Application of Artificial Intelligence Methods in Sustainable Building Design

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Abstract. The need to reduce energy consumption, resources, the introduction of new and ecological materials, the multiplicity of modern technologies available, and the complexity and multi-branch nature of architectural and construction projects means that designers must make complex and difficult decisions. This work presents the subject of currently available and used in the AEC industry project tools and provides an overview of the possibilities of using artificial intelligence methods and tools, such as Knowledge Based Engineering (KBE), fuzzy logic, neural networks, genetic algorithms, Monte-Carlo simulation. These methods can be used in the early design stage to improve decision making process and to optimize both the design process and the project itself.

Keywords: Architectural design · Pareto genetic algorithms · Knowledge Based Engineering · AEC managing tools · Decision making

1 Introduction - New Challenges in the Architectural and Construction Design Process

Sustainable building design is a comprehensive process that involves many parties that need to cooperate but cannot operate independently. Due to the need to reduce energy consumption and raw materials use, the multitude of modern technologies available, and the less available and expensive lands in the desired areas, there are countless of difficult decisions to be made during the building design and construction process [1].

The need to meet the legislative requirements, the pressure from the Investors to limit the budget and minimize project completion time maintaining high standards at the same time, puts the project teams ahead of a huge challenge: creating an individual concept and implementing multi-disciplinary, comprehensive and compatible project documentation that meets all the criteria given. The success of the project depends on a successful exchange of information, coordination and the ability to select the most

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favorable solutions and compromises. Unlike serial products, each architectural project is an individual solution that is not subject to validation and correctness tests on living models. Due to the individuality of every project the only chance to detect and eliminate imperfections before starting the production is design stage.

This paper contains a comparison analysis of the traditional approach to the AEC (architecture, engineering, construction) design process and novel design methods. In the last one participants use platforms and tools to help them design, communicate, evaluate solutions, determine budget and coordinate multi-branch design. In addition, it will present a review of the literature on the possibilities and limitations of the use of artificial intelligence methods in improving the design process.

2 Comparison of Traditional Design Methods and Advanced Tools and Platforms to Improve the AEC Project Process

In the architectural and construction industry today, the most widely used systems are: cad drawing software's used to develop 2D drawings and 3D modeling softwares to complement the design. Any change made to the project needs to be implemented separately in all drawings the change applies. At the same time, you can observe a slow transformation of the way the project is developed due to the introduction of BIM (Building Information Modeling) system as a work tool. This technology allows developing comprehensive, multi-branch 3d model of the designed object that helps to detect project defects, facilitate inter-branch coordination and saves costs related to adjustments in the execution phase. According to researches it can save about 20% of time spent checking and correcting cad drawings [2] and 30% of the time needed to prepare the documentation [3].

According to the report published in 2017, 12% of respondents using BIM on daily basic at work, 21% of organizations use it at various levels and 78% plan to introduce this technology [4]. Another research stays that using BIM is more common in larger enterprises and its users are usually younger industry representatives. The biggest barrier for introducing BIM is competency shortages and low rates for projects [5].

However, BIM system has its limitations. Possible checks of collisions, codes and rules can be applied to the completed model, after carrying out the majority of design works and after the phase covering the majority of design decisions. Then the phase of corrections and changes takes place. In some cases the corrections needed may be small but sometimes drastic and requiring a huge amount of work, time and costs.

Recently the new possibilities of using BIM in AEC has been developed. In 2018 the research was published [6] combining BIM platform possibilities to create environment for managing adaptive smart façade shading system to reduce energy consumption and improve indoor microclimate. Also the possibilities od transferring data from BIM into Game environment were taken and using the game engine to create evacuation strategy was proposed [7, 8]. The similar approach for using game engine on exported BIM 3d data has been taken to allow for late stage design review of healthcare buildings [9].

