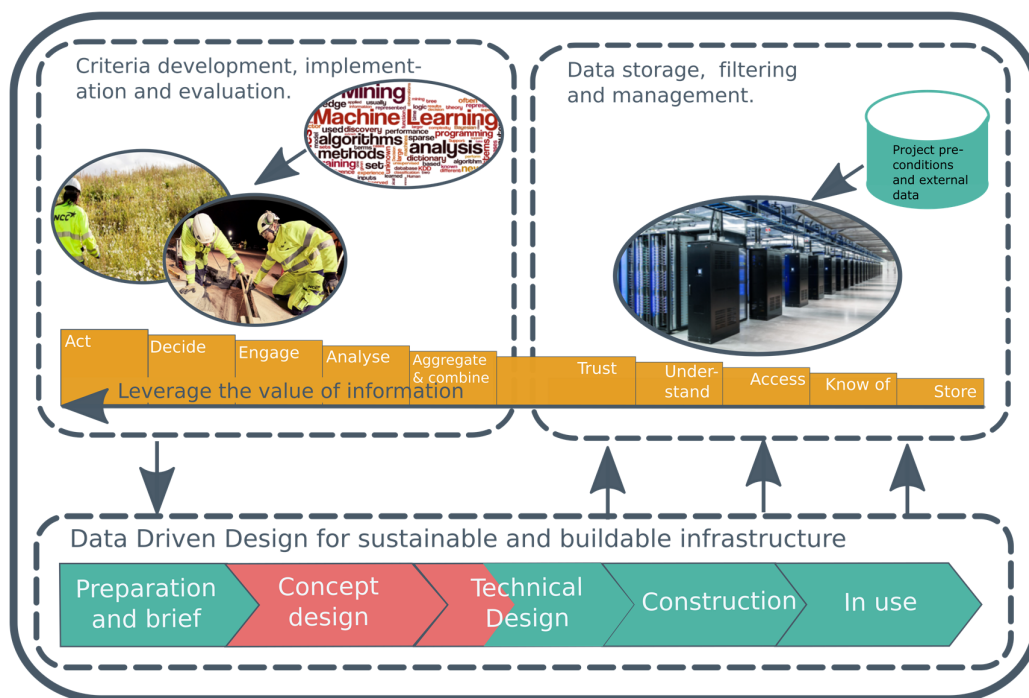


Figure 2. Data-driven design for sustainable and buildable infrastructure.

Table 2. SWOT analysis of the proposed framework.

Strengths	Weaknesses
<ul style="list-style-type: none"> • It allows to consider a large number of designs in the early design stage. • The integrated approach based on parameterization allows to save time in case of design changes. • It provides a transparent evaluation and better understanding of the influence of design choices. • It offers a good basis for discussion and decisions. • It enables choosing the most sustainable solution from a life cycle perspective. 	<ul style="list-style-type: none"> • It requires longer time to be implemented and to lead to first results. than a “traditional single case design”. • Considering a larger number of designs requires longer computing time. • Through the use of AI, some parts of the process may become less transparent and control over the optimization process may be reduced.
Opportunities	Threats
<ul style="list-style-type: none"> • The automation of monotonous design tasks can free time for designers to focus on more creative activities. • The use of AI and optimization methods can lead to substantial reduction of the computing time required to analyze a large number of designs. • Proper parameterization and documentation can facilitate reuse, improvement and extension of design calculations and models. • The direct feedback that the designer receives on his design choices, in terms of sustainability assessment, facilitates learning and experience development. • Using such a framework and gathering information from existing projects will improve the trustworthiness of the early sustainability assessment of designs. • It can be a catalyst for industrialization of the design process. 	<ul style="list-style-type: none"> • This way of working may lead to standard and too uniform structures, which lack human touch. • A growing complexity of models may affect their understandability and performance. • The use of AI raises new questions on the determination of responsibilities in case of problems or accidents. • Intellectual property rights and data ownership can constitute barriers to collaboration within projects. • There is a risk that the criteria evaluation is based on biased data and unfairly favors certain designs.

6 Conclusions

The rapid development of AI methods and the growing examples of applications in structural engineering create new possibilities in structural design. The proposed framework, integrating set-based parametric design, multi-criteria life cycle sustainability assessment and AI offers considerable possibilities to train AI algorithms. AI allows to explore the whole set of possible designs to find the most sustainable design while keeping the required computing time low.

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