Opportunities in Civil Projects with Artificial Intelligence

Citation for the original published paper (version of record):
Kjellgren, A., Kettil, P., Rempling, R. et al (2023). Opportunities in Civil Projects with Artificial Intelligence. IABSE Congress New Delhi 2023 Engineering for Sustainable Development.
http://dx.doi.org/10.2749/newdelhi.2023.1207

IABSE Congress New Delhi 2023
Engineering for Sustainable Development

Opportunities in Civil Projects with Artificial Intelligence

Alexander Kjellgren, Per Kettil

Skanska Sweden AB, Gothenburg, Sweden

Rasmus Rempling

Chalmers University of Technology, Gothenburg, Sweden

Mats Karlsson

Swedish Transport Administration, Gothenburg, Sweden

Contact: alexander.kjellgren@skanska.se

Abstract

To analyse and compare different production methods, innovative designs and sustainability are essential keys in civil projects. A promising approach is to combine automated design methods supported by artificial intelligence (AI). The purpose of this study was to identify and describe knowledge gaps in this field and necessary method development. A series of interviews were performed with experienced personnel from the construction business in order to point out how evaluation of alternatives in today's tender processes are performed. Furthermore, a literature review was carried out to determine the possibilities with AI. It can be concluded that requirement documents, and information management need to improve. Furthermore, several methods for multi-objective constrained optimization exists today. If this is combined with a set-based parametric design approach, contractors could increase their ability in finding opportunities.

Keywords: Digitalization; artificial intelligence; multi-objective optimization; automation.

1 Introduction

The EU-commission adapted a climate goal for a sustainable future, where all member states should be climate neutral by 2050 [1]. The concept of sustainability of today encompasses three categories: economic, environmental; social. Civil projects have a large impact on all these categories and will require extensive adjustments in order to successfully meet this growing demand, especially since the number of infrastructure project is expected to increase in forthcoming years [2]. To address more objectives than lowest price during design, is relatively rare. Sustainability performance is considered important during infrastructure project, although it most often comes down to overall cost, when decisions are made. A holistic view of sustainability should be adapted, where several objectives are optimized, to find a neat trade-off, when objectives are conflicting. In addition, client requirements are extensive and difficult to overview, hence enforcing constraints to contractor solutions which need careful consideration. Infrastructure projects need an increasing sustainability performance and methods to quantify and automate this process are essential for success.

As mentioned, client requirements increase, are often very extensive and several stakeholders are included. Managing client requirements properly are important when opportunities are search for in projects, hence a systematic requirement process is desirable. From a given set of requirements, together with chosen objectives, an optimal solution is searched for, which entails the need for an automated processes since the solution space will be large. By tradition, the contractor evaluates possible solutions during a tender phase, largely by previous experience by individuals. The number of studied alternatives is few, and the resolution of these evaluations are somewhat coarse. Thus, the potential to further develop methods for better alternative comparison is evident and will advance contractors in finding opportunities.

The accelerating digitalization of the construction sector is supporting the development of new tools and methods, however with varying production implementation. For instance, is *BIM* in many aspects integrated in design and production, whereas *AI* is more of a discussion subject and is never used in practice [3]. The potential in increased digital support is however large. The amount of data managed during large infrastructure projects is huge and ever-growing. The future will probably require data-driven decision making with the support of AI, where complex problems are analysed with historic data together with advanced comparison of possible solution alternatives. Automated analysis with AI, also enhances the ability for contractors to engage in creative and innovative tasks since focus may be shifted towards holistic solutions rather than detail optimization [4]. This view entails the need for *multi-objective constrained optimization* to be further developed, which is an important factor for a successful project.

In conclusion, it is probable that the focus on total sustainability performance will increase in construction projects in a near future. Furthermore, multi-objective constrained optimization with AI will be an essential tool in the pursuit of pareto-optimal sustainable designs and production methods.

2 Purpose

The purpose of the pre-study is to identify, examine and describe knowledge gaps concerning the field, described in section 1, regarding turnkey contracts in Sweden. Best-practice as to how opportunities are analysed and searched for in the projects of today from a contractor viewpoint are also to be presented, together with an evaluation of the potential with AI. Moreover, how creative, and innovative tasks are managed in projects are also examined. For the most part, turnkey contracts are addressed from their intension of contractor influence and freedom, albeit transferable points can frequently be made, for other contract types.

From this, some guiding questions have been composed which are presented below.