3 Application of Artificial Intelligence Methods in the Design Process

Due to the limitations of currently widely used design methods in the architectural and construction industry, attempts are made to improve the design process using the methods of artificial intelligence (AI - Artificial Intelligence) [10]. Attempts to use AI tools in design began in the 1980s [11]. Tools using Knowledge Based Engineering KBE, fuzzy logic, neural networks, and genetic algorithms find a wide application in the design of AEC [1, 12]. The following is an overview of publications about using AI modeling in architectural design.

3.1 Possibilities of Using KBE in the AEC Project Process

One of the most characteristic features of a knowledge-based organization (KBO) is the use of knowledge, experience and the ability to assess the problem by the staff employed. This distinguishes them from other organizations that have physical assets (e.g., airplanes, hotels, commercial goods) and organizations that are rather an intermediary and interpreter of information without producing a specific product [13, 14]. According to this definition, the organizations of the AEC industry are an example of KBO organization.

Architectural, constructional and mechanical & electrical (M&E) design offices are evaluated primarily due to their experience and potential to provide the specific project. These organizations are employed based on their ability to deliver the project, as the product itself is not yet created at the stage of selecting the designer [1].

For this reason, the greatest value for this type of organization is the knowledge and experience of staff that can easily be lost if employees change the organization. In addition, the sharing of acquired knowledge depends on the skill and willingness to provide it, which does not guarantee that all of organization projects will benefit from the knowledge of the staff that is at the disposal of the organization at a specific moment. The use of knowledge engineering tools - KBE (knowledge based engineering) can help in the effectiveness of gathering and sharing knowledge.

KBE is a field of research aimed at increasing the efficiency of the design process through the use of experience and knowledge of completed project processes and their already known effects. Knowledge Engineering Systems allow you to use the experience and knowledge gathered both by experienced and untrained designers, shortening the time to complete the task and reducing the risk of mistakes. Diagrams of knowledge engineering systems help in particular in the acceleration of routine tasks (which according to Calkin and Stokes constitute about 80% of all activities) allowing the designer - a specialist - to concentrate on creative and innovatory work [15, 16], which will affect the quality of the target product. Unlike BIM technology, which enables validation of the created model, the KBE task would enable Rule and Code compliance auto checking during the design phase [16].

KBE since the 1980s was mainly developed in the automotive, space and shipbuilding industries while in the AEC industry only to a small extent. In 2011, Haymaker presented a system scheme proposal for AEC design process based on the use of

comprehensive knowledge for a given branch that would lead designers step by step, learning and improving on the basis of received corrections and guidelines. The proposed system would consist of requirements specific to the project and broad knowledge consistent with the subject of the project. To make design decisions, the project team undergoes a 6-step process including: selection of the project team, goal definition, goal hierarchy definition, analysis of alternatives, impact analysis (each of the alternatives for each objective) and value estimation (based on a specific impact and hierarchy of values). According to Haymaker, each of the six main steps, indirect actions and dependencies between them can be properly described and automated. Similar approach have been taken by using Process Integration and Design Optimization software to carry multiple alternative for the design of classroom building instead of very few possible using traditional methods [17].

In 2015, in his publication, Singer and Bormann present an innovative approach to the KBE tools in civil engineering, which allowed the team to generate a bridge model based on given parameters: type and data concerning the bridge structure and the area. His team declared further research into the use of KBE tools in the architectural and construction industry.

3.2 Possibilities and Limitations of Using the Fuzzy Logic Method in Architectural Design

Architecture is a broad concept, considered to be one of the most important fields of art [18] and at the same time an Engineering discipline called Land Engineering according to the classification of fields and disciplines of the OECD (Organization for Economic Cooperation and development). Therefore, the quality of architecture can be assessed in many aspects: aesthetic, cultural, social, as well as economic, energy-efficient, and in the aspect of using innovative technologies. Similarly, each of its components is difficult to assess unequivocally, that is, mathematically speaking, binary (truth or false). Fuzzy logic, which is used as a problem solving tool, gives a set of indirect results - similar to human conclusions that may be used in the analysis of architectural problems. The result of the analysis cannot be unambiguously assessed as good or bad as the following examples show.

