Evaluation of a Novel Approach for Automated Inventive Conceptual Design of Building Structures

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Abstract: This research is dedicated to assessment of a method that was earlier proposed and developed in order to increase the degree of automation and software involvement into conceptual decision making during design of structural elements of buildings. Such instruments of the theory of inventive problem solving as contradiction and function analysis and trimming formed the basis of the proposed approach that was realized in a modern building information modeling software. The common logic of the approach is also provided in the article. Qualitative research methods and particularly collecting, analyzing and interpreting data were applied in this research. Firstly, a literature review of indexed journal articles in the field of the study was performed and some trends for possible development of the topic were identified. Secondly, a survey of potential users of the methodology was conducted and analyzed. The questionnaire results showed that the suggested method and its technical realization gained attraction among respondents, however, some of them are rather cautious regarding application of the approach potentials in their practice. The paper ends with evaluation results discussion, conclusion and proposals for further research.

Key words: Buildings, structures, conceptual design, automation, TRIZ (theory of inventive problem solving), function analysis.

1. Introduction

Conceptual design is a fundamental part of a project life cycle and construction stage, of course, is also not an exception. Bearing buildings' structures are clearly indispensable parts of buildings and should require special attention during design. The whole life cycle of a building, including its construction time and further operation, will be affected depending on how much competent and innovative solutions were taken at the earliest stage of design. A modern design engineer has access to unique design technologies and functional software. For instance, the BIM (building information modeling) is a process involving the generation and management of digital representations of physical and functional characteristics of buildings and the Autodesk Revit© that is one of the leading BIM software. Unfortunately, this is not always enough, especially for developing the building concepts when it is required to take unique solutions in order to achieve the best results. In this case, existing software does not provide adequate support, since computer is only a thoughtless instrument in engineer's hands during the conceptual design, however, it has a big potential to become a generator of new engineering ideas and proposals. That is why it is still relevant to suggest a technical approach that would increase the degree of automation and involvement of the software into conceptual decision making during design of buildings’ structures.

This paper is a part of a project that is aimed at developing of a new methodology for automation of the conceptual design stage of buildings’ structural systems. Such methodology assumes an analysis of the buildings’ structural systems for its optimality and novelty and subsequent improvement of these indicators. During the work on the project existing techniques have been already discussed and analyzed that may be integrated into modern design software in order to enhance the level of design automation and design creativity. After studying different approaches
of ideas generation it has been found that the TRIZ (theory of inventive problem solving) is well applicable for such purposes. TRIZ was created and developed in the former USSR by an engineer Genrikh Saulovich Altshuller. While working as a clerk in a patent office, he has analyzed a large number of patents and formulated some generic rules that would lead inventors to systematic creation of new inventive ideas [1]. Literature analysis on the topic has shown that TRIZ was successfully used for non-trivial systematic problem solving in construction and may also be a well applicable tool for achieving this project’s goals [2]. As a result, an approach was suggested for the early design stage automation in building projects where a number of TRIZ tools were integrated into a building information modeling software using an open source graphical programming tools [3, 4]. Such instruments of TRIZ as contradiction analysis, function analysis and trimming formed the basis of the proposed approach. The key goal of this particular study is evaluation of the proposed approach for automated inventive conceptual design of building structures.

2. Research Methods

Qualitative research methods that are particularly collecting, analyzing and interpreting data were applied in this research for evaluation of a novel approach for automated inventive conceptual design of building structures. This study has a number of key objectives that were, first, formulated in the form of the following RQs (research questions): RQ1—What is the current situation in the field of automation of conceptual design process in the construction projects? RQ2—What is the relevance of suggested approach? RQ3—What are possible advantages, disadvantages and to what extent it is easy to use the suggested algorithm? In order to answer these RQs, this paper is, firstly, aimed at systematization, analysis and understanding the current situation in the field of automation of conceptual design process in the construction field. Secondly, it focuses on testing the developed approach and its technical realization for understanding all the positive and negative signs and the convenience of its practical application.