- How can tender work improve when it comes to finding alternative and/or innovative solutions, while still meeting requirements with high quality together with multi-objective optimization?
- How many structural choices and technical solutions are evaluated today? How many objectives are evaluated, e.g., cost, CO_2, buildability and so on?
- Is it possible to produced models in a time efficient manner, perform multi-objective constrained optimization on these, and draw conclusions from this, as to possible opportunities?
- Which method development is necessary in order to facilitate the finding of opportunities? Can methods be developed, to enhance contractor possibilities in their work of multi objective constrained optimization?

3 Objective

Apart from answering the explicit questions formulated in section 2, the study contributes to a concrete summary of possible method development of multi-objective constrained optimization with AI. This will provide a starting point for further research to provide the construction sector with a better understanding of optimization of products and finding opportunities.

4 Method

The study is interdisciplinary and will consider several fields, for instance structural design, digitalization, AI, optimization and work processes. By a literature review together with an interview study, the intention is to examine and evaluate the formulated problem. The research front is also to be established together with the current position of the construction sector.

4.1 Literature Review

A state-of-the-art literature review has been performed according to the subjects of multi-objective constrained optimization, parametric design and decision making with (and without) the support of AI. Learning criteria for the AI was also studied in relation to structural design and comparisons of alternatives. In this review, the *possibilities* with AI were studied together with what further demands that might arise from this development, rather than implementation of AI tools. The aim was to achieve a proper view of the potential with AI and what method development that are necessary, to implement this in the construction trade.

4.2 Interview Study

Interview has been conducted to establish best practice of the tender processes of today. What are the problems? Focus was on how comparisons of alternative solutions are carried out today with vast client requirements. Furthermore, suggestions for improvements were searched for and dealt with. The selection of interviewees was based on relevant work tasks (design managers, design specialists, region managers, digital development managers, project managers, construction workflow managers) and experience. In addition, both client and contractor are represented in the selection and in total 11 interviews were carried out.

5 Results

The results, from performed literature reviews and interviews are presented next.

5.1 Literature Review

Present requirement documents are to a large extent focusing on quality and detailed requirements even though the ambition from the major client is performance requirements. This approach would enable a more holistic view on the tender process, where a higher total sustainable performance may be achieved [5]. Performance requirements are indeed more cumbersome for the client since a higher level of interpretation is possible. The client should therefore aim for sharp and carefully selected performance requirements, hence requirements that establish clear client objectives and important conditions, while not enforcing unnecessary restraint on the contractor part. The possibility to influence design and consequently sustainability is greater early in tender offers [2,6]. Thus, sustainability should be evaluated through a thorough process and where alternatives are objectively evaluated. The choice of included sustainability parameters are important since this has a great impact on the outcome, where the result may vary depending on included parameters [7]. Several studies have been performed, comparing different sustainability parameters such as: material cost [8]; cost, CO_2 and service life [9]; cost, CO_2 and safety [10]; total energy and cost [11]; or as most common, cost and CO_2 [12-16]. In addition, comparative studies of sustainability regarding different bridge types have been carried out, pointing to the fact that every project is unique. For instance, a concrete frame bridge may show the best sustainability in one case [17,18], whereas a steel-concrete solution is more optimal under other circumstances [19]. There are several standards today, describing a general framework for evaluation of sustainability performance, where an overview is presented by Ek et. al. [20]. Some hardship regarding these standards is in question since frameworks are theoretical and do not deal with practical implementation, hence one method for practical implementation of these frameworks is also suggested [20]. A case study is conducted in order to evaluate the potential of said method, where two bridges are examined [21]. Results indicate that total sustainability is multifaceted, where included parameters highly determine outcome.

Traditional design process follows a point-based design procedure, where a design suggestion is developed before the tendering process by the client. The contractor refines this suggestion, however conceptually new designs for a given project is rarely evaluated. An alternative approach is set-based parametric design (SBPD), where a set of possible solutions are developed from all different available options in the requirement documents. Specific solutions are not treated in this approach; the set of solutions is defined from the available options. Alternatives are then eliminated during the ongoing process enabling a large number of alternatives to be evaluated compared to point-based design [22,23]. From this approach, more alternatives can be maintained during a longer timeframe of the design process. A SPBD can also be defined from constraints and requirements, i.e., what is *not* possible? [24]. This view enables even more alternatives to be processed which further underlines the need for automated methods with decision analysis. Case studies with SBPD have been performed, where the method potential is evaluated. Three already built bridges were analysed and compared with SBPD [22]. Results indicate that the studied bridges could reduce cost and CO_2 significantly, when SBPD was utilized. Furthermore, reinforcement layout was studied with SBPD, indicating great potential, where the initial set of solutions were gradually reduced by constraints together with stakeholder preferences [23].

