Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 44 (2020) 76–83

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

1st International Conference on Optimization-Driven Architectural Design (OPTARCH 2019)

Sustainability evaluation of timber dwellings in the north of Sweden based on environmental impact and optimization of energy and cost

Jani Mukkavaara[a], Marcus Sandberg[a]*, Karin Sandberg[b], Anna Pousette[b], Joakim Norén[b]

[a]*Luleå University of Technology, SE-97187, Luleå, Sweden*
[b]*RISE – Research Institutes of Sweden, Laboratorgränd 2, SE-93177, Skellefteå, Sweden*

Abstract

Identifying design variations that strike the balance between environmental, energy and cost can be aided using multi-objective optimization. From the resulting Pareto-solutions, selecting a single optimal solution remains a challenge. Thus, research is still needed to increase the practical use of optimization for architectural, engineering and construction (AEC) practitioners. This paper presents the use of an optimization approach where the results and an environmental assessment are discussed with AEC practitioners. The method was tested in two case studies: a prestige tourist cottage and a multifamily residential building. Different superstructures, insulation materials and windows were varied for the cottage's envelope whilst evaluating life-cycle energy and cost. In addition, the environmental impact in terms of CO_2 emissions was evaluated for the initial and optimal design suggestions for the two different superstructures. For the residential building, the insulation material thickness and the windows were varied for its evaluation of life-cycle energy and cost. For the cottage, a report was written and then read by the practitioners and used as a base for future decisions. For the residential building, the results were presented orally for the practitioners. In both cases, it was possible to communicate the overarching results of the optimizations through visual plots, although future research should find ways to also explain the detailed results.

Keywords: Life-cycle energy, life-cycle cost, life-cycle assessment, genetic algorithm, building information modelling, practitioner accessibility

* Corresponding author. Tel.: +46920493072
E-mail address: marcus.sandberg@ltu.se

2351-9789
10.1016/j.promfg.2020.02.207

1. Introduction

Building design traditionally involves an iterative process of finding solutions that fulfill requirements regarding e.g. space, cost, structural integrity, and buildability. Nowadays sustainability has become increasingly important to consider thanks to efforts like Agenda 2030 with its 17 global goals and is often divided into three parts: environmental, economic and social. Examples of social sustainability can be safe outdoor environments or sufficiently low rental levels that ensure that tenants can afford to live there, thus avoiding segregation. Environmental and economic sustainability is often easier to measure than social sustainability since they can be quantified in CO_2-equivalents for climate impact or joules as in life-cycle energy (LCE), and money as in life-cycle cost (LCC). By using an LCE approach, it also becomes possible to balance embodied and operational energy since new building materials may save less energy during operation compared to the energy embodied during production [1]. This, however, requires the coordination of different model updates during the design process especially when other models are also included.

Building information modelling (BIM) is an approach to design where virtual models comprised of objects with geometry and related properties can be represented in different views (e.g. design, production, operation) through a building's life cycle. Simply put a BIM-model is a CAD-model with metadata and provides possibilities for evaluating a building's performance, e.g. through finite element analysis, energy analysis, production analysis, etc. Using BIM to evaluate sustainability during building design is a growing trend [2].

Connecting BIM to optimization has become a way to balance the often counteracting objectives like LCE and LCC [3,4]. Results usually end up in a Pareto optimal set of solutions, which might include a significant number of solutions and therefore hard to select from, especially for everyday practitioners in the building sector. Many companies and organizations within the building sector lack the knowledge and resources to use optimization in their everyday work. Cheik et al. [5] presented a method to select from Pareto optimal solutions, but this method requires advanced mathematical skills and may take time to learn how to implement in a smaller construction company or property-owning company. Likewise, Zavala et al. [6] use metaheuristics for choosing among an optimal set of solutions, which also require expert knowledge.

Although numerous works on building optimization exist, there is still a challenge to find methods and useful ways for everyday practitioners in the building sector to understand and be able to choose the best solution from all optimal Pareto solutions. Research involving everyday practitioners in evaluating optimization results is needed. As a first step, we have involved practitioners in evaluating a Pareto set, where we presented the overall results, not all details.

This paper presents two case studies where an optimization based on genetic algorithms [7] was used to balance environmental, energy (embodied and operational) and cost objectives during building design. Social sustainability was considered as well, where one important factor was that the rent should be low enough for the tenants but still provide a low energy use in the subarctic climate according to new building codes. Segregation of people from different social classes was to be avoided and safe environments were also important. The work intends to explore the practical use of optimization for architectural, engineering and construction (AEC) practitioners [8].