The fuzzy logic modeling method was already used in the spatial planning analysis to assess the location of individual houses of the existing housing estate [19]. The assessment was made in terms of distance from the desired places (beach and store), privacy of the location, the distance from the neighbour and view values. The analysis was performed using the Takagi-Sugeno fuzzy modeling method. The result of the analysis correctly indicated the assessment of the houses location attractiveness.

Fuzzy logic was also used to evaluate the coefficient of average daylight based on the set geometry, openness of the facade, reflectance [20]. In 2001 & 2003 Ciftcioglu and Durmisevic used Takagi-Sugeno method to determine the level of safety and comfort in the underground subway station [21, 22] based on a number of factors, including lighting, visual attractiveness, human presence, legibility of visual information, noise, temperature, etc.

3.3 The Use of Pareto Front and Genetic Algorithm in the Architectural Design

Genetic algorithms are supposed to imitate evolution. The offspring inherits the best traits selected from the group of "parents" during the evolution of many generations. Finding the best-developed offspring can also find application in the project design process [11, 12]. Due to the previously mentioned tightening of energy consumption regulations and limiting access to the resources, the growing need to reduce energy as much as possible is observed. In her work on the design of energy-saving buildings, Professor Luisa Caldas conducts research on the use of the Generative System GENE_ARCH in the early and intermediate design phase [23–25]. The system uses the Genetic Algorithm, Pareto optimization and DOE2 software. DOE2 software is available for free and is used to perform a building energy analysis allowing estimating energy consumption and usage costs based on the description of the building layout, construction, M&E systems designed, weather data and utility rates.

The system has been tested for various geographical locations and for selected tasks: finding the optimal location of windows in relation to the optimal amount of daylight and the minimum energy costs per annum; selection of optimal materials in terms of insulation requirements, costs and CO2 emissions; evolution of the desired shape of the building optimal in terms of the amount of daylight and the amount of heat supplied.

The use of the Pareto genetic algorithm allowed obtaining a group of possible solutions. The solutions are optimal in terms of energy use, material costs and the amount of daylight, leaving the final decision in the selection and implementation of the chosen solution to the designer.

In the research carried by Flager at All in 2009 [17] the optimization results of structural cost versus energy cost have been demonstrated by Pareto Front as in previous examples allowing for best solution evaluation.

3.4 Possibilities of Using Monte Carlo Simulation in the Early Stage of Designing Energy-Saving Construction

Another method tested to facilitate and improve the efficiency of design decisions at the early stage of the architectural design is a simulation developed and presented in the Torben Østergård dissertation in cooperation with the Danish office MOE [26].

The tools used are based on Monte Carlo simulations and sensitivity and uncertainty analysis as well as variability of design parameters using probability distributions. Their usefulness was presented in order to determine optimal design solutions affecting the energy efficiency of the building (energy demand, optimal amount of daylight, thermal comfort for residential buildings). The results allowed for recognition of the most desirable components of the considered building (window spans, overhangs over windows, insulating properties of windows, blinds, wall thickness, insulation thickness, etc.).

4 Proposed Development of the Research

4.1 Application of Artificial Intelligence Methods in the Implementation Stage of Design Process

While the above case studies show the attempt to apply AI modelling methods in early design stage the amount of routine tasks is performed during the tender and construction phase of design process. The implementation stage consists of value engineering application, detailed design, choice of materials, detailed specification and scheduling. Decisions made during this phase have a huge impact on project budget and final result.

To ensure that materials choices are made objectively and are not driven by lack of knowledge or benefits offered by providers and contractors interests, automation of selection process might be best solution. In the Fig. 1. we propose the concept of architectural design steps automation using AI.