When the solution space increased from a large number of available solutions, automated methods are necessary. This approach can further be enhanced with support of AI for advanced decision analysis in the search for a pareto-optimal solution. These multi-objective constrained optimization problems are necessary to solve, when the client constraints are extensive together with a growing number of sustainability objectives. Several methods exist today for decision analysis where an overview have been presented [25]. Pros and cons can be found for all methods and no best practice is concluded.

Artificial intelligence (AI) can be used when the solution space increased from degrees of freedom, constraints, and objectives. The time for FEA is extensive when the number of models that need evaluation against constraints are large. An AI may be used to search for pareto-optimality with fewer calls for FEA, enabling a larger solution space. The general digitalization in the construction sector have increased the interest in AI tools, even though no practical implementation is known [3,26]. The possibility of increased productivity and data-driven decision analyses is large, although successfully implementation in practice will require changes in standards, workflow, management, and professional knowledge [3]. A large number of AI-methods, -algorithms and -tools have been the subject of many studies in the literature. During tender processes, an AI-tool was evaluated, where the tool analysed requirement documents, yielding decision support through information structuring. Good potential is shown, although historic data and information structure need to improve [27]. Window recognition on images have successfully been carried out as basis for energy calculations [28] and an AI-algorithm have also been trained on architectural drawings to produce new drawings [29]. Increased competition and sustainability focus indicate that methods for multi-objective constrained optimization needs to improve. A framework for this approach together with the support of AI and SBPD has been suggested [30]. Large solution sets are generated whereby an AI may be trained to predict an outcome. Different AI-methods for optimization are evaluated such as *Glowworm Swarm Optimization* together with *Simulated Annealing* [31,32], whereby these methods successfully optimize several objectives. Furthermore, an *artificial neural network* (ANN) was trained together with a *harmony search* in order to predict correlations between parameters for a box girder bridge [33]. Results indicate that computation time could be reduced, although further development is necessary to find a better pareto-optimal solution. A *Hybrid Simulated Annealing* algorithm was examined to optimize multiple objectives, where it could be concluded that a reduction in total energy also reduced construction cost [34]. Additional algorithms for optimization of reinforced concrete have been evaluated from a structural point of view. For instance, the methods *Flower Pollination* [35] and *Artificial Bee Colony* [36] have both been able to successfully solve the optimization problem presented. *Bayesian Optimization* have demonstrated effective results when several constraints are enforced [37,38], for instance when time expensive calls to FEA are required to evaluate load effects. When the problem size increases from many parameters, objectives and constraints, computing power will soon be limiting the process. Metamodels are one way of dealing with this issue, where an overview has been presented with pros and cons for different methods [39]. Furthermore, Kriging based heuristic optimization is also possible as to deal with larger problem sizes [40,41].

Most often multi-objective optimization is performed, cross-section geometry, material quality, cost and CO_2 are the objectives of interest. Structural system optimization is rarer, although some examples are available. Topological optimization as to column placement for a bridge has for instance been examined with a *sequential linear programming* method [42]. Difficulties around local optimum for the method were reported albeit chosen objectives (volume, stiffness and eigenvalue) were analysed as conflicting. Likewise, column placement and span lengths were optimized for another bridge by a *genetic algorithm* and *pattern search*, where objectives were cost and environmental effect [43]. Results showed that objectives could be reduced by this approach. Optimization of shell structures has also been conducted where a form-finding algorithm evaluates loads and minimizes moment in the structure [44].

5.2 Interview Study

In general, there is more possibilities to influence design and production method early in projects phases, as for instance the tender process. Large infrastructure projects have a vast set of client requirements, originating from multiple investigations, land acquisition and social benefits. It is of great importance to see to that a client and contractor share the same objectives during a project, which is easier said than done. During a tendering process, it is appreciated from client perspective, for the contractor to be creative and to find smart solutions, while fulfilling client requirements. From this aspect, clients should give contractors as much freedom as possible in order to benefit from contractor knowledge of buildability and production experience, hence receiving low tendering offers. It is most important that requirement documents from clients are of high quality and complete. The opposite is however often the situation, where contractors receive requirement documents that are incomplete, with flaws and in addition, the contractor receive changes from the client, late in the process. In particular, site condition and geotechnical conditions have to be described properly in order for the contractor to be able to calculate a correct offer. Changes in these conditions most often render escalating costs, where conflict between client and contractor may arise.