2. Method

2.1. Multi-Objective Optimization

A multi-objective optimization approach was adopted in this study to explore the optimal solution(s) for the trade-off between embodied energy, operational energy, and operational and material cost. This was carried out by incorporating the evaluation of the objectives coupled to an optimization algorithm and employing a multi-objective optimization method to find the optimal solution(s). A stochastic population-based Generic Algorithm (GA) was chosen as the optimization algorithm as previous studies have indicated that such algorithms are favorable to this type of application, for example with respect to discontinuities that may occur due to the use of discrete variables [9]. Additionally, Pareto optimization was used as the multi-objective optimization method, which identifies optimal solutions by examining a set of feasible trade-off solutions. A solution is called Pareto optimal (or non-dominated) when there are not any other solutions that improve one objective without worsening at least another objective. To perform the multi-objective optimization, an existing framework created by the authors, that previously have been shown to perform well [3], was used. This framework applies the use of a BIM-based master model that through domain models connected to performance evaluation (e.g. of operational energy through simulation) and a multi-objective optimization approach can deliver a Pareto-based set of optimal solutions. This framework was applied to the case studies below to generate the results that were subsequently discussed with the stakeholders. A detailed description of the framework can be found in the original paper [3].

2.2. Environmental assessment

A life cycle analysis (LCA) can be used to assess a building's environmental impact over its life cycle. Different methodological choices must be considered when making an LCA. These choices can have a significant impact on the result. The most important methodological choices are the functional unit, system boundaries and the type of data used. The functional unit becomes especially important when comparing different studies. The boundaries of the system are often crucial to the outcome of an LCA. The quality of the results also depends on the choice of material data.

In the environmental assessment in this study, the LCA calculation follows the division of the life cycle into (system boundaries) modules according to EN 15804 [10], see Fig. 1. The inventory includes the following parts of the building's life cycle:

- Production, A1-3 (resource extraction, transport and production of material)
- Construction process, A4 (transport of materials to construction site)

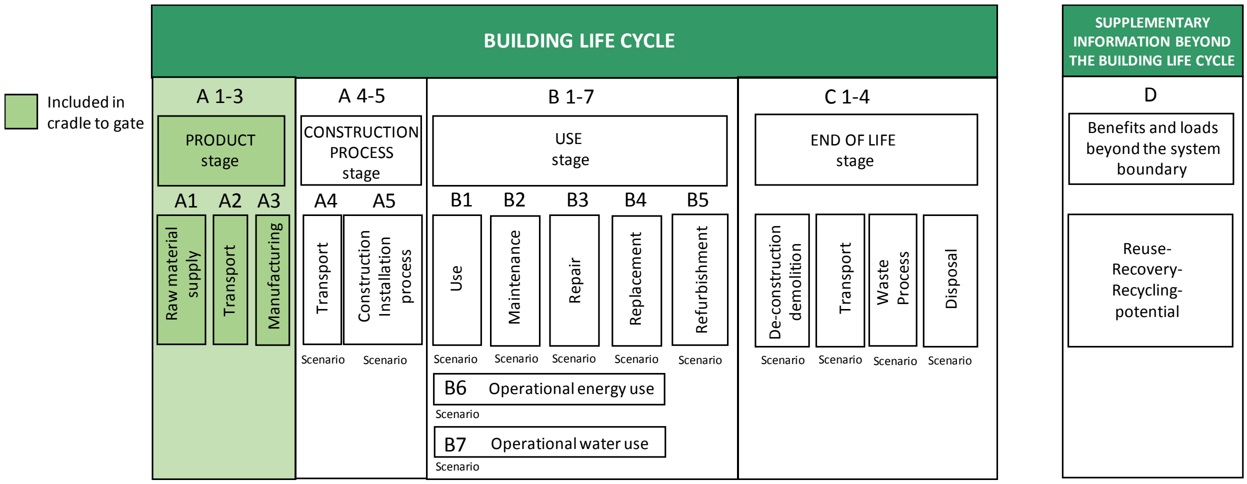

Fig. 1. Life cycle stages and modules for the building assessment according to EN 15804.

The functional unit has been selected as 1 m² of residential area (RA). The environmental impact includes emissions of greenhouse gases expressed in CO_2-equivalents. When comparing different designs, the system boundaries have been the same, which is a prerequisite for a robust comparison.