For answering RQ1 a systematic review of related literature was performed. RQ2 is answered by both analysis of existing similar proposals and collecting professional opinions using a specially developed questionnaire. For answering the RQ3 a set of questions was added into the developed questionnaire focusing on demonstration of the algorithm abilities.

3. Literature Review

The literature review was based on journal articles indexed by the Scopus database as it is the largest abstract and citation database of peer-reviewed literature. It was decided to analyze the journal publications because their review and acceptance process is stricter comparing to conference proceedings and these kinds of scientific works are more comprehensive and self-contained.

3.1 Creating the Dataset

In order to create the dataset of articles in the field of automation of early design stage in construction the following coherent search was performed: (1) the query “construction” and “design” and “automation” in Title or Abstract or Keywords. The search resulted to 3,600 papers. (2) Since those results came from different fields and included different types of documents, the subject area was limited to “engineering” and document type to “article”. Such limitation identified 1,095 articles. (3) Further, articles with irrelevant keywords such as “computer software”, “project management”, “robotics”, “computer simulation” were excluded and 628 possible targeted papers remained. (4) This number of articles was still quite large for manual analysis that is why the articles which were also related to such subject areas as “mathematics”, “physics”, “business”, “environment”, etc. were additionally excluded. After that already 187
documents were obtained that were published in journals in the field of engineering only and met the original query requirements. (5) 100 of those works were cited at least once that is why they were accepted for further manual analysis. However, after reading all the titles and abstracts carefully it had been discovered that quite many of those journal papers were not in the area of the research interest because they were dedicated to, for instance, automation of construction processes, environmental issues in construction, construction machines and logistics, etc. (6) Finally, 21 articles with appropriate titles were filtered out for reading and analyzing their full texts. All the papers were published during last 10 years and almost half of them were originated from the United States and the United Kingdom.

3.2 State of the Art

Detailed review of the discovered literature showed that automation of design for construction is still a relevant topic and building information modeling is one of its key drivers. For instance, in Ref. [5] by Becerik-Gerber and Kensek the emerging trends of building information modelling in architecture, construction and engineering were formulated by performing a survey among practitioners and students. The studied respondents in the work have identified such area as “BIM for Design & Engineering” as one of the most relevant for further research. Moreover, majority of respondents identified the role of BIM in decision making on structural configuration, system choice, etc., as a topic of possible interests. “Linking BIM to analysis tools” is also an emerging research direction. Another similar research was performed five years later by Yalcinkaya and Singh [6]. Principal research areas were revealed that indicate the patterns and trends in BIM research. “Architectural design and design decision making” as well as “Impact of BIM on design creativity and innovation”, “BIM at pre-design phase”, “Parametric modeling and design” and “BIM-supported structural analysis and design” are among them. According to the survey performed by Abrishami et al. [7] majority of the respondents have highlighted that integration of BIM and Generative Design would help to overcome many difficulties during early design stages. Moreover, most of the respondents agree that computational idea generation enhance designers’ capabilities. However, it has been revealed that none of existing systems are fully capable for purposefully manipulating conceptual design. As a result, a framework was proposed that uses generative design for conceptual design and form generation coupled with advanced BIM features for illustration, collaboration, and parametric change management. Another interesting research was done by Robertson and Radcliffe [8] regarding CAD (computer-aided design) tools and their impact on creative problem solving in engineering design. Based on a survey it was found that if CAD was used early in the design process, it was often used in an unstructured way, with the aim of trialing and visualizing alternative ideas. Hence, it was concluded that the CAD developers must change their approach to supporting conceptual design.

Some scholars have also highlighted advantages of using TRIZ tools for seeking radical innovations of construction technologies. For instance, in Ref. [9] the function modeling tool was applied in order to design a self-evolutionary model for automated generation of innovative technology alternatives. It was concluded that technology characteristics should be translated into a model that is operational for computer-aided innovation. Moreover, such a technique as Lean [10] also found its implementation in BIM in construction. Such synergy could improve construction design processes.