The challenge for a client when producing requirement documents, lies in including *as little as possible but all that is necessary*. This is of course easy in theory and difficult in practice. The client should be thorough and meticulous when preparing requirement documents, since the contractor will miss anything not provided. The contractor on the other hand, should be humble and cautious when analysing requirement documents in order to properly evaluate these, both as regards of what is written but more importantly what is not. This is the client's possibility of adding degrees of freedom for the contractor, enabling their search for opportunities and competitive pricing. The tender process in Sweden is public, which entails that all contractors receive equivalent information. This not strange, however it poses some problems for a contractor when it comes to interpreting the requirement documents. It is not forbidden for a contractor to ask questions to a public client regarding requirement documents, however the answer to said question will be presented to all contractors. From this procedure, a contractor, who sees an opportunity but is uncertain of how this solution will be received by the client, do seldom ask questions to the client, from the risk of exposing a smart solution to competing contractors. Instead, if a possible opportunity appears, the contractors will wait for the tender process to finish, before pitching this matter, granted that the contract is secured. The client should aim for performance requirements and avoid, as much as possible, detailed requirements. This approach provides contractors with increased ability to use the presented degrees of freedom to find smart solutions. Of course, detailed requirements are in some cases necessary, originating from earlier investigations or court orders, although present requirement documents include way too many unnecessary requirements. This prevents the contractor from being creative and finding smart solutions. It is desirable from both a contractor and client perspective, to allow for a large amount of contractor freedom. However, there are also an increased responsibility on the contractor side from more freedom, that should be addressed. In addition, requirements should not always be interpreted with a black and white view, there is room for dialog with the client to find mutual beneficial solutions which sometimes require some requirements to be seen from different perspectives.

In general, opportunities are found by the contractor by utilisation of the degrees of freedom, provided by the requirement documents during the tender process. It is an important part of the tender process for a contractor to search for opportunities and smart solutions since this very well can determine the outcome. This is especially important regarding large and complex projects together with a good dialog with the client. Much comes down to organisation and to have experts and competent personnel available. If an innovative solution is presented, more experienced personnel are required in order to evaluate the solution properly. Furthermore, it is beneficial to settle the organisation well before the tender process start and the organisation should include personnel, that in the case of a contract assignment, carries the production into effect.

During the tender process, a contractor should deal with evaluation of alternative solutions. This is performed today, however the amount of analysed alternative solutions are between 2 to 8 for a large project. Furthermore, these analyses are often rather coarse where alternatives are screened fairly quickly. To attain a rewarding comparison of alternative solutions, it is important to early on start this work. The contractor should search for alternatives that match its competence and in addition try to find solutions that unravel client objectives and challenges. The resolution of the alternative evaluations needs to be on a level that enables relevant data to be extruded. Moreover, the cooperation between design, calculation and production is important to easier see the opportunities.

Innovation is rare in the construction sector, which for one part is due to risk handling. New or challenging solutions come with risk for the contractor who will be responsible accordingly. From this, the benefits of creative or innovative solutions must outweigh the potential risks with said solution. Risk management is of great importance, and indeed it comes down to who the accountable part will be, if a risk does occur. In general, risks that can be managed by the contractors should also stay with the contractor. On the other hand, risks that are not obvious or risk that does not require contractor expertise, should stay with the client since the client only will have to deal with increased costs in those cases where the risk actually occurs. If a contractor manages risks in a more extensive way, clients will probably have to pay more over time, since they also pay for risk that does not occur.

In order to achieve a profound design with a competitive production method, planning is of the essence. The contractor needs to develop construction documents where all technical fields are incorporated, avoiding rework. The tender offers have potential to improve although the contractor ambition is varying.

The digitalization is important to further enhance construction productivity. Present workflows tend to be rather sequential where design, calculation and planning need increased cooperation together with a joint data flow. AI may be helpful in these endeavours, although concerns regarding black-box solutions and quality assurance exists. It is important that results are transparent and that underlaying data can be examined. Furthermore, a significant risk is also that the overall comprehension of the construction process is undermined from too much reliance on computer support. The potential with automated and digital workflow with support of AI is extensive. A data-driven approach where huge amounts of data are available, would enhance sustainable solutions where multi-objective optimization together with knowledge of historic projects are key elements.