3. Results from case studies

North of the Arctic Circle in Sweden lies Kiruna municipality where the company LKAB runs the world's largest underground iron ore mine. Due to the expansion of the mine and the ground cracks developing from this, the city needs to be moved to another location. Given the unique circumstances, the research and innovation project Kiruna Sustainability Center was launched, where new working methods of sustainable building development are explored. Working methods that ultimately in time should be possible to implement in the partner organizations, i.e.

municipalities and SME construction companies. Given this context, two case studies are here presented - a prestige cottage and a multifamily residential building, see Fig. 2. The prestige cottage was used as a warm-up case to try out the way multi-objective optimization should be combined with the LCA.

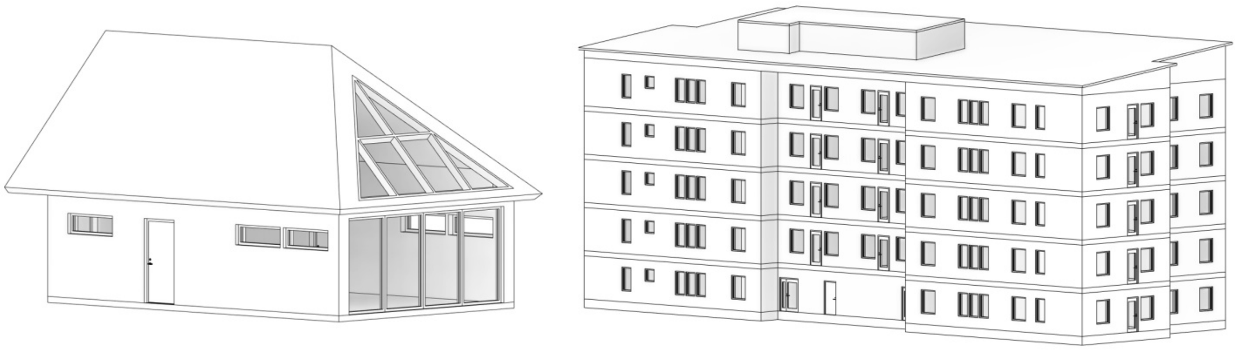

Fig. 2. A simplified model version of the architectural drawing of the prestige cottage (left) and of the multifamily residential building (right).

For both the case studies, the embodied energy is defined to include the energy used to produce materials and components (i.e. from raw materials to manufacturing). The operational energy is defined to include energy used for heating, cooling, and hot water demands for the building during its occupied period. The cost is defined by the sum of the present value of the investment cost for the building's materials and components as well as the operational costs for the operational energy. Not accounted for in this study is the energy use and cost associated with the construction phase nor the refurbishment, maintenance and end of life phases. In each of the cases, a lifespan of 50 years is used in the evaluations.

3.1. Prestige cottage

A company offering hotel, camping and cottage renting services in Kiruna plan to build new prestige cottages with a high standard mainly for foreign northern light tourists from Japan and other countries. Needs that are of importance to sustainability, such as timber materials, high tech solutions, etc. were articulated during discussions with the company owner and an architect. The initial design of this case study was detailed from the project's architect who produced a hand-drawn sketch of the cottage. The authors later recreated this as a BIM-model for use in the study (see Fig. 2).

The company wanted help with finding a sustainable building system for the cottage and we suggested trying two different building scenarios: one using a timber stud construction (built on-site) and one using a cross-laminated timber construction which partly consists of prefabricated elements. Variables used in the optimization of the prestige cottage included: insulation material and thicknesses for exterior walls, slab, roof, and two different window types. The optimization of the two different scenarios resulted in over 6000 solutions which can be seen Fig. 3. From the results, it can be seen that the timber stud alternatives had the lowest energy consumptions and cost in most cases. However, the question that remained was which one of all the timber stud solutions should be chosen.