Bernal et al. [11] focused their research on computational support for designers and identified the areas for future research. According to their results “current computational tools are design-centric, with interfaces from the perspective of the physical components, rather than designer-centric, with a focus
on supporting the actions that designers execute while they manipulate the patterns that drive the arrangement of the parts”. Computer-aided decision making in construction project development is also vital according to Książek et al. [12]. According to this research team, experts with extensive knowledge of construction industry take subjective decisions related to verbal methods of decision making.

Additionally, importance of decision making on the early building design stage was analyzed by a number of scholars. For instance, Østergård et al. [13] concluded that most of design tools are still evaluative, give little or no guidance, these tools typically provide deterministic results that evaluate the design rather than guide the design proactively. The study [14] by Petersen and Svendsen also confirms that the early stages of building design include a number of decisions which have a strong influence on the performance of the building throughout the rest of the design and construction processes. As a result, a method and a program were developed in order to reduce the need for design iterations, reducing time consumption and construction costs. The program was more regarded to energy consumption and indoor environment of buildings.

Parametric scripting is believed to be a productive tool that my help to integrate decision making tools into either BIM or CAD software. According to Nembrini et al. [15] parametric scripting has a strong potential for generating and exploring early design variants. Using such a technique, designers are able to automate geometric description and modification of architectural form. Moreover, Negendahl [16] concludes that combination of a design tool and a visual programming language can provide better support for the designer during the early stages of design. Also dealing with topological information in BIM is an integral part of the conceptual design. Paul and Borrmann [17] have presented concepts of an approach that combines relational database design principles with algebraic and point set topology and shows how complexes and topological spaces can be stored in relational databases. To make complexes suitable for building modelling it is necessary to extend them by geometric properties.

On the other hand, a number of researchers have also developed different approaches for conceptual design of structures. Some approaches were presented in form of theoretical methodologies, while for some of them the ways of automation, including BIM based, were suggested. For instance, Brown and Mueller [18] suggested using geometric multi-objective optimization for design for structural and energy performance of long span buildings. Fenton et al. [19] developed an approach for using grammatical evolution for automatic innovative truss design. Laefer and Truong-Hong [20] have concentrated on automatic generation of 3D steel structures for building information modelling. Afzali et al. [21] developed a procedure based on the MHBMO (modified honey bee mating optimization) algorithm. The technique was developed for discrete optimization of steel frames during design. Another study related to BIM-based structural framework optimization was done by Song et al. [22] who designed a hierarchical structure of a structural framework, described calculation for optimizing structural frame work construction and developed a BIM-based structural framework optimization and simulation system. Tuhus-Dubrow and Krarti [23] developed a genetic-algorithm based approach to optimize building envelope design for residential buildings. The simulation-optimization tool was developed and applied to optimize building shape and building envelope features.

Additionally, some studies related to automated layout design and creating conceptual drawings were obtained during the review. Those aspects are definitely important since they represent results of the conceptual design to a finite user or, more likely, customer. Nimtawat and Nanakorn [24] developed a genetic algorithm for automated layout design of
beam-slab floors. They identified the roles of engineers and computers in the design tasks and extracted tasks in structural design of buildings that can be automated and delegated to computers. Kwon et al. [25] developed a novel principle of shape generation.

3.3 Literature Review Summary

The review and analysis of relevant literature has shown that the BIM technology has been already developed significantly. However, there is still a considerable number of emerging trends in evolution of BIM. Computer-aided decision making, integration of BIM and generative design, creative problem solving in engineering design, automated innovation of construction technologies, computer-aided decision-making in construction, etc. are among them. Nowadays developers are also focused on increasing the level of automation. More and more functions are automated in modern software. However, the focus is shifted mainly towards detailed design, where the software is only a tool in the implementation of already made decisions. At the stage of conceptual design the level of automation is still quite low. Although this stage of design is fundamental and the level of its computer-aided support should increase. Unfortunately, developed techniques do not consider, for instance, analysis and solving technical contradictions that may often lead to new inventive solutions in design. Furthermore, analysis of conceptual model’s elements functionality does not receive proper development. The level of functionality of the system’s elements should be determined at the earliest stages of design in order to identify and eliminate the least functional elements as early as possible. This allows designers to obtain the most progressive and optimized solutions and save resources at the subsequent stages of the life cycle of the project. Those conclusions formed the basis for creating a novel approach for automated conceptual design of building structures.