6 Discussion

In order to successfully meet upcoming climate goals and demand for increased overall sustainability performance, further development of methods is necessary. The client requirements are extensive and will probably not decrease when more objectives in infrastructure projects are relevant. To successfully utilize and adapt, digital tools and automated methods, are essential if these demands are to be met. From the freedom provided by a client, a contractor has an unexploited potential in finding opportunities in projects, although the tender process needs to allow for more contractor freedom to ensure that the aim of turnkey contracts is met. Requirement documents are difficult to produce but need improvement so that contractors may utilize its expertise to the full extent. To find opportunities are important and comes down to experienced personnel. Increased support in this process, by multi-objective constrained optimization would enhance contractor in their pursuit of project opportunities. Several methods exist to perform such optimization together with AI, although none conclusive best practice regarding its implementation to design and production problems exists. To systematically evaluate a project by data-driven and objective means, will enhance contractor possibility in developing competitive tender offers. Organization is key and experienced personnel are essential in present workflow for finding opportunities. To add a new player, an AI, to this procedure could be much beneficial from providing new insights to a contractor.

7 Conclusions

When possible, clients need to enhance contractor freedom, enabling an improved search for opportunities from creative and innovative solutions. Today, this search is in large managed by experienced personnel with reference projects, discussing a few alternative solutions. An AI may produce solution suggestions in order to facilitate the search for opportunities and creative designs from this data-driven approach. Further method development is however necessary for a holistic multi-objective constrained optimization regarding sustainability to produce these suggestions.

Some specific conclusions are also made, which are presented in the list below.

- Both contractor and client have a journey ahead, in order to enhance digitalization in the construction sector to reap the potential of data-driven workflow.
- Requirement documents need to improve, and contractors need to increase their ability in pursuing opportunities.
- Alternative comparisons require advancement, both in numbers and resolution in order to better support contractors in finding opportunities.
- Several methods for multi-objective constrained optimization with AI exits, however none is implemented in present projects or tender processes.
- Set-based parametric design show potential in producing large model spaces which could be combined with optimization and AI.

8 Acknowledgements

Financial support has been received from SBUF – the Swedish construction industry’s organization for research and development.

A final thanks to all interviewees who participated.

9 References

[1] European Commission. The Commission calls for a climate neutral Europe by 2050. Press Release. Accessed 2022-11-22. (2018). URL: https://ec.europa.eu/commission/presscorner/detail/en/IP_18_6543.

[2] Mathern, A. (2021). Addressing the complexity of sustainability-driven structural design: computational design, optimization and decision making. PhD Thesis. Chalmers University of Technology. Gothenburg, Sweden.

[3] Bosch-Sijtsema, P. Claeson-Jonsson, C. Johansson, M. and Roupe, M. (2021). “The hype factor of digital technologies in AEC”. Construction Innovation. 21(4). 899-916.

[4] Rempling, R., Fall, D. and Lundgren, K. (2015). ”Aspects of Integrated Design of Structures:

Parametric Models, Creative Space and Linked Knowledge". Civil Engineering and Architecture. 3(5). 143-152.

[5] Du, G., Safi, M., Pettersson, L. and Karoumi, R. (2014). "Life cycle assessment as a decision support tool for bridge procurement: environmental impact comparison among five bridge designs". The International Journal of Life Cycle Assessment. 19. 1948-1964.

[6] Kohler, N. and Moffatt, S. (2003). "Life-cycle analysis of the built environment". Industry and Environment. 26. 17-21.

[7] Braganca, L., Vieira, S.M. and Andrade, J.B. (2014). "Early Stage Design Decisions: The Way to Achieve Sustainable Buildings at Lower Costs". The Scientific World Journal.

[8] Boscardin, J.T., Yepes, V. and Kripka, M. (2019). "Optimization of reinforced concrete building frames with automated grouping of columns". Automation in Construction. 104. 331-340.

[9] Yepes, V., García-Segura, T. and Moreno-Jiménez, J.M. (2015). "A cognitive approach for the multi-objective optimization of RC structural problems". Archives of Civil and Mechanical Engineering. 15(4). 1024-1036.