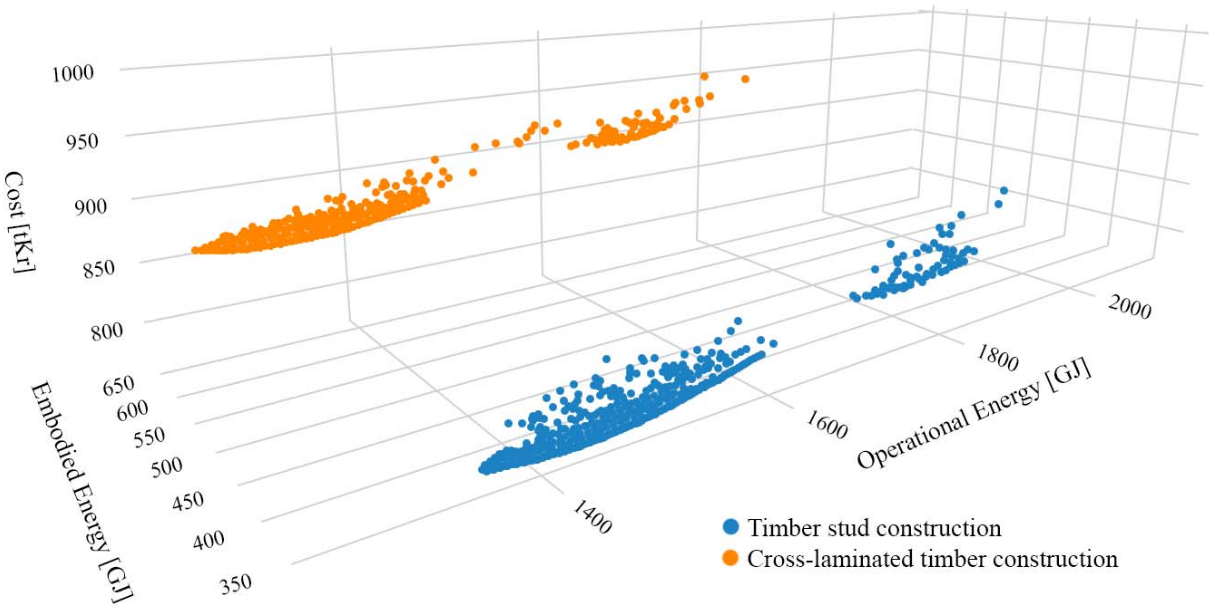

Fig. 3. All simulation results for the two different building systems for the prestige cottage (tKr – thousands Swedish Kronor).

The results were presented to the company owners through a Skype meeting where the method was described and the results were shown, including Fig. 3. Feedback was that the results were interesting for the company but they were too technical and it was difficult to understand the graphs, for example, Fig. 3. A written report was sent to them as well. A follow-up discussion was held 8 months later where they explained that the cottage project was delayed because of another project. They were also reflecting on if the design needed updating. They however thought that it is very important to get access to more information from us for future planning of this project.

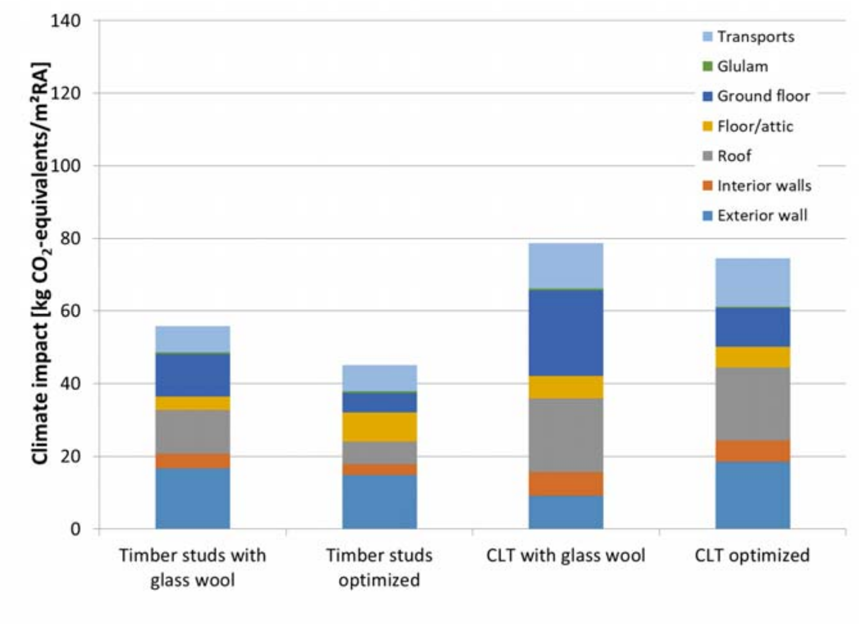

Fig. 4. Comparison of climate impact per m^2 residential area (RA) for the prestige cottage case with original and optimized versions of two different building system alternatives.