The first step would be creating products database and systematize products relevant information and certifications. Next step would allow for initial verification and automatically performed rejection of products not meeting the criteria from the set of solution based by simply False or True Logic. During the next step AI set of optimization methods would be applied to indicate the best solution in terms of specified major criteria and determining the impact on those criteria by choosing the specific product. In the next step the most optimal solution would be chosen from the best solutions accessed in previous step. The last step would allow the team to accept automatically chosen solution or to choose different solution based by graphically presented set of best possibly solutions. AI methods such as Genetic algorithm, Pareto optimization and Fuzzy Logic would be proposed and tested as AI optimization methods for objective materials choice [27].

4.2 Application of Artificial Intelligence Methods to Assume Required Daily Light Provision for Representative Room

Usually energy performance and daylight analysis are performed after the design is complete and then the recommendations are given and the energy demand is established. Only for some technologically advanced buildings complex and complicated design process is performed to find best solutions in terms of energy performance.

In the future research we would try to find soft computing methodology that would allow specifying the optimum window sizes for representative rooms in specific location for main exposure directions. The aim would be to find best window sizes to achieve best energy performance for the room. The idea of the proposed methodology would be to create simply and easily accessible tool that could be applied on early stage of the design. That would help to design sustainable buildings not only by using the best performed materials but also by using the tool recommendation and might help sustainable design become more common and accessible.

The process would consists of using DOE software to perform energy use analysis on 3d model of typical office rooms and open space generated either by CAD or 3D BIM model. The representative rooms dimensions and windows size would match the