[10] Martí, J.V., García-Segura, T. and Yepes, V. (2016). "Structural design of precast-prestressed concrete U-beam road bridges based on embodied energy". Journal of Cleaner Production. 120. 231-240.

[11] García-Segura, T. and Yepes, V. (2016). "Multiobjective optimization of post-tensioned concrete box-girder road bridges considering cost, CO2 emissions, and safety". Engineering Structures. 125. 325-336.

[12] García-Segura, T., Yepes, V., Alcalá, J. and Pérez-López, E. (2015). "Hybrid harmony search for sustainable design of post-tensioned concrete box-girder pedestrian bridges". Engineering Structures. 92. 112-122.

[13] García-Segura, T., Yepes, V., Martí, J.V. and Alcalá, J. (2014). "Optimization of Concrete I-Beams Using a Hybrid Glowworm Swarm Algorithm". Latin American Journal of Solids and Structures. 11(7). 1190-1205.

[14] Camp, C.V. and Assadollahi, A. (2013). "CO_2 and cost optimization of reinforced concrete footings using a hybrid big bang-big crunch algorithm". Structural and Multidisciplinary Optimization. 48. 411-426.

[15] Fernández, P.M., Sanchís, I.V., Franco, R.I. and Yepes, V. (2022). "Slab Track Optimization Using Metamodels to Improve Rail Construction Sustainability". Journal of Construction Engineering and Management. 148(7). 04022053.

[16] Yepes-Bellver, L., Brun-Izquierdo, A., Alcalá, J. and Yepes, V. (2022). "CO2-Optimization of Post-Tensioned Concrete Slab-Bridge Decks Using Surrogate Modeling". Materials. 15. 4776.

[17] Ek, K., Mathern, A., Rempling, R., Brinkhoff, P., Karlsson, M. and Norin, M. (2020). "Life Cycle Sustainability Performance Assessment Method for Comparison of Civil Engineering Works Design Concepts: Case Study of a Bridge". International Journal of Environmental Research and Public Health. 17(21). 1-34.

[18] Hammervold, J., Reenaas, M. and Brattebo, H. (2013). "Environmental Life Cycle Assessment of Bridges". Journal of Bridge Engineering. 18(2). 153-161.

[19] Du, G., Pettersson, L. and Karoumi, R. (2018). "Soil-steel composite bridge: An alternative design solution for short spans considering LCA". Journal of Cleaner Production. 189. 647-661.

[20] Ek, K., Mathern, A., Rempling, R., Karlsson, M., Brinkhoff, P., Norin, M., Lindberg, J. and Rosén, L. (2020). "A harmonized method for automatable life cycle sustainability performance assessment and comparison of civil engineering works design concepts". IOP Conference Series: Earth and Environmental Science. 588(5).

[21] Ek, K., Mathern, A., Rempling, R., Brinkhoff, P., Karlsson, M. and Norin, M. (2020). "Life Cycle Sustainability Performance Assessment Method for Comparison of Civil Engineering Works Design Concepts: Case Study of a Bridge". International Journal of Environmental Research and Public Health. 17(21). 1-34.

[22] Rempling, R., Mathern, A., Ramos, D.T. and Fernández, S.L. (2019). "Automatic structural design by a set-based parametric design method". Automation in Construction. 108. 102936.

[23] Parrish, K., Wong, J.M., Tommelein, I.D. and Bozidar, S. (2007). "Exploration of Set-based Design for Reinforced Concrete Structures". Lean Construction: A New Paradigm for Managing Capital Projects - 15th IGLC Conference. 15th Annual Conference of the International Group for Lean Construction IGLC 15; Conference date: 18-07-2007 Through 20-07-2007. 213-222.

[24] Lottaz, C., Clément, D.E., Faltings, B.V. and Smith, I.F.C. (1999). "Constrained-based Support for Collaboration in Design and Construction". The Journal of Computing in Civil Engineering. 13. 23-35.

[25] Penadés-Plà, V., García-Segura, T., Martí, J.V. and Yepes, V. (2016). "A Review of Multi-Criteria Decision-Making Methods Applied to the Sustainable Bridge Design". Sustainability. 8(12).

[26] Brock, J.K-. U. and Wangenheim, F. (2019). "Demystifying AI: What Digital Transformation Leaders Can Teach You about Realistic Artificial Intelligence". California Management Review. 61(4). 110-134.