In Fig. 4, the results of the environmental assessment of the different building systems are compared before and after the optimization. The original structures were based on buildings with equal U-values. The optimized solution represents the solution with the minimum sum of embodied and operational energy. The figure shows that the environmental impact will be somewhat lower after the optimization, which is mainly because the glass wool has been replaced with cellulose fiber in all building parts except in the outer walls. In Fig. 4 it is also shown that transports are a significant part of the environmental impact due to the location of the city and should therefore be considered when purchasing building materials. The results show that the choice of materials in the building systems has big influence on the climate impact.

3.2. Multifamily residential building

This case has several differences compared to the prestige cottage: firstly, this building was already designed and about to start being produced, and secondly, it is a five-story multifamily residential building. The reason for choosing this case was that a Kiruna-based property owner was interested in building more multifamily residential buildings in the future, and to investigate ways of improving the sustainability of these probable future projects. Variables used in the optimization were insulation thicknesses for exterior walls, slab, roof, and two different window types. As smaller variations were used in this case compared to the prestige cottage and the LCA was not included. Although Kiruna was in focus, the property owners also were interested in analyzing the same building in other geographic locations with a different climate, thus Malmö and Stockholm that are in the southern part of Sweden were also included, see Fig. 5.

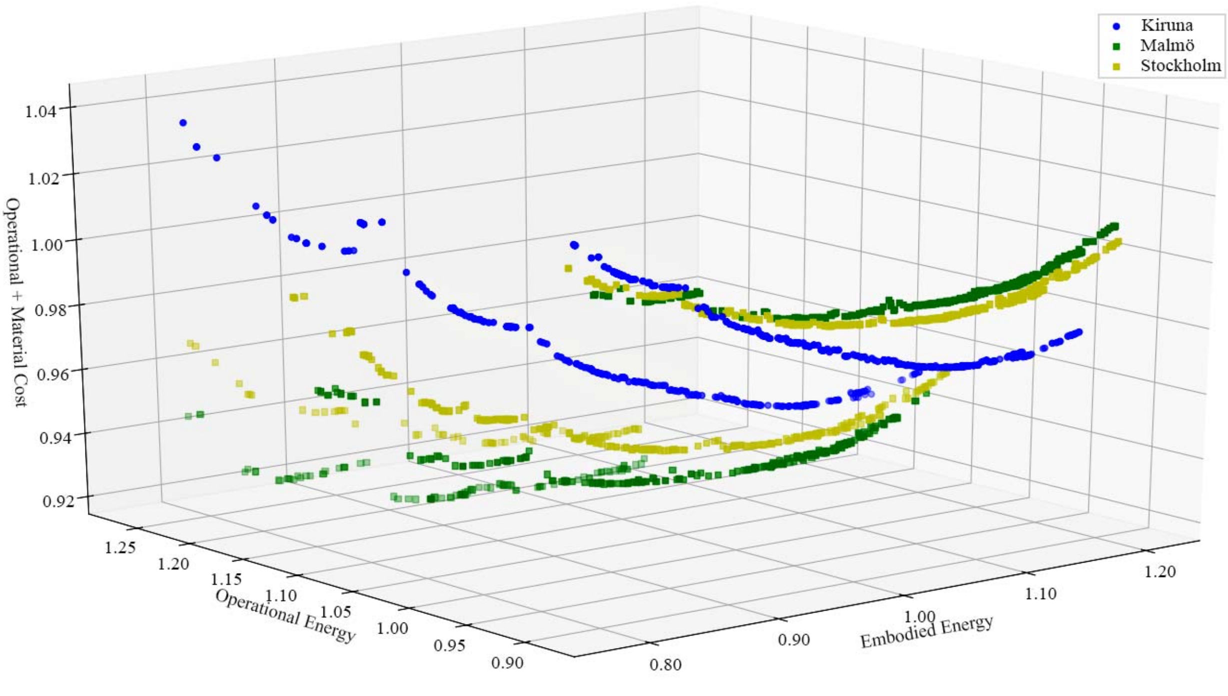

Fig. 5. All solutions for the three different cities evaluated in the multifamily residential building case. The values are normalized.

Comparing the optimal solutions with the already chosen design showed that an increase in insulation was preferred in the exterior walls, and a decrease in insulation was preferred in the slab and roof. In general, however, the optimal solutions found by the multi-objective optimization showed that the initial design of the building largely already performed well for all three objectives. This was a delight for the property owners who got this as a "certificate" of their sustainability work. Furthermore, relocating the building to the other locations (i.e. Malmö and

Stockholm) only resulted in minor adjustments to the optimal solutions with regards to the thickness of the insulation materials.