4. A Novel Approach for Automated Conceptual Design of Building Structures

After analyzing all advantages and disadvantages of existing techniques in the field of automated conceptual design of building structures a novel methodology that consists of three key steps was proposed in this study. However, those steps are conditional and for a software user they are realized via new functions that are integrated into a BIM software, particularly, Revit©. As this paper is dedicated to evaluation of the already developed approach, it is not described here in very details and only the common logic is provided. Thus, the methodology consists of three key steps in order to simplify and automate complex decision making process on early design stages.

The design starts with the step #1 that is called “shape optimization”. Here the only designer’s knowledge, skills and experience are the moving forces. This is the reason why computational support is highly required at this stage. For achieving that purpose special scripts by using a graphical programming software Dynamo have been developed. Graphical programming is a new approach in building design and it brings completely new possibilities for designers and customers and allows significantly automate early design stage. This step is not supposed to use any problem-solving techniques, hence, it is more about looking for optimal solutions but still has a significant meaning for design process. For instance, simple search for an optimal shape of a building only by changing its initial parameters (size, high, number of floors, etc.) instead of completely new design with new parameters of a structure would allow designers to significantly reduce time when project schedules are tight. Once creating a program for a building or a structure a designer can “play” with its initial parameters in order to obtain optimal or desired ones. All that would support engineers during design, shorten conceptual design stage time and accelerate decision making process.
When a required shape of a structure is obtained and there are technical contradictions to be solved in the system, a designer can start the next step #2 which is called the “contradiction analysis”. Technical contradiction is a situation when improvements of one feature of the system decrease some of its other features. Here the TRIZ Contradiction Matrix with 40 inventive principles is suggested to be used. By clicking on an element users go to the “contradiction matrix” menu and formulate technical contradictions for chosen part of design. After that designers are proposed to use a number of principles in order to solve those contradictions. For instance, for horizontal bearing structures a quite common contradiction is between strength and weight of elements. In this case a sufficient inventive principle is “Composite Materials”—change from uniform to composite (multiple) materials. Indeed, using composite materials in construction (reinforced concrete, bi-steel beams and trusses, etc.) is quite common approach. However, it is up to engineers’ decision and experience to either accept or decline suggested inventive principles in order to improve the design. In case if new inventive conceptual solutions were gained during such analysis, designers can go back to the step #1 for re-optimization.

Final step #3 in the proposed approach is the “Function analysis” of a building information model. Here software is supposed to self-analyze BIM and suggest solutions in order to improve the system. For that purpose, it is suggested to use the TRIZ functional modeling and rules of trimming. For increasing software functionality to extracting a function model from BIM model a special graphical program or script with help of Dynamo has been built. The script first automatically detects elements or components in BIM model and places them into an interaction matrix. The interaction matrix defines either elements interact with each other or not and shows all interaction between elements of the system. After that the software defines functions of elements in the Interaction Matrix. In building structures this functions are usually “holds”. However, such functions as “bends”, “expands”, “compresses”, “twists” etc. may take place. For identification of interactions the script applies specially developed rules. On the next step a function model diagram is automatically generated from the interaction matrix. This diagram shows a hierarchical structure of the components and the functions between them. Such function analysis helps to eliminate mental and thinking inertia since attention of designers is put only on elements and functions. Also, the software helps to achieve a more complete and convenient workflow for design engineers as all the steps are done within the BIM environment. Finally, having this overview is a prerequisite for applying the other TRIZ tools, such as function ranking and trimming. Trimming is a method from TRIZ used to reduce the amount of system components without losing system functionality. The method is based on transferring functions performed by a component that should be trimmed to another component. The software uses adapted rules of trimming for finding other components to perform this functionality. The component not performing any functions anymore can be removed (trimmed) from the function model without losing any functionality. As a result, the software highlights the best candidates for trimming in the BIM model and a design engineer can either accept or decline those proposals. In the function ranking functions of elements are ranked according their so-called level of usefulness. In order to perform ranking a “target function” (for instance, “carry live load”) has to be identified firstly. The more high rank belongs to the functions that are closer to the target function. So, the software chooses the furthest from the target functions as the candidates for trimming. There are also so-called “harmful functions” like “bends” or “twists” since bent or twisted elements require more materials in order to stay stable rather than tensioned ones and it may be wise to eliminate such function if it is demanded to
design cheaper but equally stable structure. Function ranking offers the user a quick overview on the structure of a system and on the importance of distribution of functions. Such analysis during conceptual design enables engineers to automatically analyze the BIM model and easily obtain progressive design avoiding complex processes of topology optimization and structural analysis which are issues for further detailed design.