[27] Cusumano, L., Saraiva, R., Rempling, R., Jockwer, R., Olsson, N. and Granath, M. (2022). "Intelligent building contract tendering - potential and exploration". IABSE Symposium Prague 2022 - Challanges for Existing and Oncoming Structures. Prague, Czech Republic. 1902-1909.

[28] Somanath, S. , Yu, Y., Nordmark, N., Ayenew, M., Thuvander, L. and Hollberg, A. (2021). "AI-baserad segmentering av fasader för att optimera renovering i en större skala". Bygg & Teknik. 21(2). 26-29. Swedish.

[29] Huang, W. and Zheng, H. (2018). "Architectural Drawings Recognition and Generation through Machine Learning". 38th Annual Conference of the Association for Computer Aided Design in Architecture: recalibration on imprecision and infidelity. Mexico City, Mexico. 156-165.

[30] Mathern, A., Ek, K. and Rempling, R. (2019). "Sustainability-driven structural design using artificial intelligence". IABSE Congress New York City 2019 - The Evolving Metropolis. 1058-1065.

[31] Yepes, V. AND Martí, J.V. AND García-Segura, T. (2015). "Cost and CO2 emission optimization of precast–prestressed concrete U-beam road bridges by a hybrid glowworm swarm algorithm". Automation in Construction. 49. 123-134.

[32] García-Segura, T., Yepes, V., Martí, J.V. and Alcalá, J. (2014). "Optimization of Concrete I-Beams Using a Hybrid Glowworm Swarm Algorithm". Latin American Journal of Solids and Structures. 11(7). 1190-1205.

[33] García-Segura, T., Yepes, V., Frangopol, D.M. (2017). "Multi-objective design of post-tensioned concrete road bridges using artificial neural networks". Structural and Multidisciplinary Optimization. 56. 139-150.

[34] Martí, J.V., García-Segura, T. and Yepes, V. (2016). "Structural design of precast-prestressed concrete U-beam road bridges based on embodied energy". Journal of Cleaner Production. 120. 231-240.

[35] Mergos, P.E. and Mantoglou, F. (2020). "Optimum design of reinforced concrete retaining walls with the flower pollination algorithm". Structural and Multidisciplinary Optimization. 61. 575-585.

[36] Jahjouh, M.M., Arafa, M.H. and Alqedra, M.A. (2013). "Artificial Bee Colony (ABC) algorithm in the design optimization of RC continuous beams". Structural and Multidisciplinary Optimization. 47. 963-979.

[37] Gelbart, M.A., Snoek, J. and Adams, R.P. (2014). "Bayesian Optimization with Unknown Constraints". Proceedings of the Thirtieth Conference on Uncertainty in Artificial Intelligence. 250-259.

[38] Mathern, A., Skogby Steinholtz, O., Sjöberg, A., Önnheim, M., Ek, K., Rempling, R., Gustavsson, E. and Jirstrand, M. (2021). "Multi-objective constrained Bayesian optimization for structural design". Structural and Multidisciplinary Optimization. 63. 689-701.

[39] Simpson, T.W., Poplinski, J.D., Koch, P.N. and Allen, J.K. (2001). "Metamodels for Computer-based Engineering Design: Survey and recommendations". Engineering with Computers. 17. 129-150.

[40] Penadés-Plà, V., García-Segura, T. and Yepes, V. (2019). "Accelerated optimization method for low-embodied energy concrete box-girder bridge design". Engingeering Structures. 179. 556-565.

[41] Mathern, A., Penadés-Plà, V., Armesto Barros, J. and Yepes, V. (2022). "Practical metamodel-assisted multi-objective design optimization for improved sustainability and buildability of wind turbine foundations". Structural and Multidisciplinary Optimization. 65(46).

[42] Sehlström, A., Johansson, H and Ander, M. (2016). "On Multi-Objective Topology Optimization and Tracing of Pareto-Optimal Structures". 29th Nordic Seminar on Computational Mechanics.

[43] Chalouhi, E.K., Pacoste, C. and Karoumi, R. (2019). "Topological and Size Optimization of RC Beam Bridges: An Automated Design Approach for Cost Effective and Environmental Friendly Solutions". Nordic Concrete Research. 61. 53-78.

[44] Ander, M., Sehlström, A., Shepherd, P. and Williams, C.J.K. (2017). "Prestressed gridshell Structures". Proceedings of the IASS Annual Symposium 2017. Interfaces: architecture engineering science. Hamburg, Germany.