4. Discussion

The use of a BIM-based optimization approach using genetic algorithms has been demonstrated for two case studies in the north of Sweden: one prestige cottage and one multifamily residential building. In our research, we have involved the practitioners in the evaluation of the results. It has been recognized that expert knowledge is still needed to perform the actual optimization runs. However, involving the practitioners in the choice of variables, objectives, etc. might increase their understanding. Compared to other ways to help to choose among the Pareto set of solutions, e.g. [5,6], we see an opportunity to reach closer to the practitioners but we need to continue developing our approach to further involve the practitioners in the analysis of the results. Using other types of color coding, clustering techniques, and including instruction movie clips could also further increase understanding. In the presented cases, the three objectives were weighted equally. To increase realism there is a need to define these weights more realistically. This, however, requires the practitioners and other stakeholders to break down their view and evaluation of sustainability, which might be challenging, especially if you have more than only two objectives.

An interesting development for the future is generative design, which is related to optimization, where digital tools are used to generate design ideas and stimulate new solutions [11]. By using generative design there is a possibility to explore solutions and in a more interactive fashion, compared to the optimization approach presented here, work with these different weights. By including possibilities for a user to evaluate qualitative measures, this also opens to a closer integration of social sustainability values.

Another potential field to look further into is decision-making methods [12]. A combination of different approaches is probably needed to be able to further approach real world problems.

5. Conclusion

Multi-objective optimization is a powerful method to balance contradictory objectives in building design such as environmental and economic sustainability. There is however still a challenge to make tools and methods accessible for the everyday practitioners in construction especially for smaller property-owning companies where financial resources and specific technical knowledge are less strong compared to high tech consultant companies for example. This paper showed an effort to visualize results to practitioners from two different case studies as a first step to involve practitioners in evaluating optimization results. Further research is needed to make optimization results even more accessible to practitioners.

Acknowledgement

The authors would like to thank VINNOVA and the Swedish Agency for Economic and Regional Growth within Kiruna Sustainability Center for providing funding for this research. The companies involved in the case studies are also acknowledged for their time and commitment.

References

[1] P. Chastas, T. Theodosiou, D. Bikas, Embodied energy in residential buildings – towards the nearly zero energy building: A literature review, Building and environment, 105 (2016) 267-282.

[2] R. Santos, A.A. Costa, A. Grilo, Bibliometric analysis and review of Building Information Modelling literature published between 2005 and 2015, Automation in Construction, 80 (2017) 118-136.

[3] M. Sandberg, J. Mukkavaara, F. Shadram, T. Olofsson, Multidisciplinary Optimization of Life-Cycle Energy and Cost Using a BIM-Based Master Model, Sustainability, 11 (2019) 286.

[4] M.R. Asl, S. Zarrinmehr, M. Bergin, W. Yan, BPOpt: A framework for BIM-based performance optimization, Energy and Buildings, 108 (2015) 401-412.

[5] M. Cheikh, B. Jarboui, T. Loukil, P. Siarry, A method for selecting Pareto optimal solutions in multiobjective optimization, Journal of Informatics and Mathematical Sciences, 2 (2010) 51-62.
[6] G.R. Zavala, A.J. Nebro, F. Luna, C.A. Coello, A survey on multi-objective metaheuristics applied to structural optimization, Structural and Multidisciplinary Optimization, 49 (2014) 537-558.
[7] K. Deb, A. Pratap, S. Agarwal, T. Meyarivan, A fast and elitist multiobjective genetic algorithm: NSGA-II, IEEE transactions on evolutionary computation, 6 (2002) 182-197.
[8] R. Evins, A review of computational optimisation methods applied to sustainable building design, Renewable and sustainable energy reviews, 22 (2013) 230-245.
[9] A.T. Nguyen, S. Reiter, P. Rigo, A review on simulation-based optimization methods applied to building performance analysis, Applied Energy, 113 (2014) 1043-1058.
[10] EN 15804, Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products, 2012.
[11] K. Shea, R. Aish, M. Gourtovaia, Towards integrated performance-driven generative design tools, Automation in Construction 14 (2005) 253-264.
[12] V. Penadés-Plà, T. Garica-Segura, J.V. Marti, V. Yepes, A review of multi-criteria decision-making methods applied to the sustainable bridge design, Sustainability, 8 (2016) 1295.