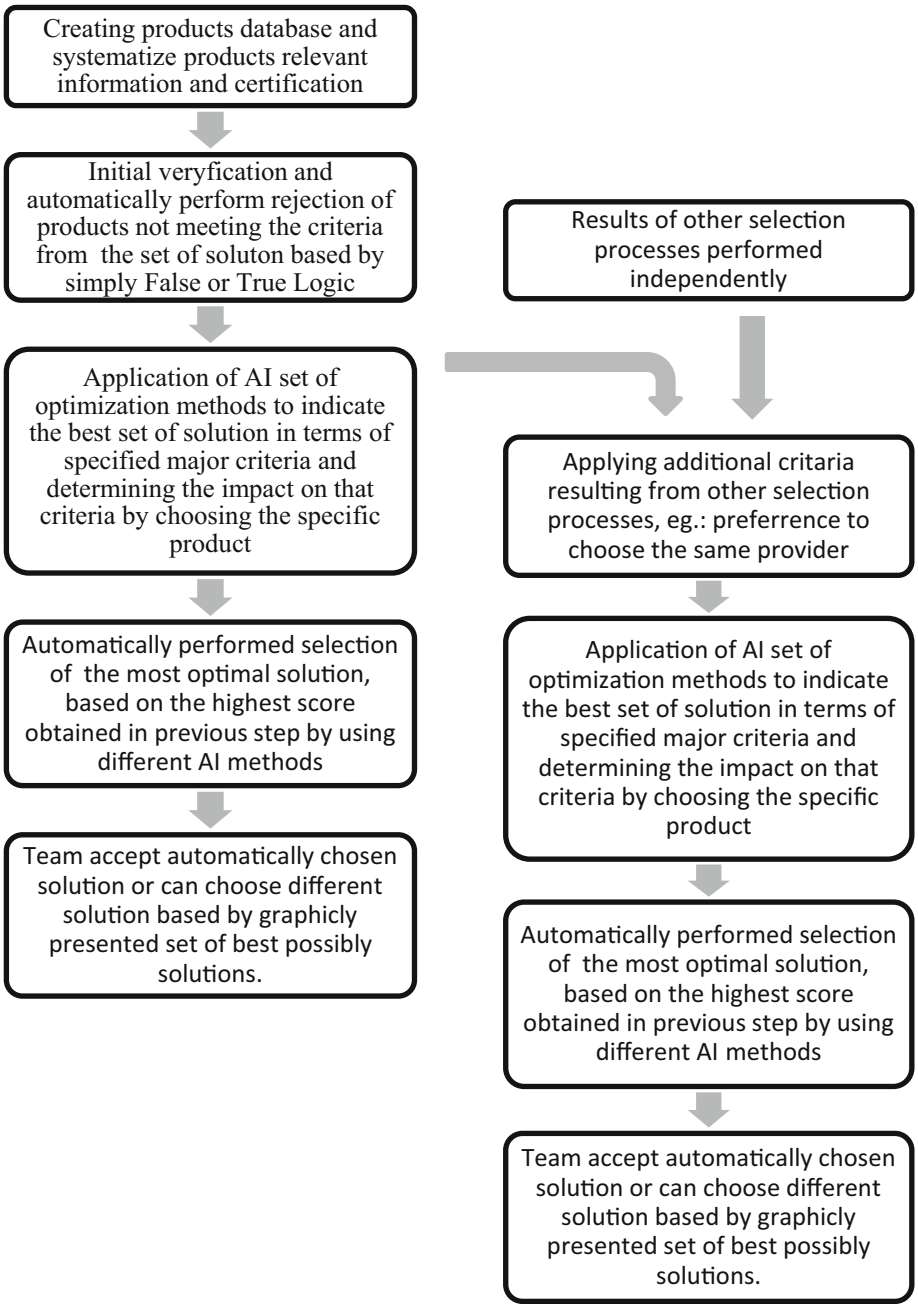


Fig. 1. The proposed concept of architectural design steps automation using AI.

office structural and façade grid according to Modern Office Standards Poland (MOSP) 2016 for cellular plan and open space plan as shown in Fig. 2 [28]. The room would have North, East, South and West exposure direction in central location in Poland. Then optimization by Pareto genetic algorithm would be perform to visualize best and worst possible solutions in terms of energy consumption and daily light provision based on windows size, type of glazing and type of blinds used.

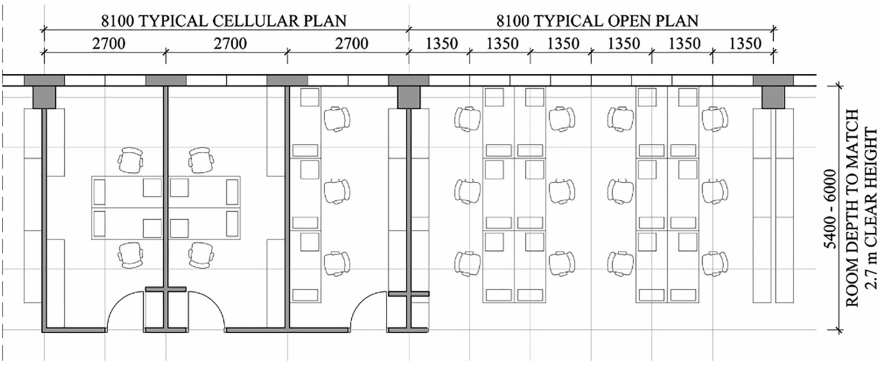


Fig. 2. Representative office grid based on modern office standards Poland 2016

5 Conclusions

AEC's design offices, consisting mainly of small and medium-sized enterprises, have less power to develop technology that helps them deliver the product than large enterprises operating on a broad international mass production market. Therefore the process of incorporating novel design tools is slow comparing to other industries.

The development of BIM technology is driven by the fact that these tools are used not only by designers, but also by investors, developers and contractors, and throughout the life of the building (Building Lifecycle Management) setting the new path of the AEC design process.

The application of artificial intelligence in the early project phases, which is possible in accordance with the above examples, would have a huge impact on improving, accelerating and rationalizing the decisions making in the early design phase. It would also make it possible to improve the energy efficiency of buildings, enabling it to meet stringent regulations and the increasing pressure to reduce the cost of building operations. The purpose of using new tools would not be to replace the designer, but to minimize routine tasks, indicate the best possible solutions, leaving decisions and creative design tasks in the hands of architects and AEC consultants.

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