All of the above steps can be repeated as many times as required by the designer. They can also be executed in any sequence, although it is recommended to apply the described logic.

5. Evaluation of the Proposed Approach

In order to evaluate the proposed approach a set of coherent questions was developed and distributed via internet-based professional societies. Survey methodology is a method for collecting quantitative information needed for further analysis [26].

5.1 Survey Design

The survey followed several coherent aims. One of them was to identify how respondents use BIM technology in their work or study processes. Moreover, we wanted to reveal what software packages are most used by them. Additionally, we needed to understand how respondents are familiar with the TRIZ and what TRIZ tools are most used. Furthermore, the survey was aimed at understanding the degree of using graphical programming in professional activities. The key purpose of the questionnaire was to collect and evaluate respondents’ opinions regarding automation of the conceptual design process in construction projects and, more importantly, test and evaluate the proposed solution and its technical realization in BIM environment.

The target group of the survey included engineers, researchers and students who had any relations to design of building structures. They might work or study in this field. The respondents were found mostly via professional or social networks in the internet by posting corresponding messages with a link to the questionnaire in professional forums, societies, student and research communities, etc. Some of the respondents received the direct link to the survey. Approximately one fifth of those who viewed the message responded to the questions.

In general, the developed survey consisted of 19 consecutive questions divided into blocks. Questions 1 and 2 were related to age and region of residence of the respondents and did not have any specific purposes. Question number 3 specified whether the respondents had any relations to design of building structures or not. This question served as a filter in order to weed out respondents not belonging to the required field. Questions 4 and 5 were about experience. Those questions helped to analyze how experienced the respondents were and in which stage of building design they mostly took part. Questions 6-11 were dedicated to design tools, software, etc. Those questions were designed in order to understand how the BIM technology is used by the respondents, what software they use, to what extent they are familiar with TRIZ and how it is applied in professional activities as well as the degree of usage of graphical programming in either work or studies. Question 12 was related to design process and frequency of changes in the design. The main block of questions was devoted to automation of conceptual design process. Questions 13-15 were general and asked opinions about benefits of how software can support a user in the design process. Questions 16-19 were offered to answer after a video demonstration of the possibilities of proposed solution for automation of early building design process.

5.2 Survey Results

As a result 78 responses were received. And 23.1% of the respondents indicated that they are not related to either design or research in the field of building structures. That is why the remaining 76.9% or 60
responses were used for further analysis. Majority of respondents were professionals with 3 to 10 years of professional experience while students and researches were presented by 20% (Fig. 1).

A significant part of the responding specialists was involved in both basic design and detailed design, however, about a half of them somehow took part in the conceptual design (Fig. 2).

We assume that this is a fairly result, since the basic and detailed designs are stages of the technical implementation of the conceptual solutions that are already taken before and, thus, require a larger human resource with a smaller creative component. More than 80% participants are familiar and use building information modeling software.

About 20% use TRIZ tools in the research and work or at least familiar with it. This result remains rather modest although it exceeds the average figures of the studies investigating this issue [27]. Probably, this was due to the fact that the survey was also posted in the groups devoted to the subject of TRIZ.

And 50% of the replies stated that graphical programming tools were never used and not known for interviewed specialist. An important positive point is the result showing that 30% to some extent regularly use the advantages of graphical programming (Fig. 3). And more than 90% declared that they regularly face changes in the design or user requirements.

The next few questions were dedicated to attitude to automation of conceptual design of building structures. And the responses were mostly positive about the proposed approach. For instance, statistics regarding a question “is it useful if the software will give you ready prompts from a database of proven solutions?” is shown in Fig. 4, “is it useful if the software will automatically analyze your conceptually designed system for functionality of its elements and suggest optimization?” is in Fig. 5 and “is it useful if the software will give clues for finding non-trivial solutions that are not common in your field of practice?” is in Fig. 6.

![Fig. 1](image1.png)  Experience in the field of building structures design among the respondents.

![Fig. 2](image2.png)  Distribution of areas of activities among the respondents.
Fig. 3  Regularity of using graphical programming tools among the respondents.

Fig. 4  The respondents' attitude regarding such a proposed software feature as giving ready prompts from a database of proven solutions.

Fig. 5  The respondents' attitude regarding such a proposed software feature as automatic analysis of a conceptually designed system for functionality of its elements and suggesting optimization.
Fig. 6 The respondents’ attitude regarding such a proposed software feature as giving clues for finding non-trivial solutions that are not common in construction design.

Fig. 7 The respondents’ attitude to demonstrated functionality of the proposed approach.

Fig. 8 The respondents’ attitude regarding probability of possible improvements that may be achieved applying functionality of the proposed approach.
Fig. 9 The proposed approach’s functions that are found the most useful and applicable by the respondents.

Fig. 10 Evaluation of novel approach for automated conceptual design of building structures.

5.3 Survey Results Analysis

At the end of the study, the respondents were shown the technical capabilities of the proposed methodology for automation of the conceptual design stage implemented in Revit©. Then they were asked to express their opinions on this matter by answering the set of specially developed questions. The respondents’ attitude to demonstrated functionality of the proposed approach is shown in Fig. 7. Statistics regarding a question “can application of the demonstrated functions improve quality and speed of your work?” is shown in Fig. 8. Fig. 9 reflects distribution of the proposed approach’s functions that are found to be the most useful and applicable by the respondents.

General evaluation of the novel approach for automated inventive conceptual design of building structures is provided in Fig. 10.

The survey results illustrate some of the positive and negative aspects. For instance, a significant part of the respondents are either familiar or use the BIM technology regularly in their professional activities. Of course, it should not be surprising nowadays. On the other hand, the graphical programming approach is still unfortunately not well known. Using TRIZ is also rather modest among construction designers. The very important result of the survey is that designers are ready for changes since majority of them have positive attitude to automation of conceptual design of building structures. They believe that it would be useful if their software would automatically analyze the concept for functionality of its elements and propose optimization or solve technical contradiction by proposing novel solutions. The main part of the survey devoted to evaluation of the demonstrated functions of the proposed approach for conceptual design of building structures automation was generally answered also in a positive way. The respondents evaluated the demonstrated functions as useful and stated that those functions could improve quality and speed of their work, the approach has
potential and could help gaining more novel and optimal conceptual solutions. The functional analysis was determined as the most useful and applicable among the demonstrated possible features of the software. However, it was also mentioned that not all the functions may be used in the real concept design and they still need development.

6. Conclusions

In the article all the stated research questions were answered consistently. The current situation in the field of automation of conceptual design process in the construction projects was studied by analyzing the thematic publications. The relevance of the suggested novel approach was proven by both summarizing the literature review and analyzing results of the specially prepared survey. Advantages and disadvantages of the proposed methodology were also evaluated by demonstrating its functionality and further collection and analysis of professional feedback. Generally, the proposed approach for automated inventive conceptual design of building structures was evaluated as interesting and having prospective. It was confirmed that such very potential instruments as graphical programming and TRIZ unfairly remain unnoticed by most specialists and our proposal reveals all their possibilities. As for further development of the approach it is suggested to follow users’ feedback and expand its functionality, convenience of use and adapt to cases from real practice.

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